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# FATE OF PLANT PATHOGENS AND PESTICIDES DURING COMPOSTING OF GREENHOUSE TOMATO PLANT RESIDUES

by

Fahad Alkoaik

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in partial fulfillment of the requirements
for the degree of

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## DEDICATION

To:

**My parents**
*Naser S. Alkoaik* and *Modhy A. Alzegadi*

**My wife**
*Najla A. Albaker*

**My children**
*Abdulaziz*, *Naser*, *Reynad*, *Meral* and *Dhary*

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# LIST OF ABBREVIATIONS AND SYMBOLS

## Abbreviations

| | |
|---|---|
| AAFC | Agriculture and Agri-Food Canada |
| ATCC | American Type Culture Collection |
| BNQ | Office of Standardization of Quebec |
| CCME | Canadian Council of Ministers of Environment |
| CFIA | Canadian Food Inspection Agency |
| CNV | Cucumber Necrosis Virus |
| DM | Dry matter |
| ELISA | Enzyme-Linked Immunosorbent Assay |
| FAO | Food and Agriculture Organization |
| FS | Fixed Solids |
| GC | Gas Chromatograph |
| ID | Inside Diameter |
| KSA | Kingdom of Saudi Arabia |
| MC | Moisture Content |
| MEC | Material Engineering Center |
| MSW | Municipal Solids Waste |
| NRAES | Northeast Regional Agriculture and Engineering Service |
| NRCC | National Research Council of Canada |
| OMW | Olive-Mill Wastewater |
| ON | Organic Nitrogen |
| PDA | Potato Dextrose Agar |
| PDB | Potato Dextrose Broth |
| PLFA | Phospholipids Fatty Acid |
| PVC | Polyvinyl Chloride |
| RPM | Revolution Per Minute |
| SCC | Standards Council of Canada |
| TC | Total Carbon |
| TKN | Total Kjeldahl Nitrogen |

| | |
|---|---|
| TMV | Tobacco Mosaic Virus |
| TNV | Tobacco Necrosis Virus |
| TOC | Total organic carbon |
| TRV | Tobacco Rattle Virus |
| TS | Total Solids |
| UN | United Nations |
| VS | Volatile Solids |

## English Symbols:

| | |
|---|---|
| a | The slope of the linear line, constant (-) |
| $A_c$ | The surface area of the cylinder ($m^2$) |
| $A_{Ci}$ | The inside surface area of the cylinder ($m^2$) |
| $A_{Cins}$ | The outside surface area of the insulation ($m^2$) |
| $A_{Co}$ | The outside surface area of the cylinder ($m^2$) |
| $A_{plexi}$ | The surface area of the Plexiglas side wall ($m^2$) |
| $A_{PVC}$ | The surface area of the PVC side wall ($m^2$) |
| b | The intercept (offset), constant (-) |
| C:N | Carbon to nitrogen ratio (-) |
| C | Carbon, dry basis (%) |
| $C_0$ | Initial concentration of the organic substrate (mg/ kg) |
| $C_i$ | Initial pesticide concentration (mg/ kg) |
| $Cp_a$ | The specific heat of the air (kJ/ kg °K) |
| $Cp_{Alumi}$ | The specific heat of the cover (Aluminum) (kJ/ kg °K) |
| $Cp_{compost}$ | The specific heat of the compost (kJ/ kg °K) |
| $Cp_{fiber}$ | The specific heat of the fiberglass (kJ/ kg °K) |
| $Cp_{plexi}$ | The specific heat of the Plexiglas side wall (kJ/ kg °K) |
| $Cp_{pvc}$ | The specific heat of the cylinder material (PVC) (kJ/ kg °K) |
| $Cp_{ss}$ | The specific heat of the stainless steel mixing shaft (kJ/ kg °K) |
| $Cp_{styro}$ | The specific heat of the Styrofoam (kJ/ kg °K) |
| $C_t$ | Pesticide concentration at time t (mg/ kg) |

| | |
|---|---|
| D | Duration of temperature ≥ 55 °C (h) |
| $\bar{dp}$ | The average particle size of the mixture (mm) |
| $dp_i$ | The average particle size in the interval (mm) |
| DW | Dry weight (g) |
| FS | Fixed solids , dry basis (%) |
| $H_2O$ | Weight of water added (kg) |
| $h_a$ | The specific enthalpy of dry air (kJ/ kg dry air) |
| $h_g$ | The specific enthalpy for water vapor (kJ/ kg water) |
| $h_i$ | The enthalpy at $T_{in}$ (kJ/ kg dry air) |
| $h_{si}$ | The convective heat transfer coefficient between the compost and the surface of the inside wall of the system (kJ/ $m^2$ h °K) |
| $h_m$ | The specific enthalpy of the mixture (kJ/ kg dry air) |
| $h_o$ | The enthalpy at $T_a$ (kJ/ kg dry air) |
| $h_{Ti}$ | The convective heat transfer coefficient between the compost and the inside surface of the cylinder (kJ/ $m^2$ h °K) |
| $h_o$ | The convective heat transfer coefficient between the bioreactor surface area and the room (kJ/ $m^2$ h °K) |
| k | Rate constant ($h^{-1}$) |
| $k_{Plexi}$ | The thermal conductivity of the Plexiglas material (kJ/ m h °K) |
| $k_{PVC}$ | The thermal conductivity of the PVC material (kJ/ m h °K) |
| $k_{Styro}$ | The thermal conductivity of the Styrofoam material (kJ/ m h °K) |
| $L_c$ | The characteristic length of the cylinder (m) |
| $LL_t$ | Number of local lesions at time t (-) |
| $M_i$ | Percent moisture content, wet basis (%) |
| $m_a$ | The mass of dry air (kg) |
| $M_a$ | Moisture content of amendment, dry basis (%) |
| $M_{aa}$ | Moisture content of amendment added = 100% for water (%) |
| $M_{Alumi}$ | The mass of the Aluminum sheet (kg) |
| $M_b$ | Moisture content of bulking agent, dry basis (%) |
| $M_c$ | Moisture content in percent (%) |

| | |
|---|---|
| $M_{compost}$ | The mass of the compost (kg) |
| $M_{cylinder}$ | The mass of the cylinder (kg) |
| $M_d$ | Desired moisture content of mix , dry basis (%) |
| $MD_t$ | Mold density at time t (µg mycelium/ g mixture) |
| $M_{fiber}$ | The mass of the fiberglass (kg). |
| $M_m$ | Moisture of the compost mixture, wet basis (%) |
| $M_{mb}$ | Moisture of compost mix before adding amendment, wet basis (%) |
| $M_{mb}$ | Moisture of mix before adding amendment (%) |
| $M_{plexi}$ | The mass of the Plexiglas side wall (kg) |
| $M_{pvc}$ | The mass of the PVC side wall (kg) |
| $M_{ss}$ | The mass of the stainless steel mixing shaft (kg) |
| $M_{styro}$ | The mass of the Styrofoam (kg) |
| $m_v$ | The mass of water vapor (kg) |
| $M_w$ | Moisture content of waste, wet basis (%) |
| $M_{wet}$ | Moisture content of material, wet basis (%) |
| N | Nitrogen, dry basis (%) |
| $N_{aa}$ | Nitrogen in amendment to be added, dry basis (%) |
| $N_m$ | Nitrogen in compost mix, dry basis (%) |
| $P_a$ | The partial pressure of the dry air (N/ $m^2$) |
| $P_{atm}$ | The atmospheric pressure (pa) |
| $P_v$ | The partial pressure of the water vapor (N/ $m^2$) |
| $P_v$ | The partial pressure of water vapor (Pa) |
| $Q_{air}$ | The inlet airflow rate ($m^3$ /h) |
| $q_{Alumi-c}$ | The heat required to raise the temperature of the aluminum cover kJ/ h) |
| $q_c$ | The heat loss through the main body of the cylinder (kJ/ h) |
| $q_{compost}$ | The heat required to raise the temperature of the medium (kJ/ h) |
| $q_e$ | The heat loss with the exhaust gas (kJ/ h) |
| $q_{fiber-c}$ | The heat required to raise the temperature of the horizontal (kJ/ h) |
| $q_m$ | The heat added by the mixing unit (kJ/ h) |

| | |
|---|---|
| $q_{mixing}$ | The heat required to raise the temperature of the mixing shaft (kJ/h) |
| $q_p$ | The heat generated by the organic substrate metabolism (kJ/ h) |
| $q_{plexi}$ | The heat loss through the Plexiglas side wall (kJ/ h) |
| $q_{plexi-w}$ | The heat required to raise the temperature of the Plexiglas side wall (kJ/ h) |
| $q_{pvc}$ | The heat loss through the PVC side wall (kJ/ h) |
| $q_{pvc-c}$ | The heat required to raise the temperature of the horizontal PVC cylinder (kJ/ h) |
| $q_{pvc-w}$ | The heat required to raise the temperature of the PVC side wall (kJ/ h) |
| $q_{pvc-w}$ | The heat required to raise the temperature of the Styrofoam insulation of the side wall (kJ/ h) |
| $q_r$ | The heat loss by radiation (kJ/ h) |
| $q_s$ | The total heat required to raise the temperature of the medium and system components (kJ/ h) |
| $R_a$ | The gas constant (J/ kg °K) |
| $R_w$ | The water constant (J/ kg °K) |
| $R_{aa}$ | C: N ratio of compost amendment to be added (-) |
| $R_d$ | Desired C: N ratio (-) |
| $r_i$ | The inner radius of the cylinder (m) |
| $r_{ins}$ | The radius of the insulation material (m) |
| $R_m$ | C:N ratio of compost mix (-) |
| $R_{mb}$ | C: N ratio of the compost mix before adding amendment (-) |
| $r_o$ | The outer radius of the cylinder (m) |
| T | The absolute temperature (K) |
| T | Temperature (°C). |
| T | The dry bulb temperature of the mixture (°C) |
| t | Time (h) |
| $\Delta t$ | The time interval (h) |
| $T_a$ | The laboratory ambient temperature (K) |

| | |
|---|---|
| $T_{Actual}$ | Actual temperature reading (°C) |
| TC | Total carbon reduction (%) |
| $T_{Corrected}$ | Corrected temperature reading (°C) |
| $T_f$ | The final temperature of the compost at the end of a time interval (°K). |
| TFG | Total amount of oil added (mL) |
| TFGi | Initial fat and grease (%) |
| TFGr | Reduction in fat and grease (%) |
| $T_i$ | The initial temperature of the compost at the beginning of a time interval (°K). |
| $T_{in}$ | The air inlet temperature (°K) |
| TKN | Total kjeldahl nitrogen reduction (%) |
| $T_m$ | Maximum temperature (°C) |
| $T_o$ | The exhaust gas temperature within a time interval (°K) |
| $T_s$ | The temperature of the outside surface of the bioreactor within a time interval (°K) |
| $T_v$ | The average temperature of the compost within a time interval (°K) |
| $\Delta T_{1\text{-}7}$ | The temperature changes in the material of the cylinder, fiber, aluminum, pvc side wall, styrofoam, plexiglas side wall, and mixing shaft within a time interval respectively (°K) |
| $U_c$ | The overall heat loss coefficient of the cylinder (kJ/ $m^2$h °K) |
| $U_{Plexi}$ | The overall heat loss coefficient of the Plexiglas side wall (kJ/$m^2$ h °K) |
| $U_{PVC}$ | The overall heat loss coefficient of the PVC side wall (kJ/$m^2$ h °K) |
| V | The total volume of the gas mixture ($m^3$) |
| VS | Volatile solids reduction (%) |
| VS | Weight of volatile solids (kg) |
| w | The humidity ratio (kg water /kg dry air) |
| w | The humidity ratio (kg water /kg dry air) |
| $W_a$ | Wet weight of amendment (kg) |
| $W_{aa}$ | Wet weight of amendment to be added (kg) |

| | |
|---|---|
| $W_b$ | Wet weight of bulking agent (kg) |
| $W_c$ | Dry weight of carbon (kg) |
| $W_{ca}$ | Weight of carbon in amendment (kg) |
| $W_{cb}$ | Weight of carbon in bulking agent (kg) |
| $W_{cw}$ | Weight of carbon in waste (kg) |
| $W_{dry}$ | Dry weight of material (kg) |
| $W_m$ | Weight of the compost mix including wet weight of waste, bulking agent, amendments, and added water (kg) |
| $W_{mb}$ | Wet weight of mix before adding in amendment (kg) |
| $W_n$ | Dry weight of nitrogen (kg) |
| $W_{na}$ | Weight of nitrogen in amendment (kg) |
| $W_{nb}$ | Weight of nitrogen in bulking agent (kg) |
| $W_{nd}$ | Dry weight of nitrogen to add to mix (kg) |
| $W_{nm}$ | Weight of nitrogen in compost mix (kg) |
| $W_{nw}$ | Weight of nitrogen in waste (kg) |
| $W_w$ | Wet weight of waste (kg) |
| WW | Wet Weight (g) |
| $W_{wet}$ | Wet weight of material in question (kg) |
| Xi | The weight fraction in the intrval (g) |
| $X_{Plexi}$ | The thickness of the Plexiglas sidewall (m). |
| $X_{PVC}$ | The thickness of the PVC sidewall (m) |
| $X_{Styro}$ | The thickness of the Styrofoam insulation (m). |
| $\rho$ | The air density ($kg/m^3$) |

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# CONTRIBUTIONS TO KNOWLEDGE

The contributions of this thesis to knowledge in the field of composting can be summarized as follows:

1. An efficient laboratory scale composting system in which the temperature and duration of thermophilic stage can be manipulated and controlled was developed.
2. The biological and thermal parameters of the composting process were defined and investigated.
3. It has been demonstrated that the heat lost through the body of an insulated bioreactor and that lost with the exhaust gas can be quantified and used to determine the amount of bioavailable carbon required to maintain a constant temperature during an extended thermophilic stage.
4. It has been demonstrated that a uniform distribution of a constant high temperature and an extension of the thermophilic phase can be achieved by adequate mixing and addition of the proper amount of bioavailable carbon source.
5. It has been demonstrated that plant pathogens and pesticides can be completely destroyed in a relatively short time in a properly designed and controlled in-vessel composting system.
6. The distributions of fungi and bacteria in the three thermal stages (psychrophilic, mesophilic and thermophilic) of the active composting zone were investigated and documented.
7. Models describing the destruction of *tobacco mosaic virus* and *Botrytis cinerea* as a function of time and temperature was developed.
8. A model describing the destruction of pirimiphos-methyl as a function of initial concentration, time and temperature was developed

# ABSTRACT

Commercial greenhouse tomato production is an intensive cropping system yielding large volume of crop per surface area and at the same time produces considerable amounts of plant residues as a result of trimming and after harvesting the crop that must be disposed of properly. Since tomato plants are subjected to an intensive use of pesticides to control insects and other disease, the proper management of crop residue is necessary to minimize their adverse effects, especially if the pathogen involved can infect subsequent crops. It was hypothesized that composting, while producing a soil conditioner that could improve soil fertility, could also inactivate plant pathogens and destroy pesticides. The aim of this study was, therefore, to develop an efficient laboratory bioreactor in which the temperature and duration of thermophilic phase of the composting process can be manipulated and controlled in order to investigate the effectiveness of the composting process in inactivating two plant pathogens (*Tobacco mosaic virus* and *Botrytis cinerea*) and destroying the insecticide pirimiphos-methyl.

The study was carried out in four separate but interrelated stages. In the first stage, an in-vessel laboratory composting system, fully equipped with a mixing unit, controlled aeration unit, thermocouples, and data logger, was developed. In the second stage, the feedstock material (tomato remains) was analyzed for total carbon, total nitrogen and macronutrients and the C: N ratio, the need for nitrogen supplement and bulking agent and the appropriate particle size of the feedstock material were determined. A set of experiments were then conducted to establish the optimum composting conditions. In these experiments, the effects of inoculum size and type and amount of bioavailable carbon source were investigated. In the third stage, a heat balance was performed on the system to determine the heat generated by mixing and metabolic activities and to establish the conditions needed to maintain a constant thermophilic temperature and to extend the duration of the thermophilic phase. In the fourth stage, experiments were conducted to investigate the influence of the established composting condition on the destruction of *Tobacco mosaic virus, Botrytis cinerea* and the Pirimiphos-methyl (Actellic) insecticide.

The moisture content remained within the optimum range of 50 – 70% at all times for all experiments due to the equilibrium between the water produced by microbial respiration and water lost with the exhaust gas. The reduction in the moisture content was influenced by the source of bioavailable carbon. The reductions in the volatile solids were affected by the source and amount of bioavailable carbon and temperature. Increasing the inoculum size or the amount of manure added to the mixture increased the reduction in volatile solids. Continuous addition of used cooking oil at higher rates resulted in lower reductions of the volatile solids as the microorganisms preferred the added used cooking oil over other sources of carbon in the mixture. The reductions in volatile solids were also affected by the temperature and the duration of higher temperature; the longer the period of higher temperature, the greater the reductions in the total volatile solids. Lower total carbon reductions were observed in the present study due to the fact that most of the carbon in the wood shaving was nonbioavailable for microbes in the short run. The ammonium nitrogen content remained relatively constant for all mixtures as a result of microbial conversion of organic nitrogen to ammonium by the mineralization process and the conversion of ammonium back to organic nitrogen (microbial protein) by the assimilation process. The nitrification of ammonium into nitrite ($NO_2$) and nitrate ($NO_3$) was inhibited by high temperature. The reduction in the total kjeldahl nitrogen (TKN) was affected by the initial TKN and carbon contents, the balance between bioavailable nitrogen and bioavailable carbon and the temperature. Increasing the inoculum size or the amount of manure added to the mixture increased the TKN reduction. The Macronutrients (Ca, Na, Fe, Mg, P, K, Zn, Cl and S) available in the composting mixtures were sufficient for microbial growth and were within the range reported in the literature for successful composting process.

The four phases of composting process (initial lag or inactive phase, exponential or active phase, stationary phase and death or maturation phase) were clearly identified in all the experiments. The heat generated from the degradation of the organic matter raised the temperature though the three thermal stages of the active phase (psychrophilic, mesophilic and thermophilic). The two lag phases (mesophilic and thermophilic) were easily identified and graphically determined. The addition of 10 % inoculum (municipal

solid compost) reduced the lag phase and increased the rate of temperature increase. However, an inoculum size higher than 10 % increased the lag phase, decreased the rate of temperature increase and increased both the maximum temperature and its duration. The mixture that received no inoculum and those which received manure never achieved thermophilic stage. The heat balance performed on the bioreactor indicated that the energy required for mixing (2.16 kJ/h) was only 83.1 % of the energy input into the bioreactor, 16.9 % was due to the heat losses in the motor assembly. The peak heat production rate (at 63 °C) was 62.5 kJ/h. The rate of heat production decreased dramatically after the temperature had reached 60 °C due to the decline in microbial growth and activity. Approximately, 36.5 % of the total heat produced was lost by conduction through the cylindrical body and side walls of the bioreactor whereas the heat losses with the exhaust gas accounted for 63.5 %.

The composting process was successful in destroying the *tobacco mosaic virus*. The TMV completely lost its ability to infect the leaves of a susceptible host after less than four days (or 126 h from the start of the composting process) of controlled thermophilic (62-65 °C) composting whereas the fungus *Botrytis cinerea* was completely destroyed after two days (or 78 h from the start of the composting process) of controlled thermophilic (63°C) composting. The relatively short time required for complete inactivation of TMV and *Botrytis cinerea* observed in this study were achieved as a result of maintaining a constant high temperature, a uniform distribution of temperature and the extension of the thermophilic stage by the continuous addition of the proper amount of bioavailable carbon (used cooking oil). The Fungi and bacteria were abundantly present in the psychrophilic phase. Some fungi appeared during the mesophilic phases and until the second day of the thermophilic phase. Bacteria dominated the thermophilic phase. The composting process was capable of destroying pirimiphos-methyl. The majority of pirimiphos-methyl (87-92 %) was destroyed within the first 102 h, depending on the initial concentration. Complete destruction of the pesticide requires approximately 438 h. The mesophilic degradation rate constant was not affected by the initial concentration of pirimiphos-methyl and was higher than that of the thermophilic phase. The thermophilic degradation rate constant was affected by the initial concentration of pirimiphos-methyl.

# 1. INTRODUCTION

Commercial greenhouse crop production is an intensive cropping system yielding large volume of food material per surface area. Permanent greenhouses are covered with glass, or fiberglass and cooling/heating systems are normally included, where as, temporary ones are covered with plastic materials with natural ventilation. The greenhouse industry is one of the fastest growing sectors of agriculture in the kingdom of Saudi Arabia (KSA) for many reasons as stated by Duwais and Hassan (1995). These include: (a) higher productivity compaired to the open field cultivation practice, for example tomato crop production in greenhouses is 7 times higher under KSA climate, (b) water conservation, 87 % of the water consumed in conventional agricultural practice is preserved under greenhouse condition for tomato crop, (c) climate parameters are controlled to suit specific crop requirements, (d) effectiveness of disease control, controled environment makes it possible to control plant pathogens effectively and economiclly, and (e) possibilty of overcoming poor soil fertility and infected soil by introduing soilless agricultural practice, or the use of artificial growing media, usually available in long plastic bags.

The only disadvantage of commercial greenhouse crop production system is that there are considerable amounts of plant remains (residues) as a result of trimming and after harvesting the crop that must be disposed off properly. Typical vegetable greenhouse operation produce 40-60 tonnes of organic residues (plant debris) per hectare per year (OMAF, 2004). Accordingly, the geenhouse industry in the KSA currently produces over 300,000 tonnes of organic wastes per year. Organic wastes come from the residues of plants including: stems, leaves, roots, and damaged and unripen fruits.

Plant waste, trimmings and residues, are usually piled near greenhouses or burned. These practices, however, cause several undesirable agronomic and environmental problems, since tomato plants are subjected to intensive use of pesticides to control insects and other diseases problems. Therefore, management of crop residues is necessary to minimize their adverse effects, especially if the pathogens involved can infect subsequent crops (Conway, 1996).

According to AAFC (2001) and OMAF (2004), composting of greenhouse wastes is considered the preferred organic waste management method for many reasons: (a) it converts the biodegradable wastes into a stable and useful product, which can generate revenues for the greenhouses farmers, (b) reduces environmental impacts of waste handling and disposal, and (c) improves productivity of the agricultural lands, where it will be applied. Since one of the challenges facing the agricultural industry in the KSA is the poor agricultural soil, composting tomato remains (residues) collected as a result of trimming and after harvesting of the fruits can produce a very promising soil conditioner that could increase soil fertility. Since one of the problems associated with the disposal of greenhouse waste is the presence of pesticides and plant pathogens, the composting system, as a controlled biological process, must be designed to accelerate the decomposition of pesticides and the destruction of plant pathogens.

# 2. OBJECTIVES

The primary aim of this study was to investigate the destruction of *Tobacco mosaic virus* and *Botrytis cinerea* and the fate of Pirimiphos-methyl (Actellic) insecticide during the composting process of tomato plant remains. The specific objectives were:

1. To develop and test an efficient pilot scale composting system suitable for chopped tomato plant residues.

2. To establish the optimum composting conditions (type and size of inoculum, bulking agent, bioavailable carbon and nitrogen, particle size) for the composting of tomato plant residues.

3. To perform heat balance on the system in order to determine:

   (a). the heat generated by mixing,
   (b). the heat generated by the metabolic activities, and
   (c). the amount of bioavailable carbon need to maintain a constant thermophilic temperature in the bioreactor.

4. To evaluate the effect of the optimum composting condition on the destruction of *Tobacco mosaic virus* and *Botrytis cinerea* and the degradation of Pirimiphos-methyl (Actellic).

# 3. SCOPE OF THE STUDY

The study was carried out in four separate but intereleted stages. In the first stage, an in-vessel laboratory composting system, fully equipped with a mixing unit, controlled aeration unit, thermocouples, and data logger, was developed

In the second stage, the feedstock material (tomato remains) was analysed for total carbon, total nitrogen and macronutrients. The C: N ratio and the need for nitrogen supplement were determined. Also, the need for bulking agent and the appropriate particle size of the feedstock material were determined. A set of preliminary experiments were conducted to establish the optimum composting conditions. In these experiments, the effects of inoculum size and the type and the amount of bioavailable carbon source were investigated.

In the third stage, a heat balance was performed on the system to determine the heat generated by mixing and metabolic activities and to establish the condition needed to maintain a constant thermophilic temperature and to extend the duration of the thermophilic phase.

In the fourth stage, experiments were conducted to investigate the influence of the established composting condition on the destruction of *Tobacco mosaic virus, Botrytis cinerea* and the Pirimiphos-methyl (Actellic) insecticide.

# 4. LITERATURE REVIEW

## 4.1 Agricultural Industry in Saudi Arabia

The Kingdom of Saudi Arabia (KSA) lies between 15.2° and 32.6° North and 34.1° and 55.5° East and covers a large area of about 2.2 million square kilometers, of which more than half is desert (Figure 4.1). The climate is generally mild in the winter and dry and hot in the summer (Al-Hazmi, 2000).

The agricultural sector in the KSA has grown at an average annual rate of 8.7% and is becoming the largest non-petroleum sector employing 16% of the population in 1998. In 1997, Saudi Arabia was awarded the Agricola Gold Medal, the highest award of the UN Food and Agriculture Organization (FAO), for its significant contribution to increasing food security in the world, encouraging agricultural development, and fighting poverty in developing countries. The KSA has reached self-sufficiency for certain food items, and is close to achieving self-sufficiency in others. In total, Saudi Arabia has reached 84 percent self-sufficiency in vegetables consumption (SA_MOA,2000).

The major vegetable crops in Saudi are shown in Table 4.1. These include: Tomato, cucumber, eggplant, squash, okra, melon, potato, carrot, and onion. In general, potatoes lead the list of vegetables with a production area of 15714 hectares yielding 394559 tonnes followed by tomatoes with a production area of 11455 hectares, yielding 271,275 tonnes. Tomato production is still meeting only 59 % of local demand showing substantial room for growth.

## 4.2 Greenhouse Tomato Production in Saudi Arabia

Tomato plant, a vine-like plant, belongs to the family Solanaceae (the nightshade family), which includes various potato, pepper, eggplant and tobacco species. The tomato plant likes sunny, hot and humid environment. It is a warm season perennial cultivated as an annual. Therefore, it is the most commonly produced greenhouse crop.

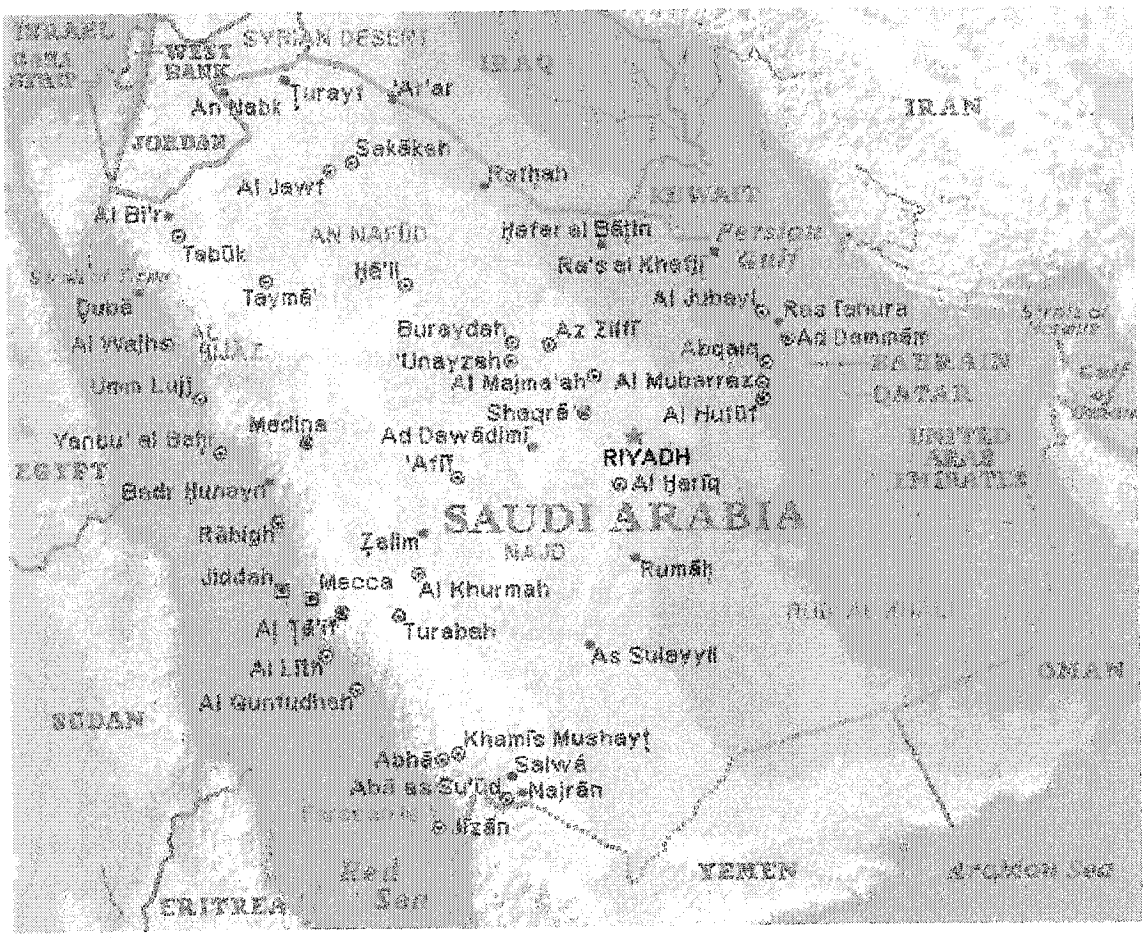



Figure 4.1. The kingdom of Saudi Arabia (SA_M, 2001).

Table 4.1. Production and area of some crops in Saudi Arabia (SA_MOA,2000).

| Crop | Specialized [1] | | Traditional [2] | | Total | | |
|---|---|---|---|---|---|---|---|
| | Production (Tones) | Area (ha) | Production (Tones) | Area (ha) | Production (Tones) | Area (ha) | S.S.R [3] (%) |
| Tomato | 98992 | 987 | 172283 | 10468 | 271275 | 11455 | 59 |
| Cucumber | 115408 | 1544 | 17357 | 1154 | 132765 | 2698 | 102 |
| Eggplant | --- | --- | 60773 | 4768 | 60773 | 4768 | 102 |
| Squash | --- | --- | 79062 | 6086 | 79062 | 6086 | --- |
| Okra | --- | --- | 50752 | 6660 | 50752 | 6660 | 94 |
| Melon | --- | --- | 98810 | 5102 | 98810 | 5102 | 87 |
| Watermelon | --- | --- | 262380 | 14044 | 262380 | 14044 | 103 |
| Potato | 253253 | 9886 | 141306 | 5828 | 394559 | 15714 | 101 |
| Dry onion | --- | --- | 95323 | 3243 | 95323 | 3243 | 42 |
| Other * | 52594 | 548 | 307435 | 17739 | 360029 | 18287 | --- |
| Total | 520247 | 12965 | 1351153 | 78103 | 1871400 | 91068 | 89 |

* Other crops include lettuce, pepper, and green beans.
1- specialized projects are for a specific crop(s).
2- traditional projects are any other projects.
3- S.S.R. Self Sufficiency Ratio.

### 4.2.1 Production

The total crop production of greenhouses in the KSA is 266,994 tonnes (SA-MOA, 2000). Among the crops grown in greenhouses, cucumber and tomato are the most important crops in the country. While cucumber has reached its maximum production of 115,408 tonnes, current tomato crop production of 98,992 tonnes is expected to double to meet the local demand. The current tomato production in various parts of the KSA are presented in Table 4.2.

### 4.2.2 Tomato Pathogens

The ministry of agriculture in the KSA had done a survey on the diseases that affect tomato crop under greenhouse environment. The official team visited many greenhouse sites and collected data related to the type of disease and the recommanded pesticide (Abu-Jawdah, 1986). The study indicated that tomato crop is susceptible to various types of insects and diseases, especially under greenhouses environment where optimum conditions of most pathogens are met. The most common insects are aphids, whiteflies, leafminers and tomato pinworms. Other insect pests are armyworms, tomato fruitworm and cabbage looper. Spider mites also can be a problem under hot, dry conditions. Aphids and leafminers, in addition to the damage caused by feeding on the plant, can spread some tomato diseases and provide infestation sites for others (Sorensen, 1993). The root knot nematode, *Meloidogyne spp*, is widely distributed in the KSA. Nematode infection renders the crops more susceptible to infection by other soil pathogens. Other diseases or disorders have been reported, such as Autogenous Necrosis, Fruit Pox, Gold Fleck, and Graywall, they are mostly believed to be genetic. Tomato plant diseases were, however, classified as bacterial, fungal, viral, and nematode diseases, in addition to the physiological disorders (APS, 2004).

4.2.2.1 Bacteria. Data on plant pathogenic bacteria in greenhouse environments in Saudi Arabia were not included in the official survey conducted by the Ministry of Agriculture. However, reported pathogenic bacteria effecting tomato crop are shown in Table 4.3 (APS, 2004). Since tomato crop optimum condition in greenhouses is globally

Table 4.2. Estimated greenhouse area and production of tomato by region in the Kingdom of Saudi Arabia during winter (SA-MOA, 2000).

| Region | 1998 | | 1999 | |
|---|---|---|---|---|
| | Area (ha) | Production (ton) | Area (ha) | Production (ton) |
| Eastern | 77 | 8470 | 110 | 19974 |
| Riyadh | 111 | 12283 | 212 | 14764 |
| Qaseem | 42 | 4606 | 85 | 6225 |
| Hail | 5 | 537 | 6 | 716 |
| Tabouk | 45 | 4961 | 14 | 2280 |
| Medinah | N/S | 47 | 7 | 725 |
| Makkah | 6 | 685 | 28 | 2374 |
| Aseer | 3 | 312 | 17 | 1203 |
| Al-Baha | 1 | 90 | 10 | 890 |
| Jizan | 0 | 0 | 0 | 0 |
| Najran | N/S | 36 | 2 | 72 |
| Al-Jouf | N/S | 30 | 3 | 272 |
| North Frontier | 0 | 0 | 0 | 0 |
| Total | 290 | 32057 | 494 | 49496 |

N/S not specified

Table 4.3. Tomato crop bacterial diseases (APS, 2004).

| Disease | Bacteria | Optimum Temperature (°C) | Thermal Death Temperature (°C) | Infected Part |
|---|---|---|---|---|
| Bacterial Canker | *Clavibacter michiganensis subsp. Michiganensis* | 24-27 | Sensitive to heat and acid | Leave, stem and fruit |
| Bacterial Speck | *Pseudomonas syringae pv* | 28-30 | 51 | Leave, stem |
| Bacterial Spot | *Xanthomonas vesicatoria pv.* | 24-32 | | Leave, stem and fruit |
| Bacterial Wilt | *Pseudomonas solanacearum* | 35-37 | 52 | Leave and stem |
| Pith Necrosis | *Pseudomonas corrugata* | 27-37 | 52 | Leave and stem |
| Syringae Leaf Spot | *Pseudomonas syringae pv.* | 28-30 | 51 | Leave and stem |

Thermal Death Temperature = Temperature necessary for the destruction of a pathogen by heat (Altman and Dittmer, 1972).

similar, diseases should be similar as well. Bacteria are sensitive to heat except for spore forming; *Bacillus cereus* (as an exopathogen of tobacco) is the only known spore forming bacterial plant pathogen (Bollen, 1985). Thermal death point for most bacterial plant pathogen, suspended in water for 10 minutes, is near 50 °C (Elliott, 1951).

4.2.2.2 Fungi. Some of the fungal diseases reported under greenhouse conditions in the KSA are shown in Table 4.4. *Pythium*, *Fusarium*, *Cladosporium*, *Botrytis*, *Alternaria*, and *Phytophthora* are among the most reported fungi affecting tomato crop under greenhouse conditions in the KSA (Abu-Jawadah, 1986). According to Bollen (1993), soil-borne fungal plant pathogens are sensitive to heat. Few species of *Fusarium Oxysporum*, which are considered as the most heat resistant fungal plant pathogen, survived after a 30 minutes exposure to more than 55 °C in moist soil. Lopez-Real and Foster (1985) stated that resting spores of the club root fungus *Plasmodiophora Brassicae* in macerated tissues survived treatment at 65 °C for 10 minutes. However, for 30 minutes, the lethal temperature was close to 55°C.

4.2.2.3 Virus. Two viral diseases are reported under greenhouse conditions in the KSA as shown in Table 4.5. The tomato yellow leaf curl virus is the cause of the most damaging tomato disease in central region of the KSA. The infected tomato plant yield is reduced by more than 70% (Abu-Jawadah, 1986). Tobacco mosaic virus is another reported virus in the KSA. It is very resistant to a range of climatic conditions as it is the most heat resistant plant virus (Bollen, 1993).

### 4.2.3 Pesticides

The term pesticide as defined by the United States of Environment Protection Agency (USEPA) as any substrate that prevents, destroys, repels, or mitigates a pest. The target pest can be an insect, weed, disease causing microorganisms, or any organism that human deem harmful. Thus the term pesticide generally covers insecticides, fungicides and herbicides (Büyüksönmez et al., 1999). However, most of the pesticides used in greenhouses are from the first two categories, insecticides and fungicides. Pesticides

Table 4.4.Tomato fungal diseases in greenhouses in the Kingdom of Saudi Arabia (Abu-Jawadah, 1986).

| Disease | Fungus | Optimum Temperature (°C ) | Thermal Death Temperature (°C ) | Time (min) | Chemical Control |
|---|---|---|---|---|---|
| Damping off, and Foot and Root Rot | *Phytophthora capsici,* | 25-30 | 44 | 0.25 | Preventive sprays with one of the following pesticides: maneb, mancozeb, captafol, thiram, tolclofos |
| | *Pythium aphanidermatum,* | 20 | 51 | 0.25 | Curative sprays by mixture of Prothiocarb , propamocarb, or metalaxyl with, Carben dazimthiophate ,thiophanate, or thiabendazole. maneb,zineb,mancozeb, captafol,chlorothalonil, propineb, arbendazim, and ulvithiophanate. |
| | *Rhizoctonia solani,* | 15-18 | 49-63 | N/S | |
| | *Fusarium oxysporum,* | 26 | 54 | 0.25 | |
| | *Colletotrichum coccodes,* | 18-28 | 56<br>46 | 5<br>20 | |
| | *and Didymella lycopersici* | 19-20 | 39 | N/S | |
| Early Blight | *Alternaria solani,and Alternaria. alternata* | 24-29 | 50 | 25 | |

N/S not specified.
Thermal Death Temperature = Temperature necessary for the destruction of a pathogen by heat (Altman and Dittmer, 1972).

Table 4.4. Continued.

| Disease | Fungus | Optimum Temperature (°C ) | Thermal Death Temperature (°C ) | Time (min) | Chemical Control |
|---|---|---|---|---|---|
| Gray Mold | *Botrytis cinerea* | 20-24 | >55 | N/S | Due to the rapid development of resistant races of this fungi, the control program should have different type of fungicides such as: Iprodione, |
| Late Blight | *Phytophthora infestans* | 21-26 | 45 | N/S | Preventive sprays: copper, mancozeb, captafol, propineb and dichlofluanid. Curative sprays: cymoxanil, metalaxyl. |
| Leaf Mold | *Fulvia fulva* | 18-26 | 70 | N/S | Maneb,Mancozeb, Chlorothalonil, Carbendazin,Thiophanate. |
| Powdery Mildew | *Leveillua taurica* | 18-25 | N/s | N/S | Preventive sprays: sulfur. Curative sprays: Carbendazin, triforine, fenarimol thiophanate. |
| White Mold (Sclerotinia) | *Sclerotinia sclerotiorum* | Winter + high RH % | 35 | few days | 1. soil sterilization, 2. vinchlozoline, 3. iprodione, or 4. procymidone. |
| Tomato Wilt | *Verticillium* sp. | 20-25 | 50-60 | N/s | -soil sterilization -soil drenching with one of |
| | *Fusaruim oxysporum* f. sp. lycopersici. | 26 | 54 | 0.25 | thiophanate., Carbendazin and Thiabendazole |

Thermal Death Temperature = Temperature necessary for the destruction of a pathogen by heat (Altman and Dittmer, 1972).

Table 4.5. Tomato virus diseases in greenhouses in the Kingdom of Saudi arabia (Abu-Jawadah, 1986).

| Disease | Virus | Transmitted By | Optimum Temperature (°C ) | Thermal Death Temperature (°C ) | ChemicalControl |
|---|---|---|---|---|---|
| Tomato Yellow Leaf Curl | *Tomato yellow leaf curl virus* | Whitefly "Bemisia tabaci" | 29-39 | 59 | - Carbofuran 5G at 50 kg/ha. At seeding time<br>- Mixture of mineral oil with one of: methidathion (I), permethrin (I), or pirimiphos-methyl (I) |
| Common Mosaic of Tomato | *Tobacco mosaic virus*, TMV | - No insect vector known.<br>- Seed-borne<br>- Mechanically spread during cultural practice. | Very resistant to a range of climatic conditions | 90-93 for short time | Seed treatment with<br>1- Trisodium phosphate.<br>2- Hydrochloric Acide.<br>3- Heat treatment at 80 °C for 24 hrs. |

N/S not specified.
Thermal Death Temperature = Temperature necessary for the destruction of a pathogen by heat (Altman and Dittmer, 1972).

stand out as one of the major developments of the modern agriculture. During the past twenty years, however, concern has arisen about their present in the environment that causes a serious threat to wildlife and mankind. Therefore, other options such as biological treatments and crop rotation have been recommended in most guidelines. However, in most parts of the world, the use of pesticides is still in practice as a disease prevention measure.

4.2.3.1 Insecticides. Insecticides are the most hazardous class of pesticides to living creatures. That is because most of them are nerve poisons that affect humans, animals, birds, fish as well as the targeted insects. The recommended insecticides in the KAS on greenhouse tomato crop are presented in Table 4.6. In general, insecticides are classified into five categories based on their chemical structure: organochlorines, organophosphates, carbamates, pyrethroids, and a general category of insecticides, which includes petroleum oils, soaps, botanical extracts, microbial toxins, insect growth regulators, and inorganic mineral dusts. The first synthetic insecticides were organochlorine compounds. They are highly resistant to both biological and chemical degradation and they accumulate in the body fat. Therefore, most of them are banned internationally including: DDT, chlordane, and dieldrin. Others, which have very limited use, include: methoxychlor, endosulfan, and lindane. The ban on organochlorine compounds insecticides was followed by the development of organophospate compounds, which are less toxic and do not bioaccumulate. However, they have higher acute toxicity compared to organochlorines. Common insecticides in this group include: pirimiphos- methyl, chlorpypifos, diazinon, and malathion. The third category is the carbamate insecticides, which are nonpersistent and have low chronic toxicity. Common carbamate insecticides are aldicarb, carbaryl, and carbofuran. The last main category of insecticides is pyrethoid, a natural plant-derived insecticide. They are stable in sun light and are effective at relatively low application rates. Cypermethrin, cyfluthrin, esfenvalerate and permethrin are commonly used pyrethriod compounds (Bűyűksőnmez et. al., 1999).

Table 4.6. Recommended insecticides in the Kingdom of Saudi Arabia on greenhouse tomato (Abu-Jawadah, 1986).

| Pesticide | Chemical | Toxicity Level | Water Solubility[1] (mg/L) | Vapor Pressure[1] (mPa) | Adsorption Coefficient[1] |
|---|---|---|---|---|---|
| pirimiphos-methyl 50% EC | O-(2-diethylamino-6-methylpirimidin-4-yl) O, O-dimethyl phosphorothioate | III | 5 | 0.00015 | N/A |
| Carbofuran | 2,3-dihydro-2,2-dimethylbenzofuran-7yl methylcarbamate | I ,II | 320 at 25 °C | 2.7 at 33 °C | 22 |
| Methidathion | S-2,3dihydro-5-methoxy-2-oxo-1,3,4-thiadiazol-3-ylmethyl O,O-dimethylphosph-orodithioate | I | 240 at 20 °C | 186 at 20 °C | 400 |
| Permethrin | 3-phenoxybenzyl (1RS)-cis,trans-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropane carboxylate | II | 0.2 at 20 °C | 0.045 at 25 °C | 100,000 |
| Malathion | diethyl (dimethoxy thiophosphorylthio) succinate | III | 130 | 5.3 at 30 °C | 1800 |

Toxicity level[1] = three common toxicity levels are indicated by signal words or numbers:

- Highly Toxic: Danger or, I
- Moderately Toxic: Warning or, II
- Slightly Toxic: Caution or, III

Adsorption coefficient[1] = is a measure of how tightly the pesticide binds to organic matter

1- Kamrin (1997).

4.2.3.2 Fungicides. Fungicides are used to control the pathogenic fungi that deteriorate the quality of the crop. Selected fungicides recommended in the KSA in greenhouse tomato crop are presented in Table 4.7. Despite their chemical differences, functionally, they are divided into three main groups; (a) protectants that are used to form a surface deposit on foliage to prevent germination, (b) eradicants that are used to control existing fungal infection, (c) and wood preservers (Büyüksönmez et. al., 1999).

## 4.3 Composting

### 4.3.1 Definition

Composting as described by the Northeast Region Agricultural Engineering Service (NRAES) is the aerobic biological decomposition of organic matter (USEPA, 1993). It is a natural process that is enhanced and accelerated by the mixing of organic waste with other ingredients in a prescribed manner for optimum microbial growth. The reaction is generally described as shown in Figure 4.2 (Tchobanoglous et al., 1993).

Composting converts an organic waste material into a stable organic product. The end result is a product that is safer to use than raw organic material and one that improves soil fertility, tilth, and water holding capacity (Murphy, 1991). In addition, composting reduces the bulk of organic material to be spread, improves its handling properties, reduces odor, fly, and other vector problems and can destroy weed seeds and pathogens (Holden, 1990; and Murphy, 1991).

### 4.3.2 Composting Phases

In the process of composting, microorganisms break down organic matter and produce carbon dioxide, water, heat and humus (the relatively stable organic end product). Under optimal conditions, composting proceeds through three phases: (a) the psychrophilic, or initial phase, (b) the mesophilic, or moderate-temperature phase, which lasts for a few days, (c) the thermophilic, or high-temperature phase, which can last from

Table 4.7. Recommended fungicides in the Kingdom of Saudi Arabia on greenhouse tomato (Abu-Jawadah, 1986).

| Pesticide | Chemical | Toxicity Level | Water Solubility[1] (mg/L) | Vapor Pressure[1] (mPa) | Adsorption Coefficient[1] |
|---|---|---|---|---|---|
| Maneb | Manganese ethylenebis (dithiocarbamate) (polymeric) | IV | 6 | Neg. at 20 °C | <2000 |
| Mancozeb | Manganese ethylenebis (dithiocarbamate) (polymeric) | III | 6 | Neg. at 20 °C | <2000 |
| Captafol | *N*-(1,1,2,2-tetrachloroethylthio)cyclohex-4-ene-1,2-dicarboximide, or 3a,4,7,7a-tetrahydro-*N*-(1,1,2,2-tetrachloroethanesulfenyl)phthalimide | III | 1-1.4 at 20 °C | Neg. at Room temp. | N/A |
| Thiram | Tetramethylthiuram disulfide | III | 30 at 25°C | Neg. at Room temp. | 670 |
| Tolclofos | *O*-2,6-dichloro-*p*-tolyl *O,O*-dimethyl phosphorothioate | III | 1.1 at 25°C | 1.84 at 24.8°C | N/A |
| Propamocarb | Propyl 3-(dimethylamino)propyl carbamate | III | 1005000 | 0.8 at 25°C | N/A |
| Metalaxyl | Methyl-N-(2,6-dimethylphenyl)-N-(2-xylyl)-DL-alaninate | III | 7100 at 20 °C | 0.293 at 20 °C | 50 |
| Carbendazim | Methyl benzimidazol-2-ylcarbamate | III | 8 | Neg. at 20°C | N/A |
| Thiophanate | Diethyl 4,4′-(*o*-phenylene)bis(3-thioallophanate) | III | very low | 0.00015 at 25 °C | N/A |

N/A not available
1- Kamrin (1997)

Table 4.7. Continued.

| Pesticide | Chemical | Toxicity Level | Water Solubility[1] (mg/L) | Vapor Pressure[1] (mPa) | Adsorption Coefficient[1] |
|---|---|---|---|---|---|
| Thiabendazole | 2-(thiazol-4-yl) benzimidazole | III | <50 | Neg. at Room temp. | 2500 |
| Zineb | Zinc ethylenebis (dithiocarbamate) | IV | 10 at 25°C | <0.01(20 °C) | 1000 |
| Chlorothalonil | Tetrachloroisoph-thalnitrile | II | 0.6 at 25 °C | 1.3 Pa at 40 °C | 1380 |
| Captan | *N*-(trichloromethy-lthio)cyclohex-4-ene-1,2-dicarboximide | | 3.3 at 25 °C | 1.3 at 25 °C | 200 |
| Iprodione | 3-(3,5-dichlorophenyl) - N-(1-methylethyl)2,4-dioxo-1-imidazo-line-carboxamide | III | 13 at 20 °C | <0.133 at 20 °C | 700 |
| Vinchlozolin | (RS)-3-(3,5-dichlorophenyl)-5-methyl-5-vinyl-1,3-oxazolidine-2,4-dione | III | 3.4 at 20 °C | 0.016 at 20 °C | 100 |
| Procymidone | *N*-(3,5-dichlorop-henyl)-1,2-dimethyl-cyclopropane-1,2-dicarboximide | III | 4.5 at 25 °C | 10.5, 18 at 20, 25 °C | N/A |
| Dichlofluanid | *N*-dichlorofluoro-methylthio-*N'*,*N'*-dimethyl-*N*-phenylsulfamide | III | Very low | 0.4 | N/A |
| Benalaxyl | methyl *N*-phenylacetyl-*N*-2,6-xylyl-DL-alaninate | | 37 | 0.67 at 25 °C | 1000 |
| Chinomethionat | 6-methyl-1,3-dithiolo[4,5-*b*]quinoxalin-2-one or *S*,*S*-(6-methylquinoxaline-2,3-diyl) dithiocarbonate | III | N/A | 1.9 | N/A |

N/A not available.
1-Kamrin (1997).

Table 4.7. Continued.

| Pesticide | Chemical | Toxicity Level | Water [1] Solubility (mg/L) | Vapor Pressure [1] (mPa) | Adsorption [1] Coefficient |
|---|---|---|---|---|---|
| Triforine | *N,N'*-{piperazine-1,4-diylbis[(trichloromethyl)methylene]}diformamide or 1,1'-piperazine-1,4-diyldi-[*N*-(2,2,2-trichloroethyl) formamide] | I | 30 at 20 °C | 0.026 at 25 °C | N/A |
| Fenarimol | (*RS*)-2,4'-dichloro-α-(pyrimidin-5-yl)benzhydryl alcohol | III | 14 | 0.065 at 25 °C | 600 |
| Folpet | *N*-(trichloromethyl-thio)phthalimide, or *N*-(trichloromethanesulfenyl)phthalimide | III | 1 | <1.3 mbar at 20 °C | N/A |
| Triadimefon | 1-(4-chlorophenoxy)-3,3-dimethl-1-(1H-1,2, 4-triazol-1-yl) butanone | III | 260 at 20 °C | <0.1 at 20 °C | 300 |
| Chlorpyrifos-ethyl | O,O-diethyl O-3,5,6 -trichloro-2-pyridyl phosphorothioate; O,O-diethyl O-(3,5, 6-trichloro-2-pyrid-inyl) phosphor-othioate. | II | 2 at 25 °C | 2.5 at 25 °C | 6070 |
| Benomyl | methyl-1-[(butylamino)carbonyl]-H-benzimidazol-2-ylcarbamate | IV | 2 | <1 at 20 °C | 1900 |

1- Kamrin (1997).

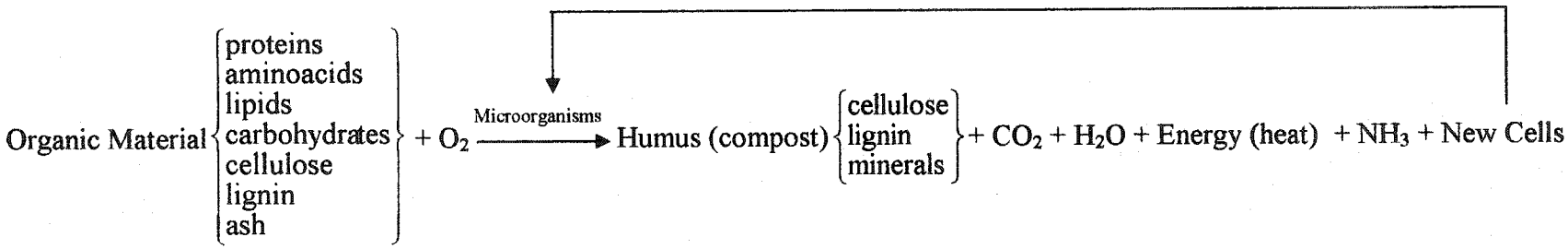



Figure 4.2. The general description of the composting process (Tchobanoglous et al., 1993).

a few days to several months, and (d) cooling and maturation phase which lasts for several months as shown in Figure 4.3. The first, second and third phases are referred to as the active phases whereas the fourth phase is referred to as the inactive phase.

4.3.2.1 The Active Phase. There are different communities of microorganisms predominate during the various composting phases (Bagstam, 1978). Initial decomposition is carried out by psychophilic and mesophilic microorganisms, which rapidly break down the soluble, readily degradable compounds (Finstein et al., 1980; and De Bertoldi et al., 1982). The heat they produce causes the compost temperature to rise (Crawford, 1983). As the temperature rises above 40°C, the mesophilic microorganisms become less competitive and are replaced by the thermophilic microorganism (Palmisano and Barlaz, 1996). At temperatures of 55°C and above, many microorganisms that are human (Table 4.8) or plant pathogens are destroyed (Tchobanoglous et al., 1993; and Bollen, 1993). Temperatures over 65°C kill many forms of microbes and limit the rate of decomposition (Haug, 1993).

During the thermophilic phase, high temperatures accelerate the breakdown of proteins, fats, and complex carbohydrates like cellulose and hemicellulose, the major structural molecules in plants (Haug, 1993; Crawford, 1983; and De Bertoldi et al., 1983). As the supply of these high-energy compounds becomes exhausted, the compost temperature gradually decreases and mesophilic microorganisms once again take over for the final phase of maturation of the remaining organic matter (Palmisano and Barlaz, 1996).

4.3.2.2 The Curing Phase (Inactive). The curing phase follows the active phases. During this phase, the rate of oxygen consumption decreases and the composting process slows to a rate where the compost can be piled without further aeration (Rynk et al., 1992; and Palmisano and Barlaz, 1996). Haug (1993) described the curing phase as compost stabilization. He stated that stabilization of compost occurs when the rate of oxygen consumption is reduced to a point where the compost can be stored without odors or anaerobic conditions.

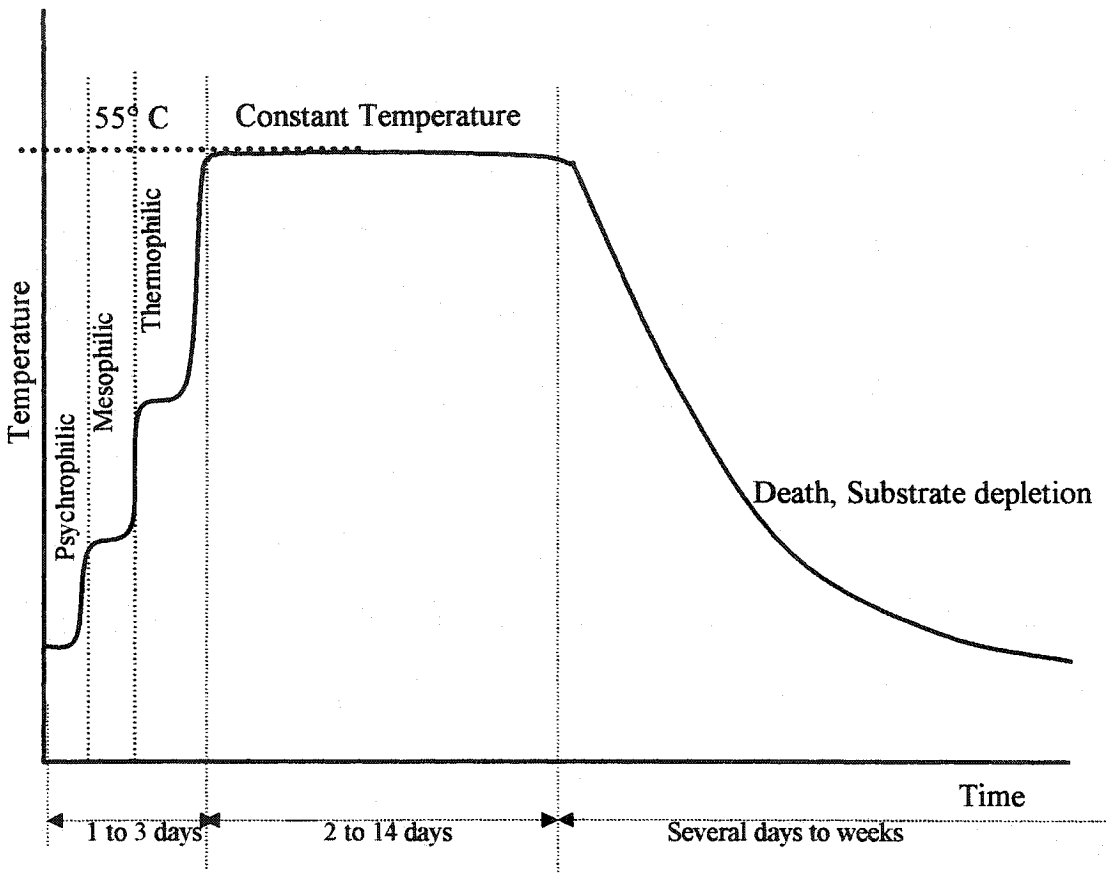



Figure 4.3. Composting phases.

After mature compost has gone through the stabilization period, maturity can be measured in a variety of ways. Jann et. al. (1960) stated that pH stabilization can be used to measure stability. Keller (1962) reported that maturity can be measured by physical, chemical, or biological characteristics. Mathur (1991) reviewed the numerous tests for biomaturity of composts. These tests include: (a) C: N ratio of compost, (b) organic C: N ratio in water extracts of compost, (c) nitrogen ratio in water extracts, (d) circular chromatography test of Alkali extracts, (e) humification indicators, (f) microbial activity, (g) water extracts of compost, (h) reheating, and (i) direct phytotoxicity. He concluded that there was no one best way for measuring maturity and no one test is adequate by itself. The test to be used and the degree of compost maturity depend on the use of the final product.

### 4.3.3 Composting Microorganisms

There are many different types of organisms that can be found in the composting environment (Figure 4.3). Factors that might influence the types and quantities of microbes are temperature, moisture, pH, aeration, and feed sources for microbes. Bacteria, actinomycetes, and fungi are the primary organisms in compost system, in addition to, algae, protozoa and viruses, which are less significant (Miller, 1993; Haug, 1993; and Finstein and Morris, 1975).

4.3.3.1 Bacteria. Bacteria are the smallest living organisms and the most numerous in compost ((Palmisano and Barlaz, 1996); they make up 80 to 90% of the billions of microorganisms typically found in a gram of compost (Table 4.9). Bacteria are responsible for most of the decomposition and heat generation in compost. They are the most nutritionally diverse group of compost organisms, using a broad range of enzymes to chemically break down a variety of organic materials (Figure 4.4).

Bacteria are single-celled and structured as either rod-shaped bacilli, sphere-shaped cocci or spiral-shaped spirilla. Many are motile, meaning that they have the ability to

Table 4.8. Temperature and time of exposure required for destruction of some common pathogens and parasites (Tchobanoglous et al., 1993).

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

Table 4.9. Identified bacteria in composting materials (adapted from Palmisano and Barlaz, 1996).

| Bacteria | References |
|---|---|
| *Alcaligenes faecalis* | Corominas et al. (1987) |
| *Bacillus brevis* | Strom (1985a) |
| *B. circulanscomplex* | Strom (1985a) |
| *B. coagulans type* A | Strom (1985a) |
| *B. coagulans type* B | Strom (1985a) |
| *B. megaterium* | Corominas et al. (1987) |
| *B. licheniformis* | Strom (1985a) |
| *B. pumilus* | Corominas et al. (1987) |
| *B. sphaericus* | Rothbaum and Dye (1964) and Strom (1985a) |
| *B. stearothermophilus* | Rothbaum and Dye (1964) |
| *B. subtilis* | Fermor et al. (1979) |
| *Clostridium thermocellum* | Palmisano and Barlaz (1996) |
| *Clostridium* sp. | Waksman et al. (1939) |
| *Escherichia coli* | Brinton and Droffner (1994) |
| *Flavobacterium* sp. | Macauley et al. (1993) |
| *Pseudomonas* sp. | Fermor et al. (1979) |
| *Pseudomonas aeruginosa* | Brinton and Droffner (1994) |
| *Serratiam* sp. | Macauley et al. (1993) |
| *Thermus* sp. | Fujio and Kume (1991) |

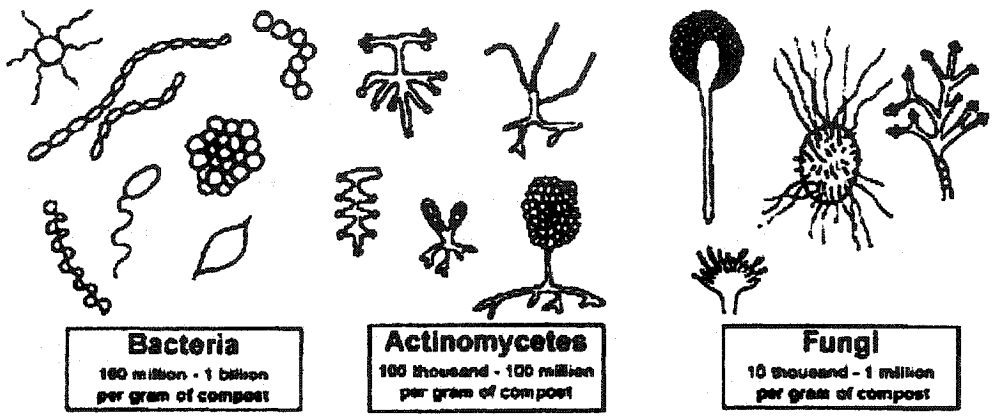



Figure 4.4. Various communities of microorganisms in composting (Rynk et al.,1992).

move under their own power (Peavy et al., 1985). At the beginning of the composting process (0-40°C), mesophilic bacteria predominate. Most of these are forms that can also be found in topsoil (Haug, 1993).

As the compost heats up to above 40°C, thermophilic bacteria take over (Gray et al., 1971). The microbial populations during this phase are dominated by members of the genus *Bacillus*. The diversity of bacilli species is fairly high at temperatures from 50-55°C but decreases dramatically at 60°C or above (McKinley and Vestal, 1984 and Strom, 1985a). When conditions become unfavorable, bacilli survive by forming endospores, thick-walled spores that are highly resistant to heat, cold, dryness, or lack of food, which become active again whenever environmental conditions are favorable (Hayes, 1968; and Fermor et al., 1979).

Once the compost cools down, mesophilic bacteria again predominate (Strom, 1985b). The numbers and types of mesophilic microbes that recolonize compost as it matures depend on what spores and organisms are present in the compost as well as in the immediate environment. In general, the longer the curing or maturation phase, the more diverse the microbial community it supports (Haug, 1993).

4.3.3.2 Actinomycetes. The characteristic earthy smell of soil is caused by actinomycetes, organisms that resemble fungi but actually are filamentous bacteria (Figure 4.4). Like other bacteria, they lack nuclei, but they grow multicellular filaments like fungi (Haug, 1993; and Palmisano and Barlaz, 1996). In composting they play an important role in degrading complex organics such as cellulose, lignin, chitin, and proteins. Their enzymes enable them to chemically break down tough debris such as woody stems, bark, or newspaper. Species appear during the thermophilic phase, and others become important during the cooler curing phase, when only the most resistant compounds remain in the last stages of the formation of humus (Bagstam, 1978; and Joshua et al., 1998).

Actinomycetes form long, thread-like branched filaments that look like gray spider webs stretching through compost. These filaments are most commonly seen

toward the end of the composting process, in the outer 10 to 15 centimeters of the pile. Sometimes they appear as circular colonies that gradually expand in diameter (Bagstam, 1978 ; and Joshua et al., 1994). Table 4.10 shows Actinomycetes recovered from composting material.

4.3.3.3 Fungi. Fungi include molds and yeasts, and collectively they are responsible for the decomposition of many complex plant polymers in soil and compost (Figure 4.4). In compost, fungi are important because they break down tough debris (Chang and Hudson, 1967 and De Bertoldi et al., 1982), enabling bacteria to continue the decomposition process once most of the cellulose has been exhausted. Some of the reported species are shown in Table 4.11. They spread and grow vigorously by producing many cells and filaments, and they can attack organic residues that are too dry, acidic, or low in nitrogen for bacterial decomposition (Haug, 1993).

Most fungi are classified as saprophytes because they live on dead or dying material and obtain energy by breaking down organic matter in dead plants and animals. Fungal species are numerous during both mesophilic and thermophilic phases of composting. Most fungi live in the outer layer of compost when temperatures are high (Fermor et al., 1979). Compost molds are strict aerobes that grow both as unseen filaments and as gray or white fuzzy colonies on the compost surface (Haug, 1993).

### 4.3.4 Composting Operating Parameters

Many researchers have studied composting as a controlled process. Recent studies include Das and Keener (1996), Rao (1996), Haug (1993), Oppenheimer et al. (1997), VanderGheynst et al. (1997), Ndegwa (1999), and Hall (1998). An excellent overall description of theoretical and practical composting processes is giving by Haug (1993). The factors affecting the composting process include: volatile solids,

Table 4.10. Identified actinomycetes in composting materials (adapted from Palmisano and Barlaz, 1996).

| Actinomycete | References |
|---|---|
| *Actinobifidan chromogena* | Fergus (1964), Lacey (1973) |
| *Microbispora bispora* | Palmisano and Barlaz (1996) |
| *Microbispora faeni* | Fergus (1971) and Lacey (1973) |
| *Nocardia sp.* | Lacey (1973) |
| *Pseudocardia thermophilia* | Fergus (1971) |
| *Streptomyces rectus* | Fergus (1971) |
| *S. thermofuscus* | Makawi (1980) |
| *S. thermoviolaceus* | Fergus (1971) |
| *S. thermovulgaris* | Fergus (1971) |
| *S. violaceus-ruber* | Fergus (1971) |
| *Streptomyces sp.* | Waksman et al. (1939) |
| *Thermoactinomyces vulgaris* | Waksman et al. (1939) |
| *T. sacchari* | Lacey (1973) |
| *Theromonospora curvata* | Fergus (1971) |
| *T. viridis* | Fergus (1971) and Lacey (1973) |
| *Thermomono spora sp.* | Lacey (1973) |

Table 4.11. Identified fungi in composting materials (adapted from Palmisano and Barlaz, 1996).

| Fungus | References |
|---|---|
| | Zygomycetes |
| *Absidia corymbifera* | Straatsma et al. (1994) |
| *A. ramosa* | De Bertoldi et al. (1983) |
| *Absidia* sp. | Gregory et al. (1963) |
| *Mortierella turficola* | Hayes (1968) |
| *Mucor miehei* | Cooney and Emerson (1964) |
| *M. pusillus* | Cooney and Emerson (1964) and Fergus (1971) |
| *Rhizomucor* sp. | Okafor (1966) |
| | Ascoycetes |
| *Allescheria terrestris* | De Bertoldi et al. (1983) |
| *Chaetomium thermophilim* | Fergus (1971) and De Bertoldi et al. (1983) |
| *Dactylomyces crustaceious* | Kane and Mullins (1973) |
| *Emericella nidulans* | Straatsma et al. (1994) |
| *Myriococcum albomyces* | Cooney and Emerson (1964) |
| *Talaromyces dupontii* | Fergus (1971) |
| *T. emersonnii* | Straatsma et al. (1994) |
| *T. thermophilus* | De Bertoldi et al. (1983) |
| *Thermoascus aurantiacus* | De Bertoldi et al. (1983) |
| *T. crustaceus* | Straatsma et al. (1994) |
| *Corynascus thermophilus* | Straatsma et al. (1994) |
| *Thielavia terrestris* | Samson et al. (1977) |

Table 4.11. Continued.

| Fungus | References |
|---|---|
| | Basidiomycetes |
| *Coprinuslagopus* | Cooney and Emerson (1964) |
| *Coprinus sp.* | Cooney and Emerson (1964) |
| *Coprinus cinereus* | Straatsma et al. (1994) |
| *Lenzites* sp. | De Bertoldi et al. (1983) |
| | Deuteromycetes (Hyphomycetes) |
| *Aspergillus fumigatus* | Fergus (1964) |
| *Humicola grisea* | Fergus (1964) |
| *H. insolens* | Fergus (1964) |
| *H. lanuginosa* | Kane and Mullins (1973) |
| *Paecilomyces variotii* | Straatsma et al. (1994) |
| *Sporotrichum thermophile* | De Bertoldi et al. (1983) |
| *Malbranchea pulchella* | Cooney and Emerson (1964) |
| *Scytalidium thermophilim* | De Bertoldi et al. (1983) |
| | Mycelia Sterilia |
| *Papulaspora thermophila* | Fergus (1971) |
| *Myriococcum thermophilim* | Straatsma et al. (1994) |

temperature, aeration, agitation, moisture content, pH, nutrients, C: N ratio, and time. An efficient composting process with quality product can only be achieved through optimizing these factors.

4.3.4.1 Volatile Solids. The composting material could be almost any organic substrate including manure, organic industrial wastes and agricultural and municipal solid wastes (Hall, 1998). The energy contained in the biological volatile solids (BVS) is the driving force for the composting process. Under optimum composting condition, the energy availability and the rate at which it is released may vary dramatically with the type of waste. Jeris and Regan (1973) found that the rate of $CO_2$ production for newsprint and stabilized mixed waste was in the range of 0.1 to 0.4 mmole $CO_2$/day/g volatile solids, while fresh mixed waste was in the range of 1 to 5 mmole $CO_2$/day/g volatile solids. Volatile solids contents of various waste sources are presented in Table 4.12.

4.3.4.2 Temperature. Several researchers addressed heat and mass transport during the composting process (Andrews and Kambhu, 1973; Bach et al., 1987; Keener et al., 1993; Haug, 1993; Strombaugh and Nokes, 1996; VanderGheynst et al., 1997; and Hall, 1998). Temperature plays an important role in the composting process. Temperature control is important for pathogen destruction, optimal respiration rates, moisture removal and stabilization of compost (Polprasert, 1989).

Composting takes place within three ranges of temperature referred to as psychrophilic, mesophilic, and thermophilic. The psychrophilic range is from –10 to 20 °C. The optimum growth of Psychrophiles is at 13 °C. The mesophiles temperature range is between 20 and 45 °C whereas thermophilic temperature is between 45 and 65°C (Ghaly et al., 1989). Temperature within the compost material is a function of the rates of heat evolution and heat loss to the environment. Temperature is both a result of and determinant of microbial activity. Enzyme activities rates, and growth rates generally double with each 10 °C rise in temperature until microorganism temperature sensitivity

Table 4.12. Various agricultural wastes characteristics.

| Material | | Volatile Solid (%)D.M | C: N ratio | References |
|---|---|---|---|---|
| Plant Residues | | | | |
| | Alfalfa | 72.6 | 46.8 | ASAE (1999) |
| | Barley straw | 68.8 | 46.8 | ASAE (1999) |
| | Wheat straw | 71.3 | 72 | ASAE (1999) |
| | Grass clippings | 85 | 20 | Palmisano and Barlaz (1996) and Tchobanoglous et al. (1993) |
| | Leaves (freshly fallen) | 90.2 | 40-80 | Palmisano and Barlaz (1996) and Tchobanoglous et al., (1993) |
| | Oat straw | 92.8 | 98.2 | Rynk et al. (1992) |
| | Potato tops | 71.5 | 25 | Tchobanoglous et al.(1993) |
| | Potato culls | 92.1 | 18.1 | Rynk et al. (1992) |
| | Potato processing sludge | 91.1 | 28.1 | Rynk et al. (1992) |
| | Soybean residues | 97.4 | 20 | Barrington et al. (2002) |
| | Tomato solid waste | 92 | 10--18 | Rynk et al. (1992) |
| | Watermelon | | 20 | Rynk et al. (1992) |
| Manure | | | | |
| | Poultry litter [a] | | | |
| | With Wood Shavings | 69.2 | 9 | Flynn and Wood (1996) |
| | With Peanut Hulls | 44 | 10 | Flynn and Wood (1996) |
| | Dairy | 83.3 | 173 | ASAE (1999) |
| | Horse | 66.7 | 25 | ASAE (1999) |
| | Sheep | 83.6 | 17 | ASAE (1999) |
| Wood | | | | |
| | Sawdust | 96.1 | 278.7 | Rynk et al. (1992) |
| | Wood (pine) | 98.8 | 723 | Tchobanoglous et al. (1993) |
| | Wood chips (Maple) | 99-99.5 | 304 | Hall (1998) |

a: Poultry Litter is a mixture of manure, bedding material, waste feed, and feathers)

thresholds are reached at which time growth subsides (Metcalf and Eddy, 1979). In general, the composting process begins in the psychrophilic range if the compost is cool (< 20 °C), or the mesophilic range if ambient temperature is above 20 °C. As decomposition begins, heat is generated exposing the the compost material to high mesophilic conditions before reaching the thermophilic range. Eventually, it returns to the mesophilic range where the early phase high metabolic activity is followed by the lower activity rate of the maturing stage ( Sayag and Andre, 1987). Although temperatures of 55 to 60 °C are reportedly best for weed seed and pathogen kill (Bollen, 1993), the mesophilic bacteria are the most effective decomposers (Rynk et al., 1992).

High temperatures are the vehicle for sanitizing the organic mass which requires an abundant oxygen supply for a proper temperature profile. Effectiveness depends on the maximum temperature attained and the duration although complete sterilization can never be guaranteed. Most dangerous pathogens can be rendered harmless if exposed to temperatures of 65 °C for 2 to 3 days. However, some less harmful sporogenous and non sporogenous survive beyond exposure to 100 °C (De Bertoldi et al.,1983). Kurihara et al. (1987) suggested an optimum temperature of 60 °C as decomposition rates are reduced at temperatures above 65 °C (Sayag and Andre, 1987). At extremely high temperatures, proteins may be denatured and biological activity may decline as population die, thus ultimately slowing the composting process. Maintaining a consistent optimal temperature may provide for faster and more complete composting, pathogen destruction, and production of stable final compost (Hall, 1998).

4.3.4.3 Aeration. Initially, aerobic composting consumes large amounts of oxygen. During the initial days of composting, readily degradable components of raw materials are rapidly metabolized. Therefore, the need for oxygen and the production of heat are greatest at early stages and then decrease as the process ages. In addition to providing oxygen, aeration removes heat, water vapor, and other gases trapped within the composting materials (Hall, 1998). If the supply of oxygen is limited, the composting process slows. A minimum oxygen concentration of 5% within the pore spaces of the composting material is necessary (Rynk et al., 1992; and Haug, 1993). Finstein et al.

(1986) reported that the required rate of aeration for heat removal is greater than that for supplying oxygen, and therefore, temperature often determines how much and how frequently aeration is required. Some reported aeration rates are presented in Table 4.13. Namkoong and Hwang (1997) reported that in a constant aeration experiment, temperature increased to 70 °C after one day and after then sharpply decreased. However, using the same mixture with different aeration regime, maximum temperature was controlled at 50 °C and 60 °C, maximum temperatures were maintained for 10 days and two days respectively.

4.3.4.4 Agitation. In addition to providing a consistent supply of oxygen to the decomposing mass, agitation is required to sustain a healthy microbial environment. Microbial growth and development is sensitive to the conditions of the thin aqueous film surrounding the organic material. This film contains dissolved and colloidal nutrients, atmospheric and metabolic gases and digestion products. Generally, considered immobile, the microbes rely on extraneous forces to remove potential toxins and inhibitors, in effect to purify the immediate environment (Haug, 1993). Methods of agitation vary with the complexity of the composting system. Simple windrows often employ a front end loader to turn the material. Many systems rely on forced air movement to not only supply oxygen, but also to agitate the substrate (Tomati et. al., 1995; Papadimitriou and Balis, 1996; Jürgen, 1999; Hall, 1998; McDonnell, 1999; and Tiquia and Tam, 2000). Still others device in-vessel mechanical turning devices that provide more controlled agitation (Paré et. at., 1999). Mixing the compost material in laboratory-scale bioreactors is generally done either manually, by emptying the bioreactor then mixing the material and returning it back to the system (Elwell et al., 1996), or mechanically, by installing a mixing unit or a rotating drum (Ashbolt and Line, 1982; Mote and Griffis, 1979; Whang and Meenaghan, 1980; Nakasaki et. al., 1985; Kubota and Nakasaki, 1991; Jeris and Regan, 1973; Schulze, 1961; and Schwab et al., 1994 ).

Frequency of agitation also vary among researchers(Schwab et al.,1994; Hansen et al., 1989; Jeris and Regan, 1973). It depends on the type of material been composted and the method of composting (Tchobanoglous et al., 1993). Hall (1998) used

Table 4.13. Some reported aeration rates.

| Aeration Rate ($m^3$/h.kgDM) | Volume ($m^3$) | Note | Reference |
|---|---|---|---|
| 0.016 | 0.105 | After 21 days temperature dropped below 35 °C. | Barrington et al. (2002) |
| 0.02<br>- | 0.015 | As base aeration, then temperature was controlled at 55-60 °C. | Hall (1998) |
| Low: 0.01<br>High:0. 06 | 0.107 | Continuous low aeration rate was used to insure adequate $O_2$ level (>10%), and then temp. feedback high aeration system was used. | Jürgen (1997) |
| Low: 0.01<br>High: 0.05 | 0.208 | Composting started at low rate. When set point temperature was reached, high rate fan was on. | Hansen et al. (1989) |
| 0.26-0.97<br>0.07<br>0.02 | 0.208 | From day 1 to 11<br>From day 11 to 21<br>From day 21 to end | Elwell et al. (1996) |
| 0 to 0.032 | 0.002 | Air was added to control oxygen concentration in each flask. | Nobel et al. (1997) |
| Low: 0.03<br>High: 0.06 | 0.208 | Aeration rate at low until the system reach 52 °C, then high rate was activated. | Schwab et al.(1994) |

manual mixing of the composted material every 5 days. Schwab et al.(1994) developed a pilot-scale composting system that rotates for 3 days at a speed of 2 rpm. While Hansen et al.(1989) utilized a rotating barrel mixer. The barrel rotates end- over- end about a contral shaft at 30 rpm for 10 minutes. However, balls of the compost mix of various diameters (25 to 50 mm) were evident. The authors concluded that mixing method is one of the most significant factors influecing the rate of composting, while mixing frequency had the greatest impact on nitrogen retention. They did not give any recommendation on the method or frequency of mixing.

4.3.4.5 Moisture Content. Moisture is necessary to support the metabolic processes of the microbes. Water provides the medium for chemical reaction, transports nutrients, and allows the microorganisms to move about. In theory, biological activity is optimal when the materials are saturated (Stentiford, 1996). However, moisture content must not exceed a level at which water in the pore spaces begins to limit the availability of air (oxygen), which would cause an anaerobic conditions (Keener et al., 1993). Microbial activity becomes inhibited as the moisture decreases below 40% and it ceases entirely as moisture content reaches 8 to 12% (Diaz et al., 1993). In practice, however, composting materials should be maintained within a much narrow moisture content range, generally between 50% to 65% (Schulze, 1961; and Haug, 1993). Some of the moisture content values used by researchers are reported in Table 4.14.

4.3.4.6 pH. The composting process is relatively insensitive to pH, within the range commonly found in mixtures of organic materials, largely because of the broad spectrum of microorganisms involved. The preferred pH is in the range of 6.5 to 8.5 (Epstein, 1997). pH becomes an important factor when dealing with raw materials that have a high percentage of nitrogen. Haug (1993) reported that a high pH (above 8.5) encourages the conversion of nitrogen compounds to ammonium, which further adds to the alkalinity. Sasaki et al. (2003) reported that pH levels above 8 will lead to ammonia volatilization and odor problems along with a failure to reach thermophilic temperature levels. Lower pH (<5) of the source material can also inhibit microbial growth (Palmisano and Barlaz, 1996, Rynk et al., 1992) leading to a longer lag phase. The pH

value will increase as a result of the utilization of organic acids as the composting process proceed (Beck-Friis et al., 2001).

Composting changes the materials and their pH as decomposition occurs. During the composting process, the pH initially drops due to the formation of organic acids. The production of ammonia from nitrogenous compounds may rise the pH. Regardless of the pH of the starting materials, composting yields an end product with a stable pH that is neutral or slightly alkaline (Epstein, 1997).

4.3.4.7 Nutrients. Organisms require a source of energy, Carbon (C) for the synthesis of new cells, and inorganic elements (nutrients) such as nitrogen (N), sulfur (S), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe), sodium (Na), and chlorine (Cl). Minor nutrients such as zinc (Zn), manganese (Mn), molybdenum (Mo), selenium (Se), cobalt (Co), copper (Cu), nickel (Ni), and tungsten (W) are also needed. In addition, organisms may also require organic nutrients, known as growth factors. They fall into the following classes: (a) amino acids, (b) purines and pyrimidines, (c) vitamins (Stanier et al., 1986). Nitrogen, phosphorus, and potassium are the primary nutrients for plants; and their concentrations in the finished compost influence the value of the compost. Many organic materials, including manure, plant residues and food wastes, contain sufficient quantities of nutrients. Excessive or insufficient carbon or nitrogen are most likely to affect the composting process (Haug, 1993; and Richard, 1992).

4.3.4.8 C:N Ratio. In general, organisms, including humans, need about twenty-five times more carbon than nitrogen. It is therefore, important to provide carbon and nitrogen in appropriate proportions. The ratio of carbon to nitrogen is referred to as the C:N ratio. A balanced C:N ratio usually ensures that the other required nutrients are present in adequate amounts. Raw materials blended to provide a C:N ratio of 25:1 to 30 :1 are ideal for active composting (Richard, 1992 and Haug, 1993). With C:N ratio below 20 : 1, the available carbon is fully utilized by microorganisms without

Table 4.14. Some reported initial moisture content.

| Composted Material | MC (%) | System Size ($m^3$) | Reference |
|---|---|---|---|
| Mixture of source separated organic household waste and chopped wheat straws. | 65 | 0.20 | Beck-Friis et al.(2001) |
| Olive tree leaves and extracted olive-press cake at 1:1 ratio | 51 | 0.62 | Papadimitriou and Balis (1996) |
| Night-soil | 74 | 0.0064 | Wan and Hwang (1997) |
| Deep litter of dairy cows | 59 | 12.8 | Sommer and Dahl (1999) |
| Dairy cow manure alone. | 60 | 0.001 | Iwabuchi et al. (1995) |
| Dog-food and wood chips<br>Separated dairy manure | 55<br>55 | 0.015<br>0.015 | Hall (1998) |
| Source separated organic household waste and chopped wheat straw. | 65 | 0.2 | Smårs et al. (2002) |
| Fish waste with different bulking agents mixture. | 68 | 0.076 | Liao et al. (1995) |
| Yard trimmings (leaves and grass) | 60 | 0.002 | Michel et al. (1995) |
| Source separated household wastes. | 70 | 0.002-0.006 | Ryckeboer et al. (2002) |
| A mixture broiler litter with bedding materials (peanut hulls or wood shavings) and wheat straws. | 50 | 0.33 | Flynn and Wood (1996) |

stabilizing all of the nitrogen. The excess nitrogen may then be lost to the atmosphere as ammonia or nitrous oxide and odor can become a problem. Mixes of materials with C:N ratio higher than 40:1 require longer composting times for the microorganisms to use the excess carbon. The C:N ratio gradually falls during composting, because of the loss of carbon in form of $CO_2$ from the starting materials. The amount of carbon lost during composting usually exceeds the nitrogen loss. However, if the starting C:N ratio is low (less than 15:1) the nitrogen losses may be large enough to cause little change in the C:N ratio. Nitrogen and Carbon losses were studied by Eghball et al. (1997). They found that nitrogen losses, from composted beef feedlot manure in outside windrows, to be associated with initial manure nitrogen content and ranged from 19.3% to 61.5%. Nitrogen losses in the form of ammonia were over 92%. Carbon losses ranged between 45% and 62%. Nitrogen losses were also studied by Martin and Dewes (1992) and were found to be in the range of between 9.6% and 19.6% during the first 10 days of composting.

4.3.4.9 Time. The length of time required to transform raw materials into compost depends upon many factors including the materials used. Temperature, moisture, frequency of aeration, and user requirements. Proper moisture content and C: N ratio plus frequent aeration ensure the shortest possible composting period. Conditions, which slow the process, include the lack of moisture, a high C: N ratio, low temperatures, insufficient aeration, large particles and a high percentage of resistant materials (such as woody materials). Typical composting times for several common applications are listed in Table 4.15.

### 4.3.5 Compost Mixture Design Process

The determination of the proper compost mix is normally a repeated process of adjusting the C: N ratio and moisture content by the addition of amendments. If the C:N ratio is not in the acceptable range, then amendments are added to adjust it. If this results

Table 4.15. Typical composting times for selected composting methods (Rynket al., 1992)

| Method | Materials | Active composting Time | | Curing time |
|---|---|---|---|---|
| | | Range (day) | Typical (day) | (day) |
| Passive Composting | Leaves, | 730-1095 | 730 | N/D |
| | Bedded manure | 180-730 | 365 | N/D |
| Windrow, infrequent turning [a] | Leaves, | 180-365 | 270 | 120 |
| | Manure, amendments | 120-180 | 180 | 30-60 |
| Windrow, frequent turning [b] | Manure, amendments | 30-120 | 60 | 30-60 |
| Passively aerated windrow | Manure, bedding | 70-84 | N/D | 30-60 |
| | Fish wastes, peat moss. | 56-70 | N/D | 30-60 |
| Aerated static pile | Sludge, wood chips. | 21-35 | 28 | 30-60 |
| Rectangular agitated bed | Sludge, yard waste or manure, sawdust | 14-28 | 21 | 30-60 |
| Rotating drums | Sludge and/or solid wastes | 3-8 | N/D | 60 [c] |
| Vertical silos | Sludge and/or solid wastes | 7-14 | N/D | 60 [c] |

a: with bucket loader.

b: with special windrow turner.

c: often involves a second composting stage, such as windrow, or aerated piles.

in high or low moisture content, amendments are added to adjust the moisture content. The C:N ratio is again checked, and the process may be repeated until meeting the acceptable condition. A mixture design process flow chart that outlines the procedure necessary in determining the compost mixture is shown in Figure 4.5. Some design parameters are presented in Table 4.16.

4.3.5.1 Determining the Need for Bulking Agent. The process normally begins with determining whether or not a bulking agent is needed. The addition of a bulking agent is necessary if the raw waste cannot support itself or if it does not have sufficient porosity to allow internal air movement. The wood chips, bark, and shredded tires are examples of bulking agents commonly used.

4.3.5.2 Calculating the Moisture Content of the Compost. After the need for and the quantity of bulking agent have been determined, the moisture content of the raw waste can be calculated using equation 4.1.

$$M_i = \frac{WetWeight - DryWeight}{WetWeight} \times 100 \quad (4.1)$$

Where:

$M_i$ = Percent moisture content, wet basis (%)

The moisture content for each additive can be determined individually and used to determine the moisture content of the entire mix. A sample of the raw waste can also be taken, weighed, dried, and weighed again after drying to determine the moisture content of the mix. Using this procedure the moisture content can be calculated as follows:

$$M_M = \left\{ \frac{\left\{ (W_w \times M_w) + (W_b \times M_b) + (W_a \times M_a) \right\} \div 100}{W_m} + H_2O \right\} \times 100 \quad (4.2)$$

Where:

$M_m$ = Percent moisture of the compost mixture, wet basis (%)

$W_w$ = Wet weight of waste (kg)

Table 4.16. Aerobic composting design and operational considerations (Tchobanoglous et al., 1993).

| Item | Comment |
|---|---|
| Particle size | Particle size should be between 25 and 75 mm for optimum results. |
| Carbon nitrogen (C: N) ratio | Initial C: N ratios (by mass) should be between 20 and 30 for optimum results. |
| Blending and seeding | Partially decomposed waste can be used to seed compost at 1 to 5 percent by weight to reduce composting lag (adaptive) time. |
| Moisture content | Optimum range is between 40 and 60 %. |
| Mixing/ turning | Mixing or turning on regular schedule or as needed to prevent drying, caking and air channeling. |
| Temperature | Optimum temperature is between 50 to 55 for the first few days and 55 to 60 for the remainder of the active composting period. |
| Control of pathogens | Temperature must be maintained between 60 to 70 ° C for at least 24 hours. |
| Air requirements | Theoretical quantity of oxygen required must be determined. |
| pH control | Optimum pH range is between 7 and 7.5. pH should not exceed 8.5 to minimize the nitrogen loss. |
| Degree of decomposition | Degree of decomposition can be estimated by measuring the final drop in temperature, degree of self heating capacity, amount of decomposable and resistant organic matter in the composted material, rise in the redox potential, oxygen uptake, growth of the fungus *Chaetomium gracilis*, and the starch-iodine test. |
| Land requirement | For a plant with a 50-ton/day capacity will be 6075 to 8100 $m^2$. |

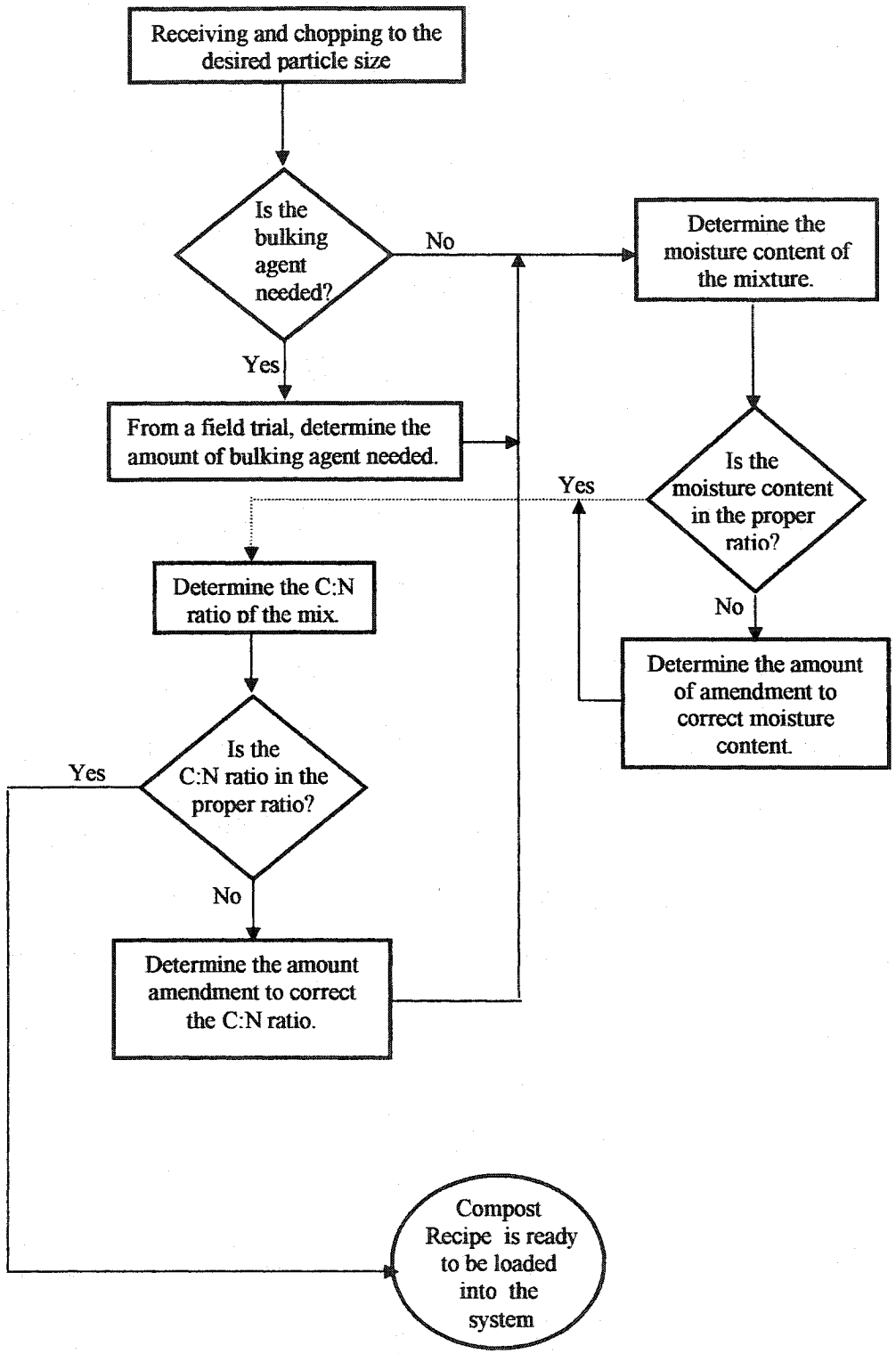



Figure 4.5. Compost mixture design flow chart (adapted from Rynk et al., 1992).

$M_w$ = Percent moisture content of waste, wet basis (%)

$W_b$ = Wet weight of bulking agent (kg)

$M_b$ = Percent moisture content of bulking agent, wet basis (%)

$W_a$ = Wet weight of amendment (kg)

$M_a$ = Moisture content of amendment (wet basis)

$H_2O$ = Weight of water added (kg)

$W_m$ = Weight of the compost mix including wet weight of waste, bulking agent, amendments, and added water (kg)

After determining the amount of amendment to be added, if any, to the compost mix that will result in a final moisture content that is between 40 and 60 percent, if the moisture content of the compost mix is less than 40 percent, adding an amendment is necessary to raise the moisture content to an acceptable level. Water is the amendment that is generally added to raise the moisture content, but an amendment that has higher moisture content than the desired moisture content of the compost mix is acceptable. It is generally best to begin the composting process when the moisture content is closer to 60 percent because the process of composting elevates the temperature and reduces moisture. If the moisture content of the compost mix is above 60 percent, the addition of an amendment is necessary to lower the moisture content at 60 percent or below. Straw, sawdust, wood chips, and leaves are commonly used. Equation 4.3 can be used to determine the amount of amendment to be added to lower or raise the moisture content of the compost mix.

$$W_{aa} = \frac{(W_{mb} \times (M_{mb} - M_d))}{M_d - M_{aa}} \tag{4.3}$$

Where:

$W_{aa}$ = Wet weight of amendment to be added (kg)

$W_{mb}$ = Wet weight of mix before adding in amendment (kg)

$M_{mb}$ = Percent moisture of mix before adding amendment (%)

$M_d$ = Desired percent moisture content of mix, wet basis (%)

$M_{aa}$ = Moisture content of amendment added = 100% for water (%)

4.3.5.3 Calculating the C: N Ratio. The C: N ratio for the compost mix is calculated from the C:N ratios of the waste, bulking agents, and amendments. The C: N ratios for various waste products and amendments are shown in Table 4.9. The C: N ratios, which are not reported in the literature, can be estimated from the amount of fixed solids (amount of ash left after organic matter is completely burned) or the volatile solids and the nitrogen content. Equations 4.4 - 4.6 are used to estimate the C: N ratio from the fixed or volatile solids.

$$C = \frac{100 - FS}{1.8} \tag{4.4}$$

$$W_c = \frac{VS}{1.8} \tag{4.5}$$

$$C:N = \frac{C}{N} = \frac{W_c}{Wn} \tag{4.6}$$

Where:

C = carbon, dry basis (%)
FS = fixed solids, dry basis (%)
$W_c$ = dry weight of carbon (kg)
VS = weight of volatile solids (kg)
C:N = carbon to nitrogen ratio (-)
N = total nitrogen, dry basis (%)
$W_n$ = dry weight of nitrogen (kg)

Using local values for C: N ratios and nitrogen or testing of the compost constituents is highly recommended (Haug, 1993). The general equation for estimating the C: N ratio of the compost mix is as follows:

$$R_m = \frac{W_{cw} + W_{cb} + Wca}{W_{nw} + W_{nb} + W_{na}} \tag{4.7}$$

Where:

$R_m$ = C: N ratio of compost mix (-)

$W_{cw}$ = weight of carbon in waste (kg)

$W_{cb}$ = weight of carbon in bulking agent (kg)

$W_{ca}$ = weight of carbon in amendment (kg)

$W_{nw}$ = weight of nitrogen in waste (kg)

$W_{nb}$ = weight of nitrogen in bulking agent (kg)

$W_{na}$ = weight of nitrogen in amendment (kg)

The weight of carbon and nitrogen in each ingredient can be estimated using the following equations:

$$W_w = \%N \times W_{dry} \quad (4.8)$$

$$W_n = W_c / C{:}N \quad (4.9)$$

$$W_c = \%C \times W_{dry} \quad (4.10)$$

$$W_c = C{:}N \times W_n \quad (4.11)$$

Where:

$W_{dry}$ = Dry weight of material (kg)

The dry weight of material can be calculated using the following equation:

$$Wdry = W_{wet} \times (100 - M_{wet})/100 \quad (4.12)$$

Where:

$W_{wet}$ = wet weight of material in question (kg)

$M_{wet}$ = moisture content of material, wet basis (%)

After determining the amount of amendment, if any, to be added to the compost mix that will result in an initial C: N ratio that is between 25 and 40, if the C: N ratio calculated is less than 25 or more than 40, the type and amount of amendment to be added to the compost mix must be determined. For a compost mix that has a C: N ratio below 25, an amendment should be added that has a C:N ratio higher than the desired

C:N ratio and vise versa. Equation (4.13) can be used to calculate the weight of amendment to add to achieve a desired C: N ratio (Rynk et al., 1992).

$$Waa = \frac{N_m W_{mb} \times (100 - M_{mb}) \times (R_d - R_{mb})}{N_{aa} \times (100 - M_{aa}) \times (R_{aa} - R_d)} \quad (4.13)$$

Where:

$W_{nm}$ = Weight of nitrogen in compost mix (kg)

$R_d$ = Desired C: N ratio (-)

$R_{mb}$ = C: N ratio of the compost mix before adding amendment (-)

$N_{aa}$ = nitrogen in amendment to be added, dry basis (%)

$R_{aa}$ = C: N ratio of compost amendment to be added (-)

$N_m$ = nitrogen in compost mix, dry basis (%)

$M_{mb}$ = moisture of compost mix before adding amendment, wet basis (%)

For a compost mix that has a C: N ratio higher than 40, a carbonless amendment, such as fertilizer, can be added to lower the C: N ratio to within the acceptable range. In this special case, the following equation can be used to estimate the dry weight of nitrogen to add to the mix:

$$W_{nd} = \frac{W_{cw} + W_{cb} + W_{ca}}{R_d} - (W_{nw} + W_{nb} + W_{na}) \quad (4.14)$$

Where:

$W_{nd}$ = dry weight of nitrogen to add to mix (kg)

After the amount of an amendment to add has been determined to correct the C: N ratio, the moisture content must be checked. If moisture content is still in the acceptable range, the compost mix design process is complete. Otherwise, moisture content must be corrected.

### 4.3.6 Composting Methods

Three basic methods of composting are described in the literatures (Haug, 1993; Tchobanoglous et al., 1993; Rhyner et al., 1995; and Rynk et al., 1992). They are

windrow composting, aerated static pile composting system and in-vessel composting system.

4.3.6.1 Windrow Method. The windrow method involves the arrangement of compost mix in long, narrow piles or windrows (Figure 4.6). In order to maintain an aerobic condition, the compost mixture must be periodically turned. The minimum turning frequency varies from 2 to 10 days, depending on the type of mix, volume, and the ambient air temperature (Haug, 1993). As the compost ages, the frequency of turning can be reduced. The size of windrow is determined by its porosity. The more porous it is, the higher it can reach. When the windrow is too large, anaerobic condition occurs inside the windrow which release odor when the pile is turned (Strom, 1985b). On the other hand, a small windrow loses heat quickly causing a drop in temperature within the windrow. Low temperature will not destroy weed seeds and pathogens (Rhyner et al., 1995). Windrows generally are 0.9 to 3.7 m in height and 2.7 to 6.0 m in width (Rynk et al., 1992; Diaz et al., 1993; and Tchobanoglous et al., 1993). The type of turning equipment used also affects the width and depth of the windrows. Turning equipment can range from a front-end loader to an automatic mechanical turner. Diaz et al. (1993) recommended a triangle or conical shaped windrow because the overall volume of the hot zone is greater, but for dry windy conditions they recommended a loaf shaped, flattened top, because of the ratio of exposed surface to overall volume.

Some advantages of using windrow system are: rapid drying, ability to handle high volumes, good product stabilization, and low capital investment (Rhyner et al., 1995). The disadvantages of the windrow method include: a low space efficiency, high operational costs as piles must be turned, vulnerable to climate changes, odors released on turning, and large volume of bulking agent is required (Rynk et al., 1992).

Moisture content is a critical parameter that affects oxygen transfers within the pile. Hall (1998) composted sludge with 50% moisture content using windrow method, while Hamoda et al. (1998) stated that moisture content higher than 60 % will limit oxygen diffusion within the composting medium.

Figure 4.6. Typical windrow shapes (Rynk et al., 1992).

Hänninen et al. (1995) studied the decomposition of organic matter of source-separated biowaste during 18 months of windrow composting process. Organic matter was measured as the volatile solids percentage of initial dry matter. The reduction in organic matter was 74% of the initial dry matter, the reduction in carbon content was 52% of the initial total carbon, and the C: N ratio decreased from 23.6: 1 to 15.6: 1.

Lopez-Real and Baptista (1996) composted cattle manure in a windrow system and found that the C: N ratio decreased from the initial value of 29.9: 1 to 12.9: 1, the volatile solids decreased by 10.3% of the initial volatile solids, the moisture content decreased by 17.5% of the initial value, and the total volume decreased by 72% over the 6 weeks composting period

Fernandes and Sartaj (1997) compared static pile composting using natural aeration method (windrow) and aerated static pile using either positive or negative aeration method. Thermophilic temperature (>55 °C) lasted longer in windrow and negative aeration pile than in forced aeration pile. However, low $O_2$ concentrations were measured at the bottom and middle of the windrow and the negative aerated pile during the early stages of the process. Total mass reduction of 32%, mainly due to water evaporation, was observed. The C: N ratio of the composted material in the windrow dropped from the initial value of 21.9: 1 to 18.9: 1.

4.3.6.2 Aerated Static Pile Method. As described by Rynk et al. (1992), Rhyner et al. (1995), and Tchobanoglous et al. (1993), the aerated static pile method involves blending the compost material and then stacking the mix on perforated plastic pipe or tubing through which air is drawn or forced. The outer side of the pile generally is insulated with finished compost or other material. The compost mixture height generally ranges from 2 to 4 m, and the width is usually twice the depth. Individual piles are spaced about one half the distance of the height. Air movement through the pile occurs by suction (vacuum) or by positive pressure (forced) through perforated pipes or tubing. A filter pile is normally used to absorb odor if air is sucked through the pile (Figure 4.7). Some advantages of the static pile method include: low capital cost, higher pathogen destruction, good odor control, and good product stabilization (Rhyner et al., 1995). The

disadvantages include: low space efficient, vulnerable to climate impacts, difficult to work around pipe, high operating cost and maintenance.

Tomati et al. (1995) composted olive-mill waste water (OMW) with wheat straw (10 litters of OMW to 1 kg straw) using forced aeration static pile for 140 days. OMW was added every 3 days to adjust the moisture content of the pile. Thermophilic stage lasted for 35 days. C: N ratio dropped from the initial value of 40: 1 to 28.2: 1 by the end of the thermophilic stage, and continued to drop to 11.5: 1 by the end of the maturation stage. A rapid increase in the material pH from (6.6 to 9.0) was noticed at the beginning of the mesophilic stage, which dropped after 5 days of composting due to the breakdown of substrates into acid intermediates and then slowly increased to 8.8 after 20 days. Total organic carbon decreased from the initial value of 45.2 % DM to 40.4% DM by the end of thermophilic stage and continued to decrease to 35.3% DM by the end of the maturation stage (140 days).

Lopez-Real and Baptista (1996) reported that the volume of the material in the aerated static pile was reduced by 55.3 % of the initial volume after 6 weeks of composting. The C: N ratio decreased from the initial value of 31.7: 1.0 to 15.1: 1.0, the volatile solids decreased by 15.3 % of the initial volatile solids and the moisture content decreased by 11.8 % over the same period.

Fernandes and Sartaj (1997) studied the composting of poultry manure slurry amended with sphagnum peat using forced aerated pile. A total mass reduction of 32% was reported in composted material, due mainly to water vaporization. The C: N ratio dropped from the initial value of 21.9: 1.0 to 19.8: 1.0.

4.3.6.3 In-vessel Method. The in-vessel method involves the mixing of organic waste with a bulking agent in a reactor, or vessel and the addition of a controlled amount of air over a specific detention time. This method has the potential to provide a high level of process control for moisture, aeration, and temperature. There are varieties

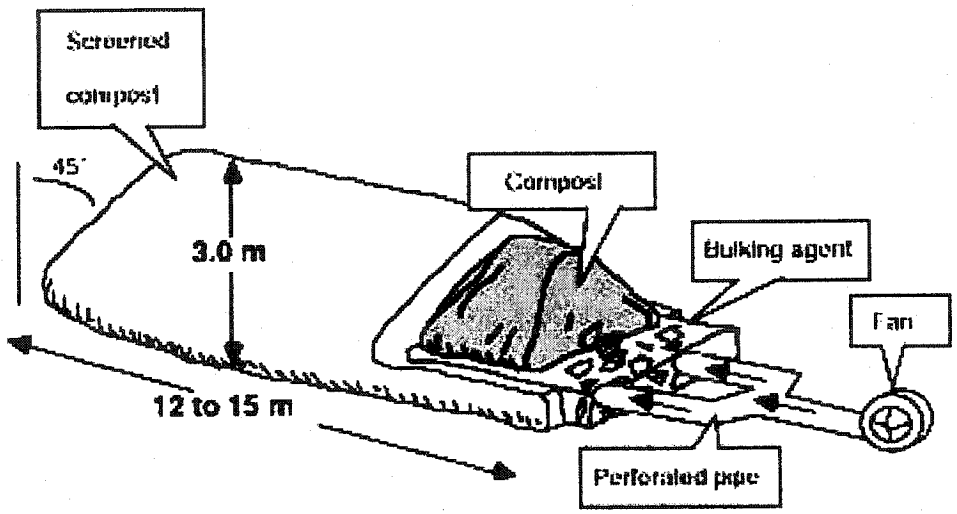



Figure 4.7. Aerated static pile (Tchobanoglous et al., 1993).

of in-vessel methods with different combinations of vessels, aeration devices, and turning mechanisms (Rynk et al., 1992; and Tchobanoglous et al., 1993). Some of the advantages of the in-vessel method include: space efficiency, good process control, protection from adverse climate conditions, good odor control, potential for heat recovery, and can be designed as a continuous process rather than a batch process. The disadvantages of this system include: high capital cost for equipment, careful management is required, dependent on specialized mechanical and electrical equipment, potential for incomplete stabilization, mechanical mixing needs to be provided, less flexibility in operation mode than with other methods (Rynk et al., 1992).

4.3.6.3.1 Bin Composting: Probably this method is the simplest in-vessel method. The materials are contained by walls and usually a roof. The bin itself may simply be wooden slatted walls with or without roof, a grain bin, or a bulk storage building (Figure 4.8). The building or the bin allows higher stacking of materials and better use of space than free-standing piles (Rynk et al., 1992).

Hansen et al. (1989) conducted experiments on poultry manure using a 0.208 $m^3$ composting bin to determine the controllable factors that have the most significant impact on the rate of organic matter decomposition. In less than 24 hours, the temperature below the top of the compost surface reached 52 °C, while the temperature of the bottom surface reached only 43 °C. A dry matter reduction of 16.9 % and a total nitrogen reduction of 29.1 % were reported. Most of the mass reduction was in the form of water evaporation (61.3 %).

Flynn and Wood (1996) composted broiler litter with different type of bedding materials (wood shavings and peanut hulls) mixed with wheat straw, peanut hulls, pine bark and paper mill sludge. The C: N ratio gradually declined and stabilized after approximately 84 days near 14: 1 for wheat straw, while other mixes remained above 20: 1. The final pH values of the composted materials were influenced by the source mix, only 5.8 for pine bark composted with poultry litter of wood shavings, but in the range of 6.7-6.9 for the rest of the mixtures.

Benny et al. (1996) composted a sieved municipal solid waste (<5 cm) in a plastic bins (about 1 $m^3$ each) for 132 days. They observed the three typical phases of composting: psychrophilic, mesophilic and thermophilic. Thermophilic temperature (>45 °C) was observed for 4 weeks and declined reaching the ambient temperature after 60 days. The C: N ratio decreased rapidly from 28: 1 to 18: 1 after only 20 days and slightly declined to 12.2 after 60 days and remained constant for the rest of the experiment.

4.3.6.3.2 Rectangular Agitated Beds: The rectangular agitated bed system combines controlled aeration and periodic turning (Rhyner et al., 1995). As shown in Figure 4.9, the composting takes place between two walls, which form long, and narrow channels referred to as beds. Raw materials are placed at the front end of the bed by a loader. As the turning machine moves forward, it mixes the compost and discharges the compost behind it. With each turning, the machine moves the compost a set distance toward the end of the bed. The capacity of the system is dependent on the number and the dimensions of the beds. In commercially available systems, bed ranges from 1.6 to 6 meters in width. The depth of the bed is usually 1 to 2.5 meters (Rynk et al., 1992).

McKinley et al. (1985) composted 250 tones of raw sewage sludge with hard wood bark chips and saw dust as bulking agents using agitated bed method for 2.5 weeks to establish correlation between some of the composting controllable factors (pH, organic content, C: N ratios, Protein, and temperature) and biomass activity. The initial pH values were in the range of 6.5 to 7.0, while the final pH values were in the range of 8.2-9.0. The pH did not correlate with biomass activity. The volatile solids (organic matter) decreased over the experimental time, the C: N ratio (as total carbon to total nitrogen) highly fluctuated due to the variation of the composition of the substrate, and protein content increased over time. None of the parameters correlated with biomass activity. Of all the parameters measured during the process, temperature was found to have the most dramatic and consistent effect on microbial activity.

Paré et al. (1999) studied the fate of trace metals during composting of biosolid, municipal solid waste and wood chips as a bulking agent using a rectangular agitated bed

Figure 4.8. Aerated composting bin (Rynk et al., 1992).

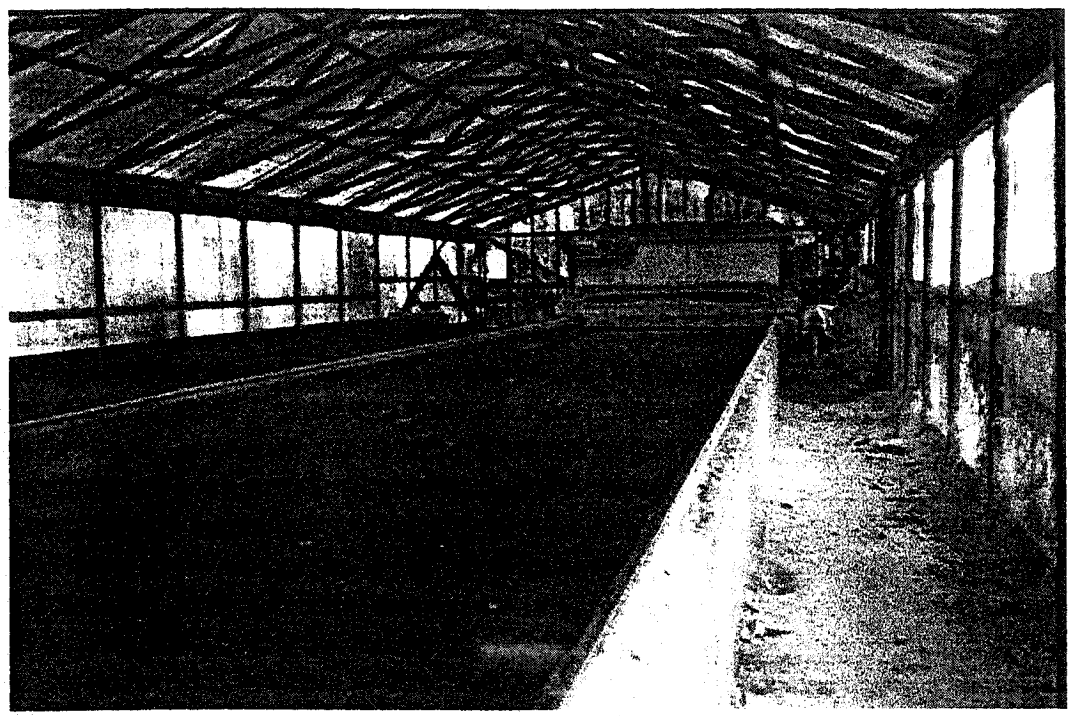


Figure 4.9. Rectangular agitated bed composting system (Rynk et al., 1992).

method. The total nitrogen concentration of the material during the composting process increased by 59.6 % at the end of the experiment (41 days), while total carbon decreased by 22.4 % over the same period of time.

4.3.6.3.3 Rotating Drums: A different system uses a horizontal rotary drum to mix, aerate and move the material through the system (Figure 4.10). The drum is mounted on large bearings for easy turning. A drum is 3.4-meter in diameter and 36.6-meter long and has a daily capacity of approximately 50 tons with a resident time of three days (Rynk et al., 1992 and EPA, 1998). Further decomposition of the material is necessary and is accomplished through a second stage of composting, usually in windrow or aerated static piles. Air is supplied through the discharge end and is incorporated into the material as it tumbles. The air moves in the opposite direction as the material. The compost near the discharge is cooled by fresh air. The drum can be either open or partitioned. An open drum moves all material through continuously in the same sequence as it entered. The speed of rotation of the drum and the inclination of the axis of the rotation determine the residence time (Rynk et al., 1992).

Schwab et al. (1994) investigated some of the controllable parameters of composting using a simulated solid waste in a pilot-rotating drum at a speed of 2 rpm for three days, and then the composted materials were transferred to a barrel. The average temperature inside the bioreactor increased from an ambient temperature of 27 °C to above 55 °C in the first 24 hours and stayed above 50 °C for the first 12 days, except for a transient decrease during the materials transfer. Volatile solids decreased steadily from the initial value of 50 % DM to 33 % DM on day 85 and no further reduction was notice. The C: N ratio increased rapidly in the first three days, and then decreased steadily from the initial value of 40: 1 to 25: 1 on day 40 and stayed constant for the rest of the experiment.

VanderGheynst and Lei (2003) investigated the microbial community structure dynamics in an aerated rotating composting system. They found that aeration had an impact on the compost average temperature, and thus microbial community structure and

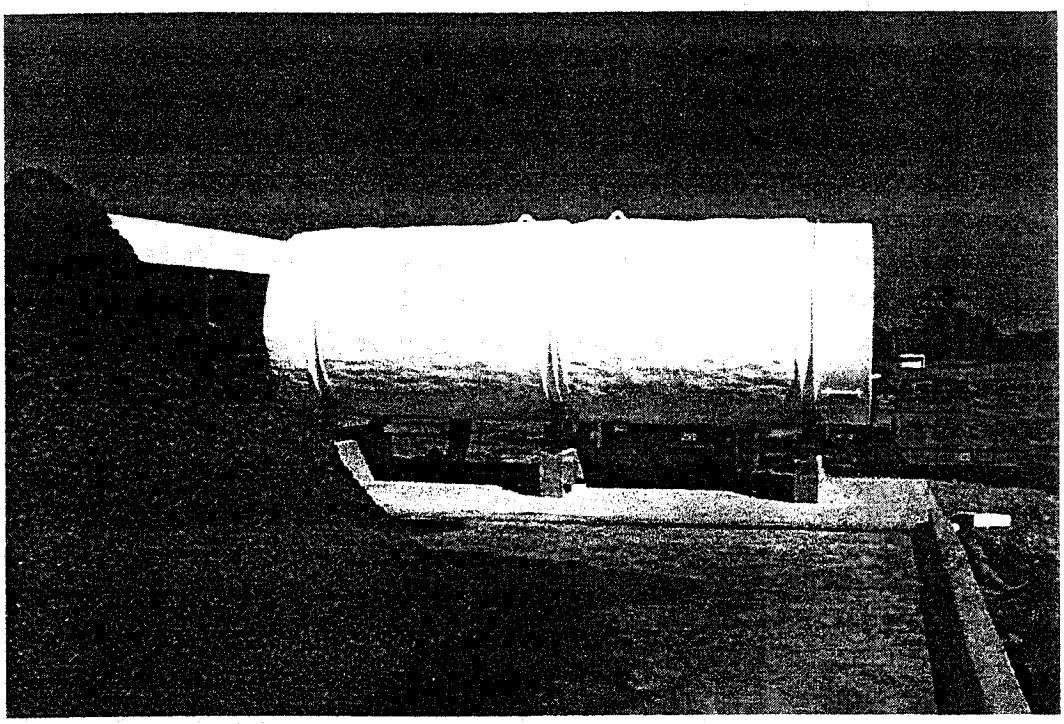


Figure 4.10. Rotating drum composting system (Rynk et al., 1992).

dynamics as measured by phospholipids fatty acid (PLFA) analysis. Drum rotation had a larger impact on microbial community structure dynamics when the process was aerated at 0.013 ($m^3$/hr.kg) than at 0.04 ($m^3$/hr.kg).

### 4.3.7 Compost Quality

There is a great deal of variation in organic nitrogen content and trace element concentration from one compost to another due to differences in type of composted material as seen in Table 4.17. However, the value of compost is determined by its quality. Compost quality is defined by two terms depending on its final use: maturity and stability (McDonnel, 1999). Maturity refers to the lack of phytotoxicity when compost is used as soil amendment on plant production system. Stability refers to the level of biological activity of the compost. Microbial activity of unstable compost will consume nitrogen and oxygen, and generate heat, carbon dioxide and water vapor. Several methods have been developed to determine both maturity and stability. The methods are based on the determination of one or more of the chemical, physical, phytotoxic and microbial characteristics of the compost. Since the number of the existing methods to determine compost quality is very large, the use of a combination of methods is a common practice (Inbar et al., 1993). A list of methods to determine maturity and stability is given in Table 4.18.

4.3.7.1 C: N Ratio Method. The C: N ratio, as a common practice is the measurement of both total carbon and total nitrogen in the solid matrix, has been proposed as maturity and stability indexes (Chanyasak and Kubota, 1981; Garcia et al., 1992; Diaz et al., 1993; Iannotti et al., 1994; Flynn and Wood, 1996; Switzenbaum et al., 1997; and Epstein, 1997). A solid phase C: N ratio less than 20: 1 is suggested for stable compost (Switzenbaum et al., 1997).

Tomati et al. (1995) evaluated the C: N ratio to assess the extent of stability. The C: N ratio started from an initial value of 35.6: 1 and decreased to a value of 28.2: 1 by the end of the thermophilic stage and to 11.5 at the end of the maturation stage (110 days).

Table 4.17. Chemical composition of various type of compost.

| Material | Nitrogen (% DM) | Phosphorous as $P_2O_5$ (% DM) | Potasium (% DM) | C/N ratio | Reference |
|---|---|---|---|---|---|
| Cow manure | 1.7-2 | 1.0 | 2.0 | 10-18 | Golueke,1972 |
| Poultry manure | 5-6.3 | 1.9 | 1.2 | 15 | Chou and Cheng,1996 |
| Horse manure | 1.2-2.3 | 1.0 | 1.6 | 25 | Golueke,1972 |
| Digested sludge | 2-4 | 1.5 | 0.2 | NR | Haug,1993 |
| Garbage | 2.0-2.9 | 1.1-1.3 | 0.8-2.2 | NR | Chanyasak and Kubota, 1981 |
| Yard wastes | 1.95 | NR | NR | 22.8 | Haug,1993 |

DM: Dry Matter.
NR: Not Reported.

Flynn and Wood (1996) studied the carbon and nitrogen losses after 84 days of composting broiler litter mixed with different bulking agents (wheat straw, peanut hulls, pine bark and paper mill sludge). Initially, different mixtures were prepared with C: N ratio ranging between 22: 1 and 34: 1. The final C: N ratio dropped to 13: 1 to 28: 1 respectively, indicating that a constant C: N ratio level can not be establish for different mixtures, which agrees with the results reported by Vanlauwe et al. (1997). However, it can be use as an indicator with another maturity index.

The C: N ratio measurements vary depending on the composted material. Problem in determining what fraction of the total organic carbon is readily available for microbial consumption is a major drawback of this parameter (Morel et al., 1985).

Determination of C: N ratio in water extract has been proposed as a variation of the C: N ratio in solid matrix (Chanyasak and Kubota, 1981). The water extract analysis is based on the assumption that microorganisms in solid phase system, such as composts, are attached to the solid surfaces and are active at the water-solids interface. Insoluble components are decomposed by secreted microbial enzymes into water-soluble compounds and subsequently taken up by the microbial cells. As a result, analyses of the components in the water extract may indicate true microbial activity (Chanyasak and Kubota, 1981).

Iannotti et al. (1994) investigated water-soluble organic carbon and nitrogen fractions for indication of compost stability. Screened compost material were made into a saturated paste, acidified, and then analyzed for soluble organic carbon. The soluble organic carbon to nitrogen ratio correlated well with stability based on the destruction percentage of volatile solids.

4.3.7.2 pH Method. pH measurements (as compost ages) has been proposed as an index to determine compost stability (Epstein, 1997). As the composting process begins, pH values drop rapidly to about 5 (due to organic acid and carbon dioxide production) (Zucconi and De Bertoldi 1987) and slowly rise to values between 7 and 8 where it remains when the compost is stable (Miller, 1992).

Table 4.18. Summary of methods to determine compost quality (Switzenbaum et al., 1997; and Valat et al., 1991).

| Method | Analyses |
|---|---|
| Chemical analyses | Solid matrix: |
| | Oxygen content [S] |
| | Oxygen demand test [S] |
| | Carbon to nitrogen ratio [B] |
| | pH [B] |
| | Cation exchange capacity [B] |
| | Nutrient content [B] |
| | Humification parameters [B] |
| | Metal content [M] |
| | Hydrophobicity [M] |
| | Water extract: |
| | Carbon to nitrogen ratio [B] |
| | Nitrogen content [B] |
| | Polysaccharides content [B] |
| | Amino acids, volatile fatty acids [B] |
| Physical analyses | Heat output [S] |
| | Color [B] |
| | Odor [B] |
| | Solid destruction (TS & VS content) [B] |
| | Water holding capacity [M] |
| Biological analyses | Microbiological: |
| | Indicator organisms [S] |
| | Respiration ($O_2$ uptake & $CO_2$ evolution) [B] |
| | Biochemical: |
| | ATP content [B] |
| | Enzyme activity (i.e. dehydrogenase,lipase) [B] |

S- Stability
M-Maturity
B- Both stability and maturity.

Tomati et al. (1995) used the initial and final pH ratio to assess the extent of stability. At the beginning of the mesophilic stage, pH rapidly increased from 6.6 to 9.0. After 5 days, a drop was observed. Then pH slowly increased reaching a value of 8.8 after 20 days.

Flynn and Wood (1996) studied the pH at regular interval during 84 days of composting broiler litter mixed with different bulking agents (wheat straw, peanut hulls, pine bark and paper mill sludge). At the end of the experiment, the compost pH was 5.8 for pine bark composted with wood shaving litter and was significantly lower than value reported for paper mill sludge compost, which dad an average value of 6.9.

Brewer and Sullivan (2003) evaluated a variety of stability and maturity indexes for yard trimming compost at the end of the maturation phase (133 days). Reported values of pH of the final compost were between 6.5 and 7.0. They concluded that chemical tests such as pH of the compost showed less promise as maturity indicators, but may provide valuable information on the quality of the final compost.

4.3.7.3 Humification Method. Humification related parameters have been used to represent compost stability and maturity (Adani et al., 1997; Jimenez and Garcia, 1992; Veeken et al., 2000; and Wu and Ma, 2002). According to Broadbent (1965), humus can be divided into humic and non-humic components. The non-humic group is less complex and easily degraded, consisting of readily identified compounds such as polysaccharides (McDonnel, 1999; Bernal et al., 1998; Hsu and Lo, 1999; and Sanchez-Monedero et al., 1999). The humic group is more stable and can be further divided into three groups based on solubility and resistance to decay. Fulvlic acid is the lowest in molecular weight and therefore, the easiest to degrade and is soluble in both acid and base. Humic acid is higher in molecular weight and soluble in base. Humin is the highest in molecular weight, the most resistant to decay and insoluble in acid or base (Brady, 1984).

Paré et al. (1998) studied the transformation of carbon during composting of animal manure and shredded paper. Total water soluble, acid-hydrolyzable and non-

hydrolyzable carbon contents were determined on compost sampled on day 0, 11, 18, 26, 33, 40 and 59 after the composting process initiated. Water soluble and acid-hydrolyzable carbon decreased during composting process, whereas non-hydrolyzable form of carbon remained relatively constant.

Wu and Ma (2002) attempted to establish a simple and reliable compost stability test. The study was based on 18 sample collected from five composting facilities and extracted sequentially with water for 2 h. and 0.1 M NaOH for 2 and 24 h. The extractable organic carbon was further classified as Fulvlic acid and humic acid by adjusting the pH to < 2. Compost stability was estimated with a $CO_2$ evolution method. They concluded that it is recommended to apply the extractable fulvlic acid test using water and NaOH extraction method for 2h for measuring compost stability because of their high correlation with $CO_2$ evolution.

Eggen and Vethe (2001) evaluated several chemical parameters to establish stability indices for different types of compost (paper mill sludge compost, fish compost, biowaste compost from windrow composting system and biowaste compost from reactor treatment) replacing respiration rate. Compost matter, water extracts and NaOH extracts were analyzed. When all composts were statistically treated together, water-soluble total organic carbon was the only parameter that correlated significantly with respiration rate ($R^2$=0.82, P<0.0001). They concluded that total organic carbon (in fulvlic acid fraction) and water soluble nitrogen (total and organic) were the chemical indices that correlated with respiration rate when dealing with biowaste.

4.3.7.4 Microbiological Method. Respiration is a parameter related to the catabolic metabolism of microorganisms and thus represents indirectly the state of microbial activity. Respiration rate can be determined through measurements of oxygen uptake rate (Ianotti et al., 1994) and/or carbon dioxide evolution (Switzenbaum et al., 1997). The rationale for this determination is that a decrease in microbiological oxygen consumption or carbon dioxide production of a compost sample indicates decreasing biological metabolism (Haug and Ellsworth, 1991).

Several researchers have suggested different values for both $O_2$ uptake rate and $CO_2$ production rate. Reported oxygen uptake rates for stable compost vary from 40 to 100 mg/ kg TS-h (Morel et al., 1985) or less than 1.5 mg/ kg VS-h (Epstein, 1994). With respect to $CO_2$ evolution, the reported values ranged from 120 to 210 mg/kg TS-hr (Epstein, 1997; and Hue and Liu, 1995).

Other approaches for directly measuring microbial activities have been suggested, including: the ratio of thermophilic bacterial counts to the total aerobic bacteria, total numbers of thermophilic or characterization of thermophilic and fungal groups (Switzenbaum et al., 1997). McDonnell (1999) stated that assessing stability or maturity through direct organism identification are not ideal because microorganisms may be present, but essentially dormant until the right environment occurs.

## 4.4 Canadian Guidelines

Three organizations are involved in the development of standards and regulations in Canada including: Agriculture and Agri-Food Canada (AAFC), the Provincial and Territorial Governments which are represented by the Canadian Council of Ministers of the Environment (CCME) and the Standards Council of Canada (SCC) which is represented by Office of Standardization of Quebec (BNQ). The necessity and feasibility of establishing safety criteria for compost have led AAFC, the CCME and the BNQ to cooperate to develop uniform criteria while giving sufficient flexibility for the different organizations to work within their mandates and reach their objectives. The five categories of quality criteria for compost considered by these three organizations include: maturity, foreign matter, trace elements, pathogenic organisms, and organic contaminants (CCC, 2004).

The BNQ standard, which identifies three types of compost, classifies the products in decreasing order of quality: Types AA, A and B. Generally, the classification is based on the level of compost quality and safety. The classification itself is based on the total organic matter, foreign matter and trace elements in the compost. The other

criteria do not differ between the 3 classes of compost. Compost classified as Types AA and A is of high quality, while the specified requirements for type B compost are considered to be the minimum necessary to obtain a good compost. Because of its trace element content, Type B compost must be accompanied by appropriate use instructions when sold and distributed (CCC, 2004). Types AA and A compost have the same concentration limits for trace elements. All three types of compost have the same criteria regarding maturity and pathogenic organisms.

### 4.4.1 Maturity

When evaluating the quality of the compost, the maturity is an important characteristic to consider. The CCME, BNQ and AAFC have determined that maturity is an inherent compost characteristic. According to the BNQ standard, compost will be deemed mature if it meets two of the following requirements: (a) C: N ratio < 25, (b) oxygen uptake rate < 150 mg $O_2$/kg VS/h, (c) germination of cress *(Lepidium sativum)* seeds and of radish *(Raphanus sativus)* seeds in compost must be greater than 90 percent of the germination rate of the control sample, and the growth rate of plants grown in a mixture of compost and soil must not differ more than 50 percent in comparison with the control sample. In addition to BNQ requirements, the CCME add two other alternatives: (a) compost will not reheat upon standing to greater than 20 °C above ambient temperature and (b) compost must be allowed to mature for at least 21 days after the thermophilic phase is completed. Other criteria include: (a) reduction of organic matter must be 60 percent by weight and (b) compost must be allowed to mature for at least 21 days after the thermophilic phase is completed. If no determination of maturity is made, the compost must be cured for a six-month period and the state of the curing pile must be conducive to aerobic biological activity. The curing stage begins when the pathogen reduction process is complete and the compost no longer reheats to thermophilic temperatures.

### 4.4.2 Foreign Matter

Canadian guidelines take foreign matter in compost into consideration. BNQ and CCME established three different foreign matter mass content limits for types AA, A and B compost. They defined foreign matter as any matter over a 2 mm dimension that results from human intervention and having organic or inorganic constituents such as metal, glass and synthetic polymers (plastic and rubber) that may be present in the compost but excluding mineral soils, woody material and rocks. Foreign matter content as a percentage of oven-dried mass for the three types of compost type AA, A, B are $< 0.01$, $< 0.5$, $< 1.5$, with maximum dimensions of 12.5, 12.5 and 25 mm, respectively. All three types of compost must not contain sharp foreign matter, defined as any matter measuring over a 3 mm dimension that may cause damage or injury to humans and animals during or resulting from its intended use. The AAFC position regarding foreign matter takes into consideration the product safety aspect by considering the level of tolerance for sharp objects but the aesthetic aspect of compost is not taken into consideration.

### 4.4.3 Trace Elements.

A trace element as defined by BNQ is any chemical element present in compost at a very low concentration, which is essential to plant growth (particularly Cu, Mo, Zn) and heavy metals, which could be harmful to human health and to the environment. Table 4.19, 4.20, and Table 4.21 show the different elements covered by BNQ, CCME and AAFC for compost type AA, A and B, respectively.

### 4.4.4 Pathogens.

Canadian guidelines only consider human pathogens. There is no given information about plant pathogens. They provided guidelines for sludge base-compost by using faecal coliforms and salmonellae as sefety indicators. Some of these pathogens and their destruction temperature were listed in Table 4.8. According to AAFC (2001),

Table 4.19. Maximum trace element concentration limits for compost established by BNQ (CCC, 2004).

| Trace Element | Compost Category AA and A Maximum Concentration (mg/kg DM) | Compost Category B Maximum Concentration (mg/kg DM) |
|---|---|---|
| Arsenic | 13 | 75 |
| Cadmium | 3 | 20 |
| Cobalt | 34 | 150 |
| Chromium | 210 | 1060 |
| Copper | 100 | 757 |
| Mercury | 0.8 | 5 |
| Molybdenum | 5 | 20 |
| Nickel | 62 | 180 |
| Lead | 150 | 500 |
| Selenium | 2 | 14 |
| Zinc | 500 | 1850 |

Table 4.20. Maximum trace element concentration limits for compost established by CCME (CCC, 2004).

| Trace Element | Compost Category A | Compost Category B | |
|---|---|---|---|
| | Maximum Concentration (mg/kg DM) | Maximum Concentration (mg/kg DM) | Acceptable Cumulative Metal Additions to Soil (kg/ha) |
| Arsenic | 13 | 75 | 15 |
| Cadmium | 3 | 20 | 4 |
| Cobalt | 34 | 150 | 30 |
| Chromium | 210 | * | * |
| Copper | 100 | * | * |
| Mercury | 0.8 | 5 | 1 |
| Molybdenum | 5 | 20 | 4 |
| Nickel | 62 | 180 | 36 |
| Lead | 150 | 500 | 100 |
| Selenium | 2 | 14 | 2.8 |
| Zinc | 500 | 1850 | 370 |

* Limits for copper and chromium are not established in the Fertilizers Act.

Table 4.21. Maximum trace element concentration in sewage sludge and sewage-based by-products (AAFC, 2001).

| Trace Element | Maximum Acceptable Concentration Within Product (mg/kg DM) | Acceptable Cumulative Metal Additions (mg/kg DM) |
|---|---|---|
| Arsenic | 75 | 15 |
| Cadmium | 20 | 4 |
| Cobalt | 150 | 30 |
| Mercury | 5 | 1 |
| Molybdenum | 20 | 4 |
| Nickel | 180 | 36 |
| Lead | 500 | 100 |
| Selenium | 14 | 2.8 |
| Zinc | 1850 | 370 |

compost and sludge subjected to sale and use must be safe, must not contain any pathogenic organisms or the type and number of such organisms must be reduced to an acceptable level. AAFC adapted the USEPA's sludge regulations, which require that faecal coliforms to be less than 1000 MPN/gram of total solids, and non-detectable salmonellae (< 3 MPN/ 4 grams of total solids).

Compost that is known to have human pathogens shall either have pathogenic organisms count that does not exceed the limits stated by AAFC, or undergo one of the following treatments: (a) if in-vessel composting method is used, the solid waste shall be maintained at an operation temperature of 55 °C or greater for three days, (b) if windrow composting method is used, the solid waste shall be maintained at an operation temperature of 55 °C or greater for at least fifteen days, in which time the windrow shall be turned at least five times to ensure that all feedstock are exposed to the high temperature region, and (c) if aerated static pile composting method is used , the solid waste shall be maintained at operation temperature of 55 °C or greater for three days, making sure that the pile is covered with an insulating layer of material (mature compost or wood chips) to ensure that all area of the feed material are exposed to the required temperature.

### 4.4.5 Organic Contaminants

Many commonly available and used insecticides and herbicides are non-persistent (they quickly break down or disperse following their application). As a result, the residual concentrations in compost made from green waste are not of major concern to all the three organizations (CCME, AAFC, and BNQ). However, all the three organizations (CCME, AAFC, and BNQ) require further information on organic contaminants in Canadian compost. Therefore, research in this field is needed as AAFC suggested. Michel et al. (1997) stated that pesticides are found in incoming yard trimmings. They particularly specified diazinion, at a concentration of 5 ppm, as the most found insecticide received in composting facilities in Illinois. Other pesticides such as 2, 4-D, a postemergence broad leaf herbicide, with a concentration of 5.5 ppm has also been reported by Lemmon and Pylypiw (1992) and as high as 80 ppm after standard

application has been reported by Bugbee and Saraceno (1994). Pendimethalin, a pre-emergence broad leaf and grass weed herbicide, was also reported with a concentration of 5 to 40 ppm (Lemmon and Pylypiw, 1992). Even at low level, pesticides can be toxic to some life forms (Michel et al., 1997). According to National Research Council of Canada (NRCC), compost contaminated with as low as 2 ppm of 2, 4-D, for example, significantly reduces plant growth. Some pesticides are persistent as phenanthrene was found in a high concentration (89 to 93% of the initial concentration) after composting process (Racke and Frink, 1989).

## 4.5 The Fate of Plant Pathogens during the Composting Process

The fate of plant pathogens during the composting process of infested plant residues have been reviewed by Bollen (1993), Golueke (1991), Hoitink and Fahy (1986), Hermann et al. (1994), Churchill et al. (1995), and Ryckeboer et al. (2002). These pathogens included: bacteria, nematodes, fungi, and viruses. Inactivation of phytopathogens during the composting process can be the result of heat generation during the thermophilic stage, microbial competition, or production of toxic substances during the decompostion of organic material (Bollen, 1993; and Elorriota et al., 2003).

### 4.5.1 Bacteria

Bollen (1993) reported that plant pathogenic bacteria are sensitive to the composting environment. Elliott (1951) indicated that the thermal death temperatures of most pathogenic bacteria are near 50 °C. For example, *Clavibacter michiganensis* subsp. *michiganensis*, one of the most heat resistant bacterial plant pathogen, has a thermal death temperature of 53 °C. Other plant pathogenic bacteria studied during the composting process include *Erwina carotovora*, which did not survive in compost that reached 40 °C (Hoitink et al., 1976; and Bruns et al., 1993) or 15 minutes at 70 °C (Elorriota et al. (2003); and *Pseudomonas phaseolicola*, which did not survive in compost that reached 35 °C (Lopez-Real and Foster, 1985). Bollen (1993) concluded that it is unlikely that bacterial plant pathogens could survive the aerobic composting process,

where temperature of the composted material could reach more than 50 °C. Elorriota et al. (2003) investigatied the fate of three phytopathogenic bacteria (*Pseudomonas syringae pv. Syringae, Xanthomonas campestris pv. Vesicatoria,* and *Erwina carotovora subsp. Carotovora*) during the composting process, none of them was able to survive the composting process environment for more than 50 hours at 50 °C. Higher temperature treatment reduced the required time even further.

### 4.5.2 Nematodes

Nematodes, including root knot and cyst-forming species, are highly sensitive to composting environment and did not survive during the composting process (Bollen, 1993). Wallace (1963) reported that *Meloidogyne hapla* did not survive treatment at 50 °C for one hour or 45 °C for 4 hours. Bollen (1993) reported complete elimination of *Meloidogyne incognita* during composting, at 57 °C, of infested tomato residue. Bollen (1993) concluded that transmission of plant pathogenic nematodes with properly prepared compost is unlikely.

### 4.5.3 Fungi

Hoitink et al. (1976) tested Rhododendron crowns and roots infected with *Phytophora cinnamomi* and *Pythium irregulare*, Sugarbeets infected with *Rhizoctonia solani*, Geranium tissues infected with *Botrytis cinereai* during the composting process. Fungi were placed inside a pile of hardwood bark and a control treatment as another pile without the addition of nitrogen source (high C: N ratio). Maximum temperature of the compost pile was in the range of 40-60 °C for 10 to 12 weeks, while it was only 25 °C in the control pile. Among all pathogenic fungi, *P. cinnamomi, P. irregulare*, and *R. solani* were reisolated.

Bollen (1993) reviewed the survival some of fungal plant pathogens during the composting process including: *Armillaria mellea, Botrytie allii, B. cinerea, Didymella lycopersici, Phomopsis sclerotioides, Phytophthora cinnamomi, P. cryptogea, P. infestans, lasmodiophora brassicae, Pyrenochaeta lyoopersici, Pythium irregulare,*

*Rhizoctonia solani*, *Rhisoctonia sp.*, *Sclerotnia sclerotiorum*, *Sclerotiumcepivorum*, *S. rolfsii*, *Stromatinia gladioli*, *Thielaviopsis basicola*, *Verticillium dahliae*, *Olpidium brassicae*, and *Fusarium oxysporum*. He concluded that the composting process is very effective in sanitizing crop residues infested with these pathogens.

Bruns et al. (1993) studied the fate of *Plasmodiophora barssicae* during the composting process of high wood chips content mixed with organic household waste, using windrow method. *P. barssicae* was inactivated during the ideal composting condition, where high temperature of about 60 °C and optimum moisture content of 50 % were maintained, of wood chips and organic household waste after 14 weeks. However, in a treatment utilizing solely wood chips, the pathogen survived the composting process even with high temperature of 55 to 63 °C. They concluded that plant pathogens can generally be eradicated depending on the pathogen type, source of the composted material, and the composting method applied.

Lodha et al. (2002) studied the survival of *Macrophomina phaseoline*, a heat resistant soil-borne fungal plant pathogen that causes dry root rot of clusterbean, at various stages of composting process of a mixture of infected residues of clusterbean and pearl millet. The mixture was enriched with 4 % urea-N and buried 60 cm compared to 2 % urea-N and buried 30 cm. Windrow composting method was utilized in this experiment, in which temperature varied from 48 to 51 °C at 30 cm and 60 to 62 °C at 60 cm depth. They concluded that thermophilic phase (48 to 62 °C) was not enough to completely inactivate *M. phaseoline*. However; further reductions (54 to 61 %) were achieved when moistened compost materials were exposed to heat (48 to 53 °C) during summer days.

Suarez-Estrella et al. (2003) investigated the effect of thermophilic stage of composting on the phytopathogen fungus *Fusarium oxysporum f. sp. Melonis* infected vegetable residues were composted using windrow method. A complete inactivation of this fungus was achieved after 2 to 3 days of thermophilic composting process. Confirmation of the result was done by conducting in-vitro experiments (lab-scale), and temperature values of 45, 55, 65 °C were tested. Although all temperature treatments

were effective, they only differ in the length of time required to achieve complete eradication of the fungus.

Ryckeboer et al. (2002) combined short-term (1 to 2 days) high temperature (52 °C) anaerobic digestion and thermophilic aerobic composting of source separated organic household waste (at 58 °C for 19 days, or at 68 °C for 12 days) to study the fate of *Plasmodiophora brassicae*. The fungus was destroyed to below detectable level within one day of high temperature anaerobic digestion. Other plant pathogens were also sensitive to this method. They concluded that short-term high temperature anaerobic digestion followed by thermophilic composting is a highly efficient process for the eradication of pathogens in the solid waste.

### 4.5.4 Viruses

According to Bollen and Volker (1996), viruses are more resistant during the composting process than other pathogens (such as bacteria, fungi, and nematodes). Lethal temperatures of most viruses are much higher than those that are commonly attained during the composting process. The lethal temperatures of cucumber necrosis virus (CNV), tobacco mosaic virus (TMV), tobacco necrosis virus (TNV), and tobacco rattle virus (TRV) are 75-80, 90-93, 75-90, and 78-80 °C, respectively.

Bollen (1993) reported that only one out of five tested trials, complete inactivation of TRV during composting process of infected plant residue for 6 days with a maximum temperature reaching 68 °C had occurred. However, Bollen et al. (1986) reported that TRV was eradicated during farm scale static pile composting method where maximum temperature recorded remained below 60 °C. Even though, complete inactivation of some viruses were not achieved, their vectors can not resist the composting environment. Therefore, infection of a crop grown on a compost-amended soil can occur only if both the virus and the vector survive the composting process (Bollen, 1993).

TRV is transmitted by free-living nematodes, which are very sensitive to heat. The fungus *Olpidium brassicae* transmits TNV, which is among the heat resistant root-infecting fungi. Bollen et al. (1986) reported that the temperature required to destroy the resting spores of this fungus was in the range of 57.5-62.5 °C, which can be achieved during the composting process. Bollen (1993) concluded that special care must be given to TMV because of its wide range of hosts and its direct ability to infect roots without the need for vectors.

Ryckeboer et al. (2002) combined short-term (1 to 2 days) high temperature (52 °C) anaerobic digestion and thermophilic aerobic composting of source separated organic household waste (at 58 °C for 19 days, or at 68 °C for 12 days) to study the fate of TMV. Two days of anaerobic digestion did not reduce the concentration of TMV. However, when the short-term anaerobic treatment was followed by 19 days of thermophilic composting, the concentration of the infection was reduced by a factor of almost three orders. The other aerobic treatment (at 68 °C for 12 days) was even better compared to 19 days at 58 °C. Although, complete inactivation of the virus was never achieved, they concluded that a short-term high temperature anaerobic digestion followed by a thermophilic composting is highly efficient process for the eradication of pathogens in the solid waste management.

## 4.6 The Fate of Pesticides during the Composting Process

The fate of pesticides during the composting process have been reviewed by Lemmon and Pylypiw (1992), Michel et al. (1995, 1996, 1997), Vandervoort et al. (1997), Reddy and Michel (1999), and Fogg et al. (2003).

Lemmon and Pylypiw (1992) investigated the fate of some pesticides including: the pre-emergence herbicide pendimethalin and three organophosphate insecticides (diazinon, chlorpyrifos and isofenphos), in grass clipping and the resulting compost. They found that these pesticides rapidly disappeared from grass clippings soon after application. After three weeks of composting, pesticides were present at concentration below 1 mg / kg.

Vandervoort et al. (1997) investigated the fate of several pesticides during the composting process of grass clippings including: organophosphate insecticide chlorpyrifos, the herbicides 2,4-D, isoxaben, triclopyr, clopyralid, and a plant growth inhibitor flurprimidol. The changes in concentration of pesticides were monitored during the composting process, sampling at 14, 28, 36, 128, and 365 days. The patterns of pesticides loss during the composting process were similar for all of the pesticides. The concentrations of isoxaben, flurprimidol, triclopyr, and chlorpyrifos were below the detection limit of 0.01 ppm of the method used after 365 days. The 2,4-D concentration declined from the initial concentration of 183 ppm to less than 2 ppm after 365 days of composting. Samples taken from turned and unturned pile as well as interior and exterior were compared. In general, samples concentrations were lower from turned pile and from the interior of the pile.

Michel et al. (1995, 1996, and 1997) studied the fate of three common lawn care pesticides: the insecticide diazinon, and two herbicides (2,4-D, and pendimethalin). $^{14}C$-radiolabeled pesticides were used to follow the products of pesticides decomposition. They found that 50% of 2,4-D was mineralized after 50 days of composting, 23% was converted to humic acids, and 19.5% was unextractable (bonded to compost particles). Only 11% of diazinon was mineralized after 54 days of composting. In addition, 36% formed IMHP, a by-product of diazinon that is water soluble and less toxic, 19% of diazinon was incorporated into humic fraction of the compost, and 32% of initial concentration of diazinon was unextractable. Pendimethalin was found to be more resistant to biodegradation than both 2,4-D and diazinon. Approximately, 13% of the pendimethalin was mineralized. They also found that volatilization was negligible for all the three pesticides.

Reddy and Michel (1999) reviewed the fate of four common lawn care pesticides: the insecticide diazinon, and three herbicides (2,4-D, atrazine and pendimethalin) during the composting process of yard trimmings amended with $^{14}C$-radiolabeled pesticides to track the products of each pesticide decomposition. They found that the pesticides have different fate during the composting process. The herbicide 2,4-D was rapidly mineralized and transformed into high molecular weight humic compounds, 48% of the

original concentration was mineralized and the rest was transformed into high molecular weight humic compounds or was unextractable. Diazinon was not readily mineralized (only 11 %), while the rest underwent rapid transformation to a less toxic water-soluble metabolites and unextractable residues. Pendimethalin was mostly converted into unextractable residues (73 %). Finally, atrazine mineralization was low (2-7 %) and varied with different lignocellulosic substrates.

Fogg et al. (2003) investigated the fate of some pesticides including: isoproturon, pendimethalin, chlorpyrifos, chlorothalonil, epoxiconazola, and dimethoate during the composting process of a mixture of soil, compost, and wheat straw. They were applied as a mixture and alone to compost and plane topsoil. They found that degradation was faster in compost than in soil, both when the pesticides were applied as a mixture or individually. However, pesticides applied as a mixture were slower than when applied alone. $DT_{50}$ values measured in the mixture were generally less than 5 months and the majority of $DT_{90}$ values were less than 1 year, which indicate that composting process are able to degrade a complex mixture of pesticides better than soil. $DT_{50}$ and $DT_{90}$ are defined as the amount of time it takes for 50 and 90 percent of the parent compound to disappear, respectively (Kamrin, 1997).

# 5 . EXPERIMENTAL APPARATUS

The experimental set up shown in Figures 5.1 was specifically designed and constructed for this study. It consisted of a frame, three bioreactors, air supply units, and data acquisition unit.

## 5.1. The Frame

The frame was made of two parts as shown in Figure 5.2. The main part was made of three aluminium sheets (3.2 mm thick). The central one measured 330× 1100 mm and the two side sheets measured 140× 1100 mm each. They were soldered together making a vertical channel (U-shaped) with a length of 1100 mm, a width of 330 mm and a depth of 140 mm. This U-shaped stand held the mixing motors, flow meters, air and exhaust gas manifolds and tubing, and the thermocouple wires. The second part of the frame was a horizontal supporter made of three 50× 50 mm aluminium angles (3.2 mm thick), two of which measured 700 mm and were fixed to the main part by means of four 6 mm diameter stainless steel bolts and nuts, whereas the third one measured 328 mm and kept the other two angles 330 mm apart. The three were aluminium angles permanently soldered together.

## 5.2. The Bioreactor

The designed bioreactor provided space for 3.0 -3.5 kg (wb) of compost mixture plus 25 % of the volume as a head space. Each bioreactor (Figure 5.3) was constructed of 203 mm inside diameter (ID) polyvinyl chloride (PVC) sewer pipe. The length and the wall thickness of the tube were 520 and 5 mm, respectively. They were horizontally fixed to the main frame as shown in Figure 5.4. One end of the tube was covered with a removable circular Plexiglas plate (for cleaning purpose) of 203 mm diameter and 6 mm thickness. This plate was recessed and secured into the cylinder by means of six stainless

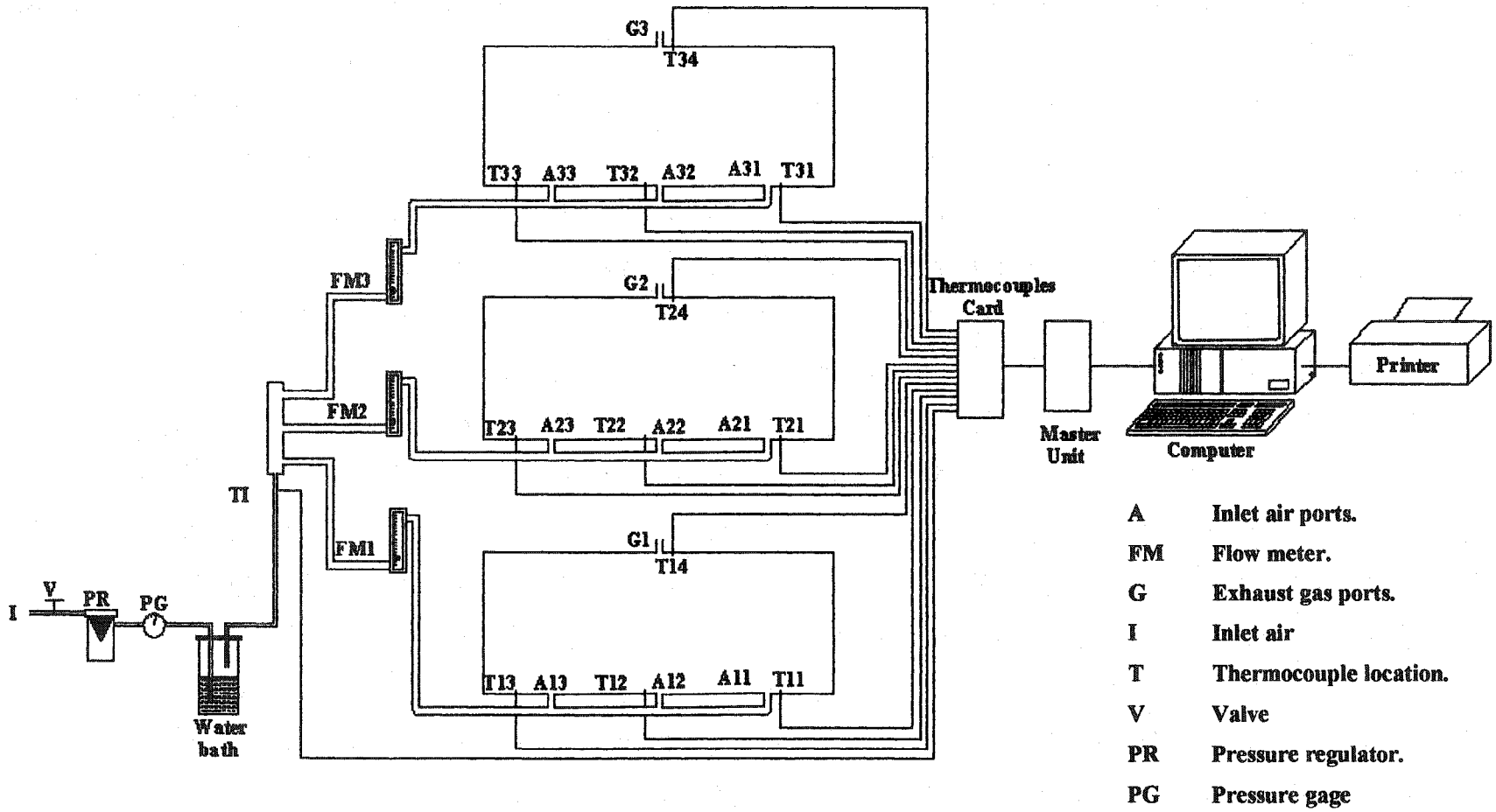



Figure 5.1. Experimental set up.

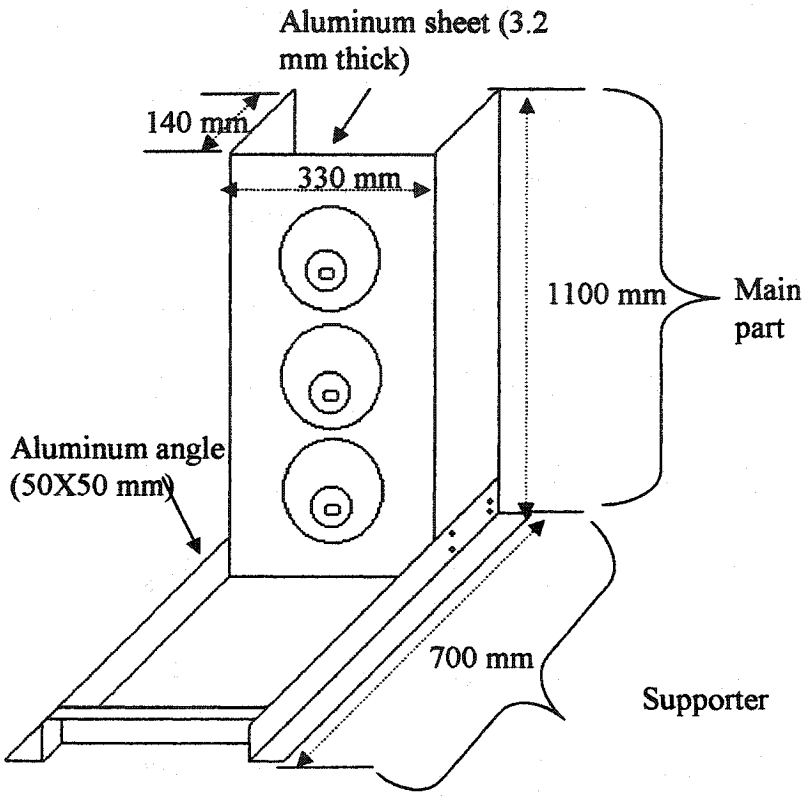



Figure 5.2. Detailed schematic of the frame.

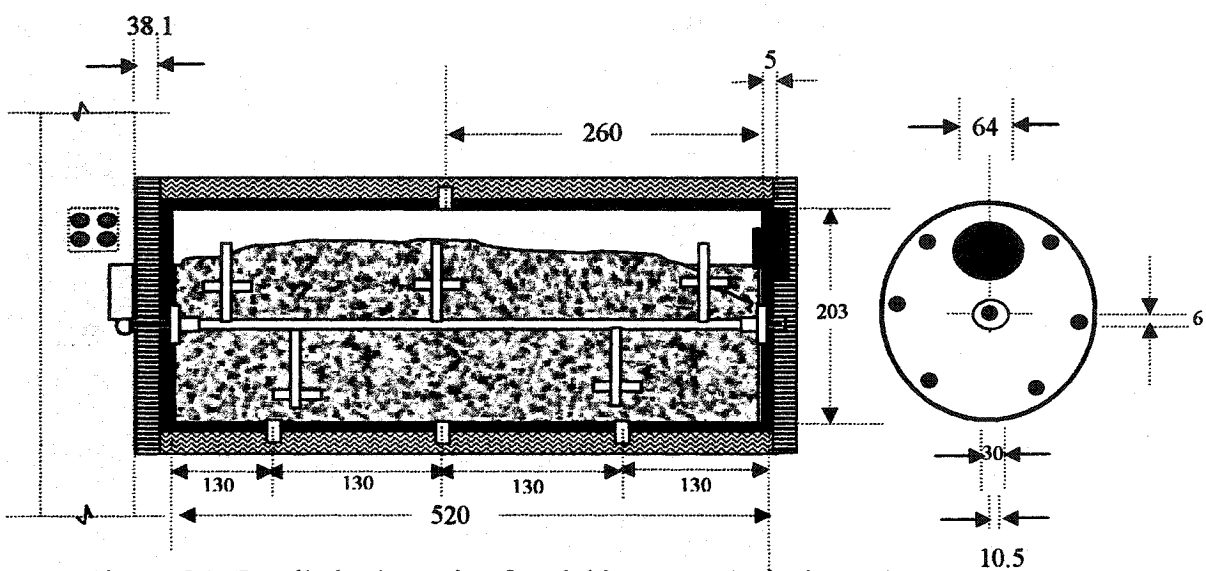


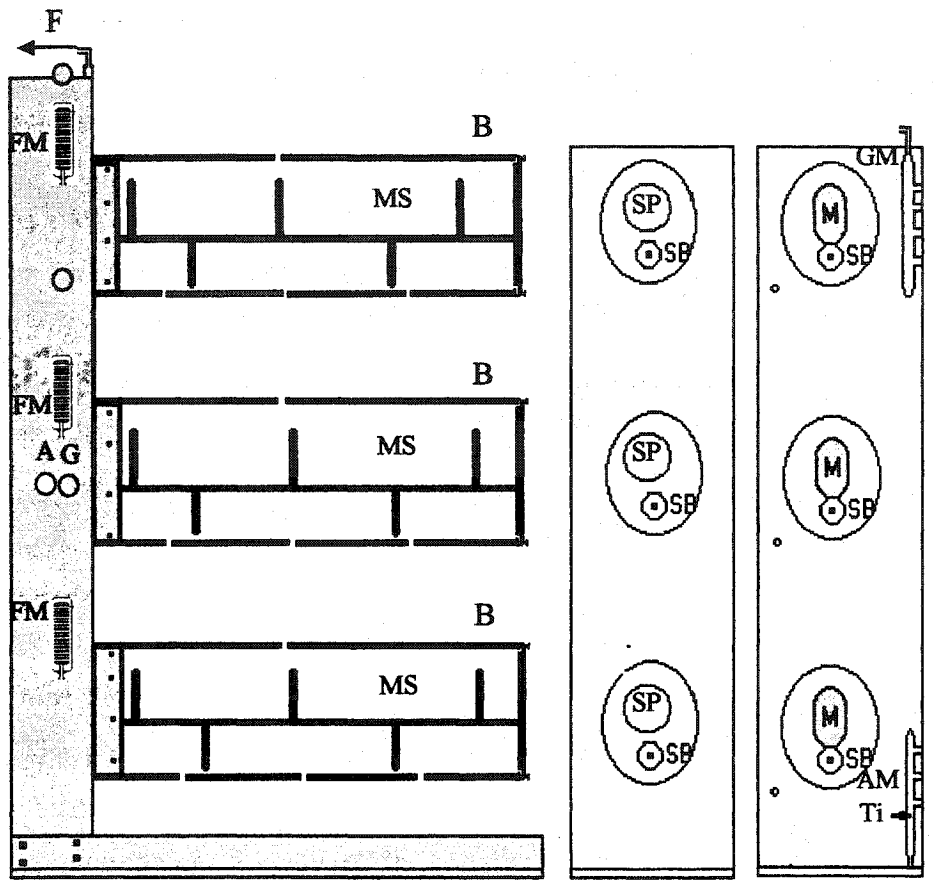

Figure 5.3. Detailed schematic of each bioreactor (units in mm).

steel screws (6 mm). A rubber gasket lining (O-ring, 2.5 mm thick) was added to the inner side of the removable circular plate to keep it tight. There was a small circular window (64 mm in diameter) on the removable circular plate, which was closed with a rubber stopper (No.13) and used as a sampling port. The other side of the tube was covered with a fixed circular PVC plate of 203 mm diameter and 6 mm thickness. This plate was glued PVC/711 (IPS Corp., Gardena, CA) into the tube and secured by means of six stainless steel screws (6 mm diameter). The fixed circular plate was fitted in to an aluminium ring, which was fastened into the frame by means of four bolts (6 mm) and nuts. There were three holes at the bottom and one at the top of the bioreactor, which were drilled and threaded to take a 12 mm nylon hose barb. The three holes at the bottom were connected to a manifold by 6.4-mm diameter tygon tubing and used for aeration, whereas the fourth one at the top was used for the exhaust gas. Both the removable and fixed circular plates were insulated with 38.1 mm thick Styrofoam layer, while the tube was insulated with 38.1-mm thick Fibreglass. The three bioreactors were fixed into the frame as shown in Figure 5.4.

Inside each bioreactor, a removable 10.5 mm diameter solid stainless steel shaft was mounted on two bearings (Figure 5.5). There were 5 stainless steel collars on the shaft in which five bolts of 69 mm in length and 6 mm diameter each were mounted. The shaft was rotated (5.76 rpm) by a thermally protected electric motor (Model No. 127P1486/B, D. C., Sigma Instruments Inc., Braintree, Mass, USA).

## 5.3. Air Supply

The air was supplied continuously to the bottom of the bioreactor from the laboratory air supply (Figure 5.6) at the chosen airflow. It passed through a pressure regulator and a pressure gage to maintain a pressure around 5 kpa in order to ensure equipment and connections safety. The regulated air then passed through a water bath to humidify the inlet air to nearly 100% saturation, and then passed through a flow meter




(a) Front -View. (b) Side-View (c ) Back-View

| | |
|---|---|
| A | Air Sampling Port. |
| M | Air Manifold. |
| B | Bioreactor. |
| F | Frame. |
| FM | Flow Meter. |
| G | Gas Sampling Port. |
| GM | Gas Manifold. |
| M | Mixing Motor. |
| MS | Mixing Shaft Unit. |
| SP | Material Sampling Port. |
| SB | Mixing Shaft Bearing. |

Figure 5.4. Various views of the bioreactors arrangement.

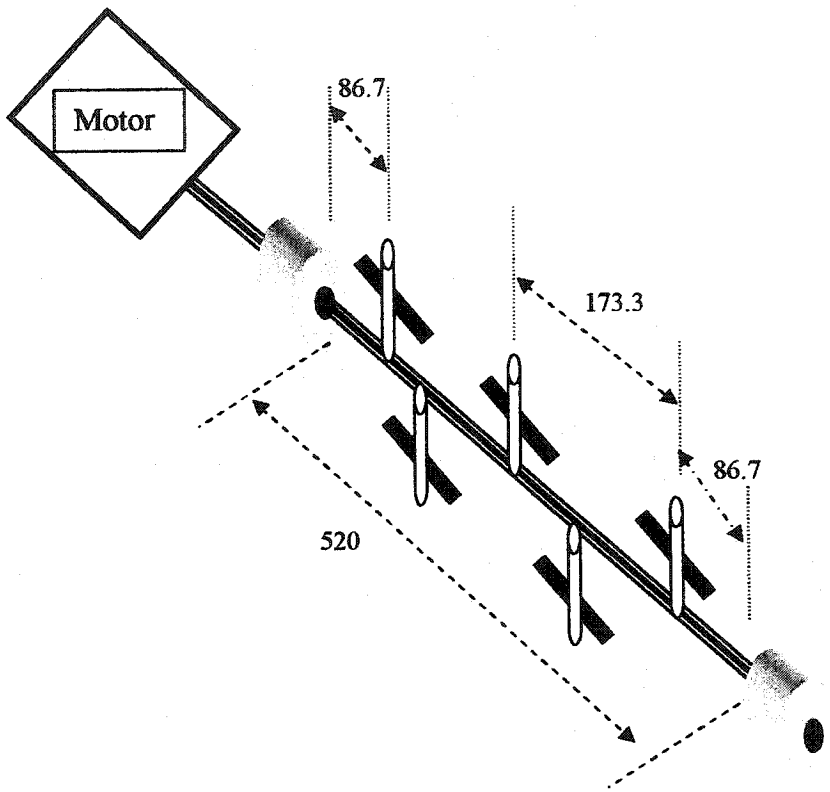
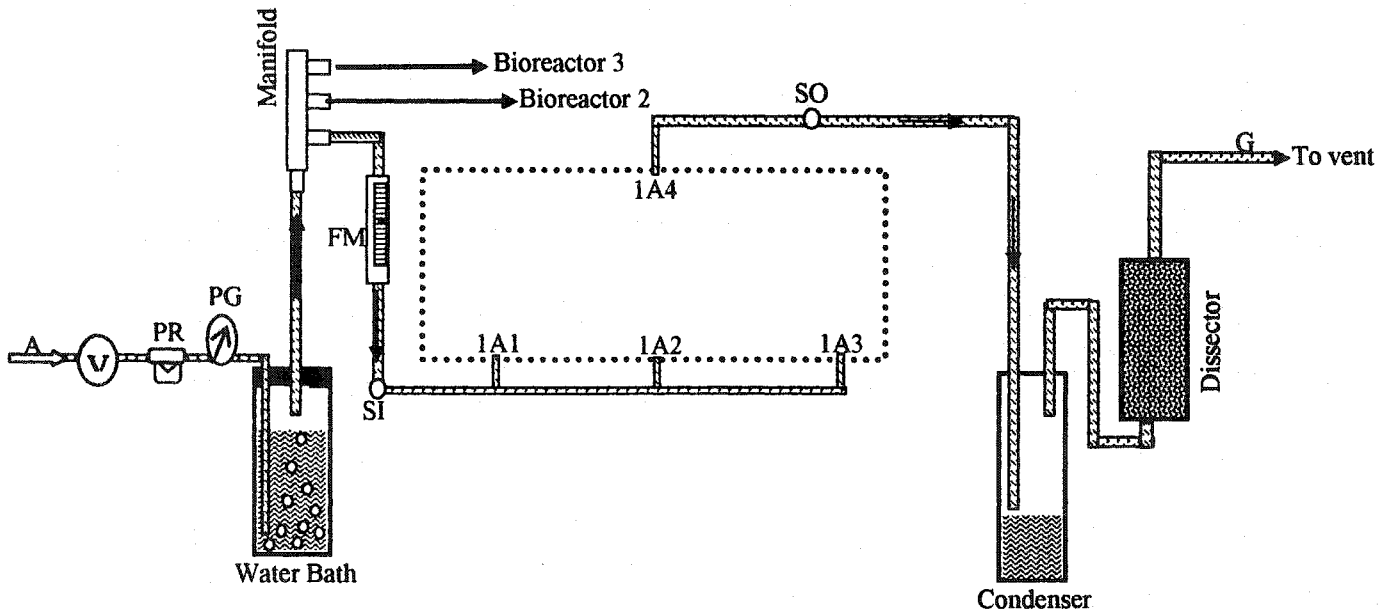



Figure 5.5. Mixing unit of each bioreactor (dimensions in mm).




| | |
|---|---|
| A | Inlet air. |
| 1A 1,2,3 | Inlet air ports for the first bioreactor. |
| 1A 4 | Outlet gas port for the first bioreactor. |
| SI | Inlet air sampling port. |
| SO | Outlet gas sampling port. |
| FM | Flow meter. |
| G | Exhaust gas. |
| V | Valve |
| PR | Pressure regulator. |
| PG | Pressure gage. |

Figure 5.6. The aeration unit used with each bioreactor.

(No 32461-14, Cole-Parmer Instrument Company. Vernon Hills. Illinois. USA) to control and measure the volume of air entering the bioreactor. The flow meter had a 4" scale and a range of 2-20 standard cubic foot per hour (0.0566-0.566 $m^3/h$).

Sampling of the inlet air was taking from a rubber sampling septum right before the air entered the bioreactor. After the air entered the bioreactor, it passed vertically upward through the compost and exited at the top of the bioreactor as shown in Figure 6.6. When the gas left the bioreactor, it passed through a rubber sampling septum, then through a condenser and finally through a desiccator to capture the moisture in the exhaust gas. Both air entrance and exit tubes were covered, along with the bioreactor, with insulation material.

## 5.4. Data Acquisition Unit

The data acquisition unit consisted of a master unit, scanning card, software, temperature sensors, a personal computer and a printer (Figure 5.7).

### 5.4.1 Master Unit

The master unit (Multiscan 1200, Omega, Stamford, CT) used was a high-speed instrument that was connected to a computer via RS 232 interface.

### 5.4.2 MTC/24 Thermocouple/Volt Scanning Card

The Thermocouple/Volt Scanning Card (MTC/24, Omega, Stamford, CT) contained 24 isolated differential input channels. Each channel can be programmed to receive inputs from thermocouple type J, K, T, E, R, S, B, and N, or from any of the following voltage ranges: ± 100 millivolts, ± 1 volt, ± 5 volt and ± 10 volts with an accuracy of ± 0.02 % of each range. Temperature values can be returned in any of the following units: °C, °F, °K, °R, and mV.

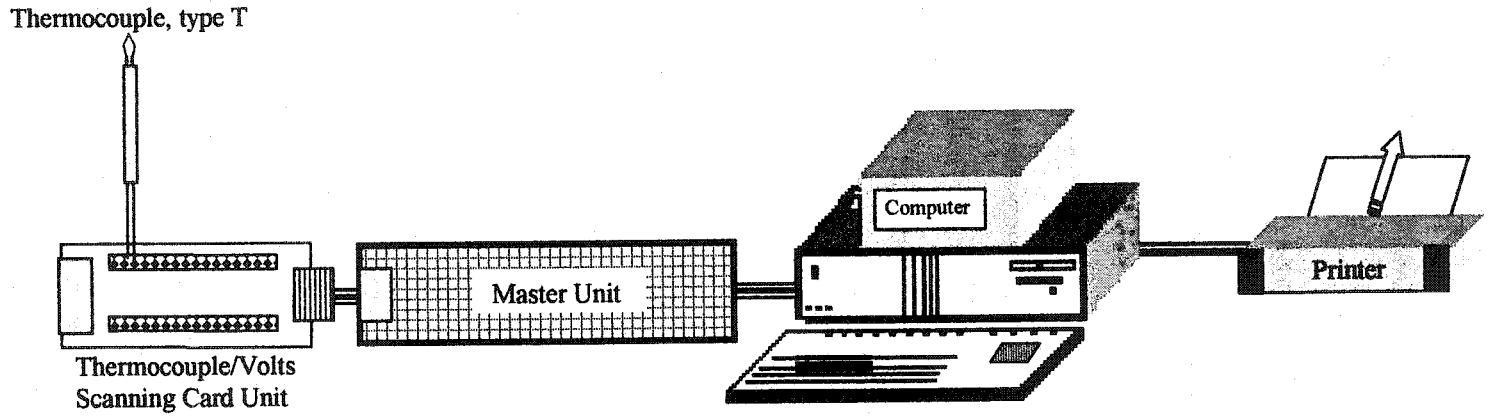



Figure 5.7. Data acquisition unit.

### 5.4.3 TempView Software

The Tempview (Omega, Stamford, CT) used was a Microsoft Window Based setup and acquisition application software that featured a graphical spreadsheet-style user interface, which allowed easy configuration of hardware and acquisition and display parameters. The Tempview software provided a non-programmable approach that enabled data collection and display.

### 5.4.4 Temperature Sensors

Four type T (copper-constantan) thermocouples (Cole Parmer, Chicago, IL, USA) were used for each bioreactor for temperature measurements. The thermocouples were inserted through specially constructed fitting (Figure 5.1). The thermocouples and their location are shown in Figure 5.1. The thermocouples T1, T2, and T3 were located at the bottom of the bioreactor 1 and were used to measure the temperature of the compost mass. The thermocouple T4 was located at the top of the bioreactor, near the outlet air hole (21 mm away) and was used to measure the temperature of the exhaust gas. The thermocouples T5, T6, T7, and T8 were used for bioreactor 2, and thermocouples T9, T10, T11, and T12 were used for bioreactor 3 at similar locations to those in bioreactor 1. The thermocouple Ti was used to measure the supplied air temperature, while the thermocouple Ta was used to measure the ambient air (room) temperature. Thermocouple locations, on the bottom of all bioreactors, were chosen to be far enough from the inlet air (65 mm away) to minimize the negative influence of inlet air temperature.

### 5.4.5 The Computer and Printer

An IBM compatible personal computer (Pentium IV) was used. The computer had 256 MB of random access memory (RAM), 40 GB hard disk and 1.2 MB (3 1/2") and a floppy drive. The computer also had a R232 C serial synchronous communications interface and centronics parallel printer interface. An hp (Hewlett Packard) laser jet 4 printer was used.

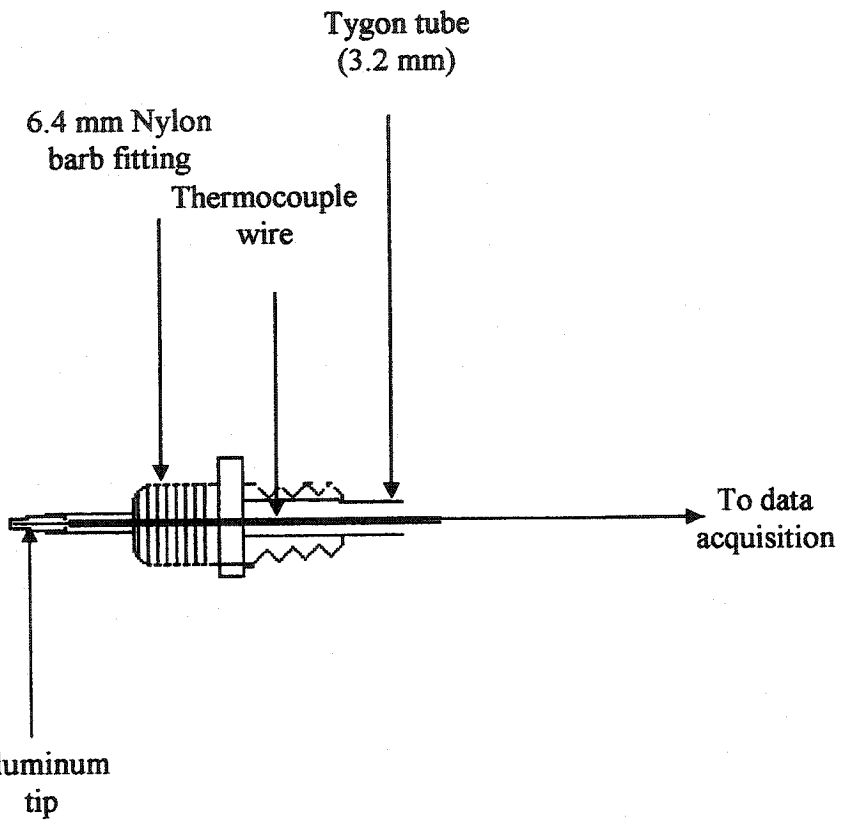



Figure 5.8. Detailed schematic of a thermocouple fitting.

# 6. EXPERIMENTAL DESIGN

The experiments were carried out in two phases: primary and secondary. The primary phase (Figure 6.1) was devoted to establish the optimum conditions of composting process whereas the secondary phase (Figure 6.2) was devoted to investigating the degradation of Pirimiphos-methyl 50% EC insecticide and the destruction of *Botrytis cinerea*, and Tobacco *mosaic virus* (TMV) during the composting process.

In the primary phase, the carbon to nitrogen ratio was first calculated and the need for (and amount of) a supplementary nitrogen source and/or micronutrients were determined. Then, the need for a bulking agent was assessed, based on particle size analysis of the tomato remains, and the final makeup of the mixture was determined. Finally, experiments were carried out to study: (a) the effect of inoculum size (municipal compost) at six levels (0, 10, 20, 30, 40, and 50 % on dry weight basis), (b) the addition of sugar as a bioavailable carbon source at three applications, (c) the addition of dairy cow manure as an inoculum and bioavailable carbon source at six levels (0, 10, 20, 30, 40, and 50% on dry weight basis), (d) the addition of cheese whey and used cooking oil as bioavailable carbon sources, (e) heat analyses, and (f) the continuous addition of used cooking oil to compensate for heat losses and maintain constant thermophilic temperatures. Two replicates were preformed for each experiment.

In the secondary phase of the study, three sets of experiments were carried out to study the effectiveness of the established optimum composting condition on the destruction of the pathogenic mold (*Botrytis cinerea*), *Tobacco mosaic virus* (TMV) and Pirimiphos-methyl 50% EC insecticide. These sets of experiments were carried out for 24 - 144 h (1-6 days) from the start of the thermophilic stage as shown in Figure 6.2.

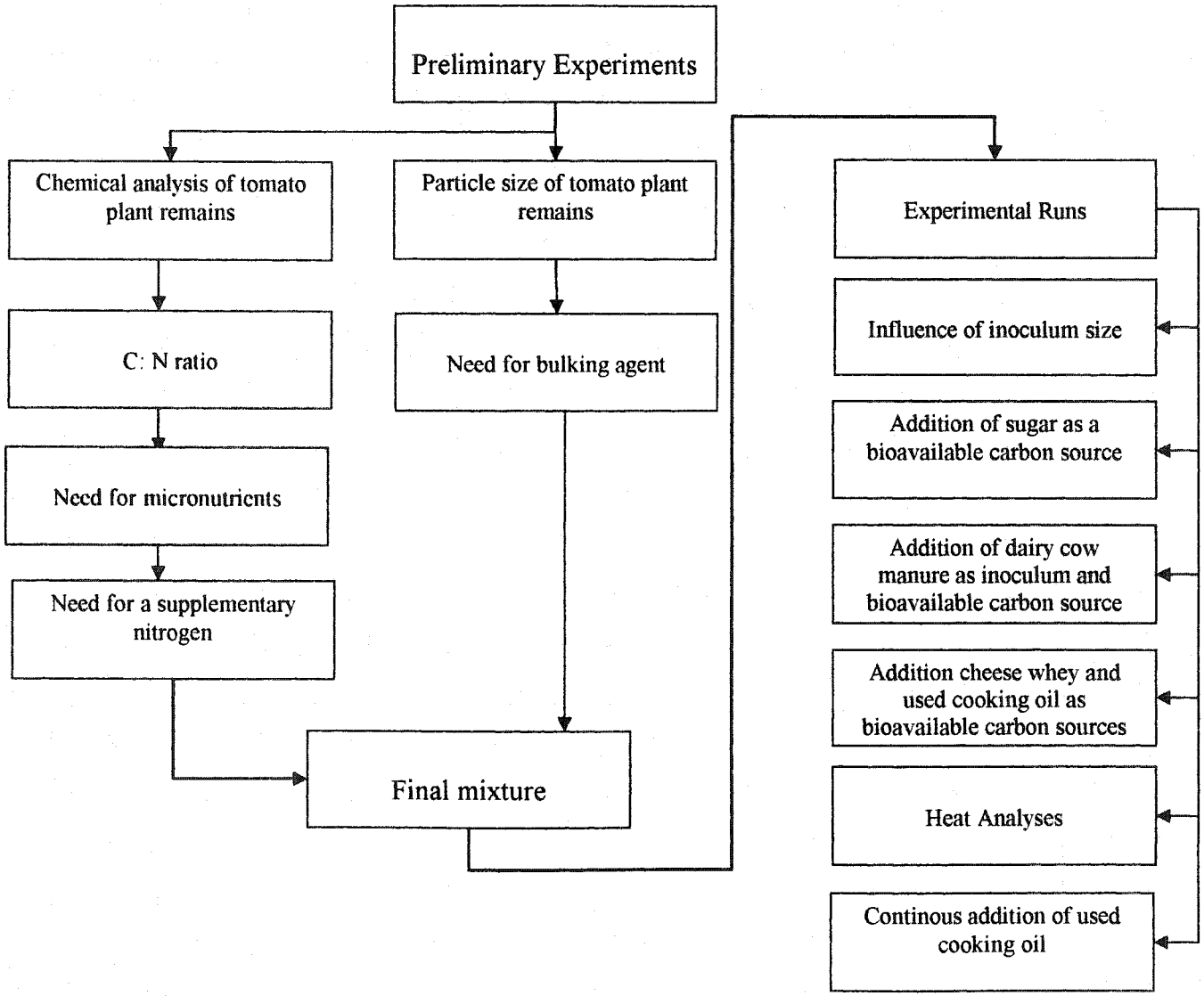
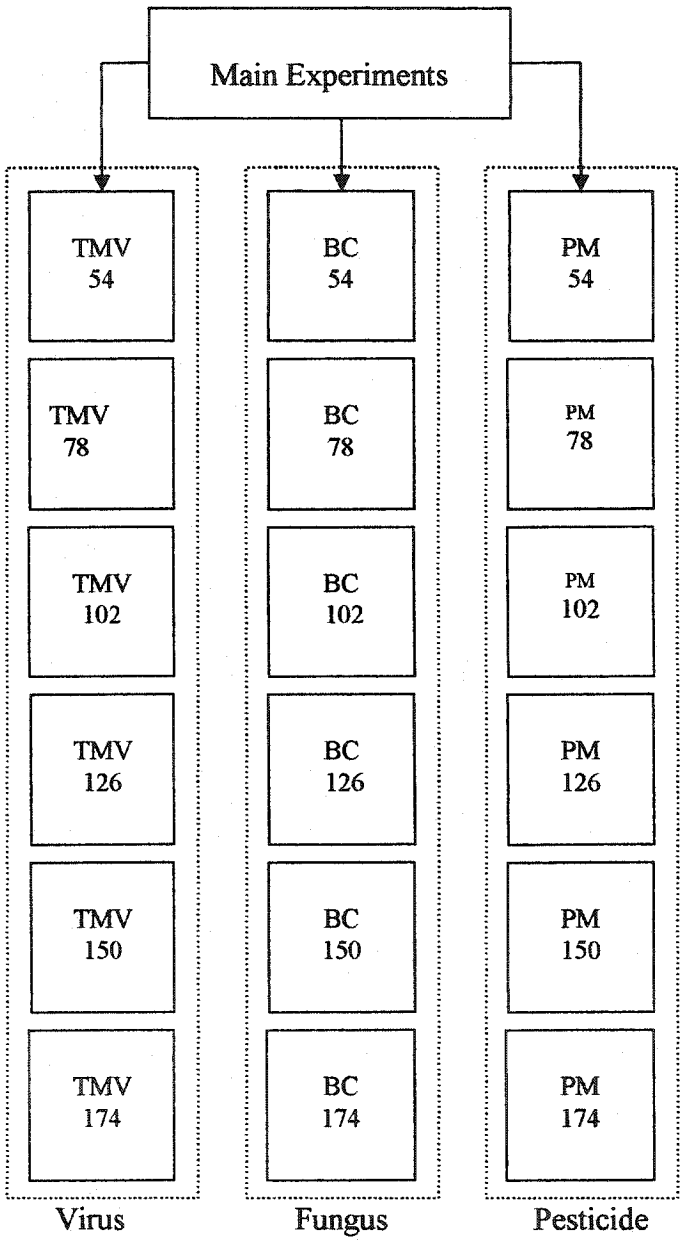



Figure 6.1. Experiments design for the primary experiments.




PM : Pirimiphos-methyl 50% EC insecticide,
BC 54 : *Botrytis cinerea* after 54 h of composting,
TMV 54 : *Tobacco mosaic virus* (TMV), after 54 h of composting.

Figure 6.2. Experimental design for the secondary experiments.

# 7. EXPERIMENTAL MATERIALS

## 7.1 Tomato Trimmings Collection and Preparation

The tomato plant (Golden Boy) remains required for all experiments were collected (at once) from a large commercial greenhouse in Truro, Nova Scotia. Tomato plant remains, consisted of leaves, stems, and some fruits. The tomato plant remains were collected at average moisture content (MC) of approximately 90%. They were randomly picked from the pile that was left out side the greenhouse as a result of the daily trimming of the tomato plants. Thirty heavy-duty polyethylene bags were filled with tomato residues and transported to the Biological Engineering Department at Dalhousie University, Halifax, Nova Scotia. Each bag weighted approximately 13 kilograms. The tomato plant residues were left over night in the Waste Management Laboratory at room temperature (≈ 25 °C) to partially dry (MC 76 %). They were then chopped into small pieces using a gas motor powered shredder (Model No. 242A645-515, SHP, Briggs and Stratton, Plainfield, NJ, USA). The chopped tomato mixture was left for three consecutive days on the floor to dry (MC 35%) before grinding using a hammer mill (Model C-H, Horvick Manufacturing, INC. Moorhead. Minnesota, USA). Grinding was carried out to reduce the particle size in order to enhance the microbial degradation process. The ground tomato mixture was left for two consecutive days on the floor to dry (MC 13 %), then was tightly bagged and placed in a freezer (-20° C) until needed. Some characteristics of the tomato mixture (stems, leaves and fruits) are presented in Table 7.1. Particle size analysis was then performed on the mixture using a known dry weight of the mixture (250 g) to determine the average particle size according to the procedure described by Kunii and Levenspiel (1991). The average particle size (Table 7.2) was calculated using the following equation:

$$\bar{dp} = \left\{ \frac{1}{\sum^{(all)i} (X/dp_i)} \right\} \tag{7.1}$$

Where:

$\bar{dp}$ = the average particle size of the mixture (mm)

Xi = the weight fraction in the interval (g)

dpi = the average particle size in the interval (mm)

Table 7.1. Some characteristics of the tomato residues.

| Characteristics | Measured Value |
|---|---|
| Moisture Content (%) | 13.00 |
| Total solids (TS) (mg/g DM) | |
| Volatile solids (VS) [1] | 693.00 |
| Ash | 307.00 |
| Nitrogen (mg/g DM) | |
| Total Kjeldahl Nitrogen | 31.00 |
| Ammonium Nitrogen | 2.20 |
| Carbon (mg/g DM) | |
| Total | 310.00 |
| Organic | 260.00 |
| Elemental Composition (mg/g DM) | |
| Ca | 51.00 |
| Na | 0.70 |
| Fe | 0.40 |
| Mg | 4.70 |
| Zn | 0.00 |
| K | 57.60 |
| Cl | 0.07 |
| P | 10.50 |
| S | 7.90 |
| Others[2] | 174.10 |

1- Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2- Others include: Mostly silica, and other elements.

Table 7.2. Particle size distribution.

| Mesh Opening (mm) | Material Held (g) | Weight Fraction (%) | Weight Fraction/Mesh Opening |
|---|---|---|---|
| 25.0 | 5.9324 | 0.0237 | 0.0010 |
| 12.5 | 117.3385 | 0.4694 | 0.0376 |
| 6.3 | 99.5319 | 0.3981 | 0.0632 |
| 4.0 | 11.8822 | 0.0475 | 0.0119 |
| 1.0 | 14.7298 | 0.0589 | 0.0589 |
| <1.0 | 0.5852 | 0.0023 | 0.0047 |

Average particle size = 5.6 mm. $\sum$= 0.1773

## 7.2 Municipal Compost

A 15-day old municipal compost was obtained from a municipal solid waste composting facility operated by Miller Composting Corporation, Dartmouth, Nova Scotia. It was added to the tomato trimmings mixture in order to introduce a wide range of active composting microorganisms. Some characteristics of the municipal compost are presented in Table 7.3.

## 7.3 Wood Shaving

The wood shaving used in some of the experiments as a bulking agent was collected in small polyethylene bags (~3 kg) from a local lumber mill (Barrett Lumber Co., Limited. Lower Sackville, Nova Scotia) and stored in the Biotechnology Laboratory until required. The wood shavings were ground using a hammer mill (Model C-H, Horvick Manufacturing, INC. Moorhead. Minnesota, USA) to achieve a uniform particle size distribution before mixing with the tomato remains. Some characteristics of the wood shavings are presented in Table 7.4.

## 7.4 Dairy Cow Manure

The dairy cow manure used in some of the experiments was collected in small polyethylene bags (~10 kg) from a local farm (Winding River Farms, Ltd., Stewiacke, Nova Scotia) and stored in a freezer at –10 °C in the Biotechnology Laboratory until required. Some characteristics of the dairy cow manure are presented in Table 7.5.

## 7.5 Urea (Nitrogen Source)

Urea [$CO(NH_2)_2$] was used in this study as an additional nitrogen source (46% nitrogen). It was purchased from a local distributor (Halifax Seed Co. inc., Halifax, Nova Scotia. Canada). Urea was added to the composting mixture to adjust the C: N ratio to

Table 7.3. Some characteristics of the municipal compost.

| Characteristics | Measured Value |
|---|---|
| Moisture Content (%) | 58.6 |
| Total solids (TS) (mg/g DM) | |
| Volatile solids (VS) [1] | 854.6 |
| Ash | 145.4 |
| Nitrogen (mg/g DM) | |
| Total Kjeldahl Nitrogen | 18.0 |
| Ammonium Nitrogen | 5.2 |
| Carbon (mg/g DM) | |
| Total | 440.0 |
| Organic | 350.0 |
| Elemental Composition (mg/g DM) | |
| Ca | 20.0 |
| Na | 6.2 |
| Fe | 2.8 |
| Mg | 1.8 |
| Zn | 0.1 |
| K | 7.8 |
| Cl | 0.3 |
| P | 2.7 |
| S | 2.3 |
| Others[2] | 101.4 |
| C:N | 24.4 |

1- Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2- Others include: Mostly silica, and other elements.

Table 7.4. Some characteristics of wood shaving.

| Characteristics | Measured Value |
|---|---|
| Moisture Content (%) | 8.2 |
| Total solids (TS) (mg/g DM) | |
| Volatile solids (VS) [1] | 997.4 |
| Ash | 2.6 |
| Nitrogen (mg/g DM) | |
| Total Kjeldahl Nitrogen | 0.93 |
| Ammonium Nitrogen | 0.16 |
| Carbon (mg/g DM) | |
| Total | 480.0 |
| Organic | 390.0 |
| Elemental Composition (mg/g DM) | |
| Ca | 0.8 |
| Na | 0.0 |
| Fe | 0.0 |
| Mg | 0.1 |
| Zn | 0.0 |
| K | 0.6 |
| Cl | 0.0 |
| P | 0.0 |
| S | 0.9 |
| Others[2] | 0.2 |
| C:N | 516.1 |

1. Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2. Others include: Mostly silica, and other elements.

Table 7.5. Some characteristics of dairy cow manure.

| Characteristics | Measured Value |
|---|---|
| Moisture Content (%) | 78.3 |
| Total solids (TS) (mg/g DM) | |
| Volatile solids (VS) [1] | 827.0 |
| Ash | 173.0 |
| Nitrogen (mg/g DM) | |
| Total Kjeldahl Nitrogen | 18.0 |
| Ammonium Nitrogen | 3.4 |
| Carbon (mg/g DM) | |
| Total | 430.0 |
| Organic | 340.0 |
| Elemental Composition (mg/g DM) | |
| Ca | 7.8 |
| Na | 3.0 |
| Fe | 0.9 |
| Mg | 4.5 |
| Zn | 0.0 |
| K | 35.2 |
| Cl | 0.7 |
| P | 4.7 |
| S | 3.3 |
| Others[2] | 112.9 |
| C:N | 23.9 |

1. Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2. Others include: Mostly silica, and other elements.

30: 1. The choice of Urea was based on the recommendation of Manios and Balis (1983) as Urea has been considered to be a more effective source of nitrogen for composting than $(NH_4)_2SO_4$ and $KNO_3$ in initiating and maintaining intense respiratory activity. The quantity of nitrogen required was calculated as follows (Haug, 1993):

Nitrogen required = (total carbon / desired C: N) – total available nitrogen (7.2)

## 7.6 Sugar

Commercial sugar was purchased from a local distributor (Atlantic Super Store, Halifax, Nova Scotia. Canada). Sugar solution was prepared by dissolving 666.7 grams of sugar in 1 L distilled deionized water.

## 7.7 Cheese Whey

The cheese whey used in some of the experiments was obtained from Farmer's Cooperative Dairy Plant in Truro, Nova Scotia, in 60-L plastic containers. The container were sealed and transported to the Biotechnology Laboratory and stored in a freezer at –10 °C until required. Some characteristics of the cheese whey are presented in Table 7.6.

## 7.8 Used Cooking Oil

The used cooking oil used in some of the experiments was obtained from a local fast food restaurant in Halifax, Nova Scotia. It was stored at room temperature in the Biotechnology Laboratory until required. Some characteristics of the used cooking oil are presented in Table 7.7.

## 7.9 Slaughter House Wastewater

The slaughter house wastewater was obtained from a local slaughter house (Windsor, Nova Scotia) in 60-L plastic containers. The container were sealed and transported to the Biotechnology Laboratory and stored in a freezer at –10 °C until required. Some characteristics of the slaughter waste water are presented in Table 7.8.

Table 7.6. Some characteristics of cheese whey.

| Characteristics | | Measured Value |
|---|---|---|
| Moisture Content (%) | | 93.2 |
| Total solids (TS) | (mg/L) | |
| Volatile solids (VS) [1] | | 61550.0 |
| Ash | | 6750.0 |
| Nitrogen | (mg/L) | |
| Total Kjeldahl Nitrogen | | 1560.0 |
| Ammonium Nitrogen | | 260.0 |
| Total Carbon | (mg/L) | 27784.3 |
| Elemental Composition | (mg/L) | |
| Ca | | 429.0 |
| Na | | 684.0 |
| Fe | | 42.0 |
| Mg | | 94.0 |
| K | | 1670.0 |
| Cl | | -- |
| P | | 154.0 |
| S | | 483.0 |
| Others[2] | | 3677.0 |
| Total Oil and Grease | (mg/L) | 4700.0 |
| Carbohydrates[3] | (mg/L) | 50,000.0 |
| Proteins[4] | (mg/L) | 8125.0 |
| pH | | 5.0 |
| C:N | | 17.8:1 |

1. Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2. Others include: Mostly silica, and other elements.
3. Total Carbohydrate =100- Proteins % - Fat % - Mc % - Ash %.
4. Protein Content = Organic Nitrogen X 6.25.

Table 7.7. Some characteristics of used cooking oil.

| Characteristics | | Measured Value |
|---|---|---|
| Moisture Content (%) | | -- |
| Total solids (TS) | (mg/L) | |
| Volatile solids (VS)[1] | | 999500.00 |
| Ash | | 500.00 |
| Nitrogen | (mg/L) | |
| Total Kjeldahl Nitrogen | | 200.00 |
| Ammonium Nitrogen | | 0.40 |
| Total Carbon | (mg/L) | 704521.0 |
| Elemental Composition | (mg/L) | |
| Ca | | 52.00 |
| Na | | 273.00 |
| Fe | | 13.00 |
| Mg | | 7.00 |
| K | | 9.00 |
| Cl | | 674.00 |
| P | | <9.80 |
| S | | 2110.00 |
| Others[2] | | 146.00 |
| Total Oil and Grease | (mg/L) | 908,000.00 |
| Carbohydrates[3] | (mg/L) | 80255.00 |
| Proteins[4] | (mg/L) | 1247.50 |
| pH | | 6.00 |
| C:N | | 3522.6:1 |

1. Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2. Others include: Mostly silica, and other elements.
3. Total Carbohydrate =100- Proteins % - Fat % - Mc % - Ash %.
4. Protein Content = Organic Nitrogen X 6.25.

Table 7.8. Some characteristics of slaughter house wastewater.

| Characteristics | | Measured Value |
|---|---|---|
| Moisture Content (%) | | 99.0 |
| Total solids (TS) | (mg/L) | |
| Volatile solids (VS)[1] | | 7400.0 |
| Ash | | 2600.0 |
| Nitrogen | (mg/L) | |
| Total Kjeldahl Nitrogen | | 1000.0 |
| Ammonium Nitrogen | | 180.0 |
| Total Carbon | (mg/L) | 3857.4 |
| Elemental Composition | (mg/L) | |
| Ca | | 440.0 |
| Na | | 528.0 |
| Fe | | 14.0 |
| Mg | | 18.0 |
| K | | 107.0 |
| Cl | | 638.0 |
| P | | 12.7 |
| S | | 198.0 |
| Others[2] | | 1480.3 |
| Total Oil and Grease | (mg/L) | <200 |
| Carbohydrates[3] | (mg/L) | 820.0 |
| Proteins[4] | (mg/L) | 6380.0 |
| pH | | 8.0 |
| C:N | | 3.9:1 |

1. Volatile solids are the organic matter (largely carbon, oxygen and nitrogen) which are lost at 550°C, leaving only the ash.
2. Others include: Mostly silica, and other elements.
3. Total Carbohydrate =100- Proteins % - Fat % - Mc % - Ash %.
4. Protein Content = Organic Nitrogen X 6.25.

## 7.10 Plant Pathogen

Two plant pathogens were used in this study: *Tobacco mosaic virus* (TMV) and the mold *Botrytis cinerae*. They were obtained in freeze-dried forms from the American Type Culture Collection (ATCC, Manassas, VA). The growing temperature range and lethal temperature for these microorganisms are shown in Table 7.10. It must be noted here that bacteria were excluded from the study since the lethal temperature for most pathogens are below 55 °C.

*Tobacco mosaic virus* (TMV) is a rod-shaped virus (300 × 18 nm) with a central hollow cavity (Knapp and Lewandowski, 2001). It is the most persistent plant virus known (Bollen, 1993). It has been known to survive more than 50 years in dried plant parts (Pfleger and Zeyen, 1991; and Zitter and Provvidenti, 1984). It is most commonly introduced virus into plants through small wounds caused by handling and by insects chewing on plant parts. The most common sources of virus inoculum for TMV are the debris of infected plants that remains in the soil and seed. Once the virus enters the host, it begins to multiply by inducing host cells to form more viruses (Figure 7.2). Infected plants serve as reservoirs for the virus and the virus can be transmitted easily (either mechanically or by insects) to healthy plants (Knapp and Lewandowski, 2001; Pfleger and Zeyen, 1991; and Zitter and Provvidenti, 1984 ).

*Botrytis cinerae* (grey mold) is an important plant pathogen with a wide host range of living and dead tissues during the winter months, which may act as inoculum sources. The sclerotia germinate to produce conidiophores and darkness is essential (Carlile et al., 2001). Sclerotia, up to 5 mm in length, are resistant to environmental extremes and act as overwintering resting bodies and have a black ring and a light interior composed of a dense mass of hyphae (Zitter, 1986) as shown in Figure 7.3. Spores are borne on branched conidiophores, and the arrangement of the spores gives the fungus its name, from the Greek *botrys*, meaning a bunch of grapes (Zitter, 1986). Sporulation occurs under a wider range of temperature and wetness conditions. At 20°C, rachides

Table 7.10. Optimum and lethal temperatures of the pathogens used in this study.

| | Pathogen | Type | Optimum Growth Temperature Range (°C) | Thermal Death Temperature (°C) |
|---|---|---|---|---|
| 1 | *Botrytis cinerea* | Mold | 20-24 | > 55 |
| 2 | *Tobacco mosaic* | Virus | Wide range of climatic conditions | 90-93 |

Thermal Death Temperature = Temperature necessary for the destruction of a pathogen by heat (Altman and Dittmer, 1972).

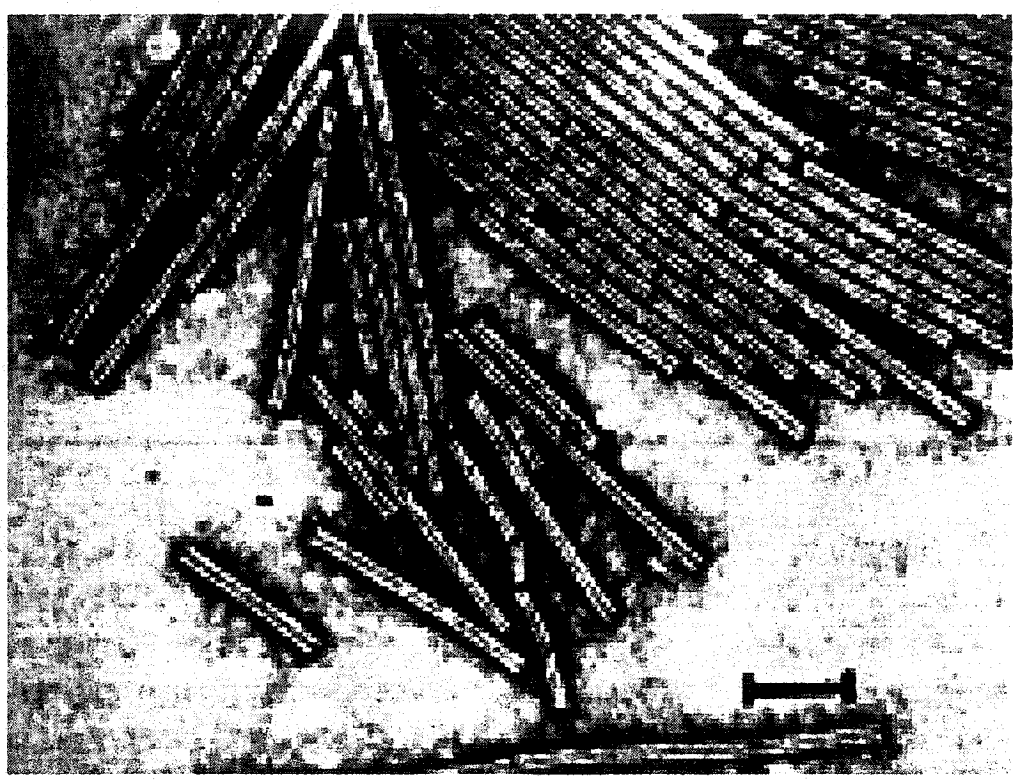


Figure 7.1. Tobacco mosaic virus (APS, 2001 ).

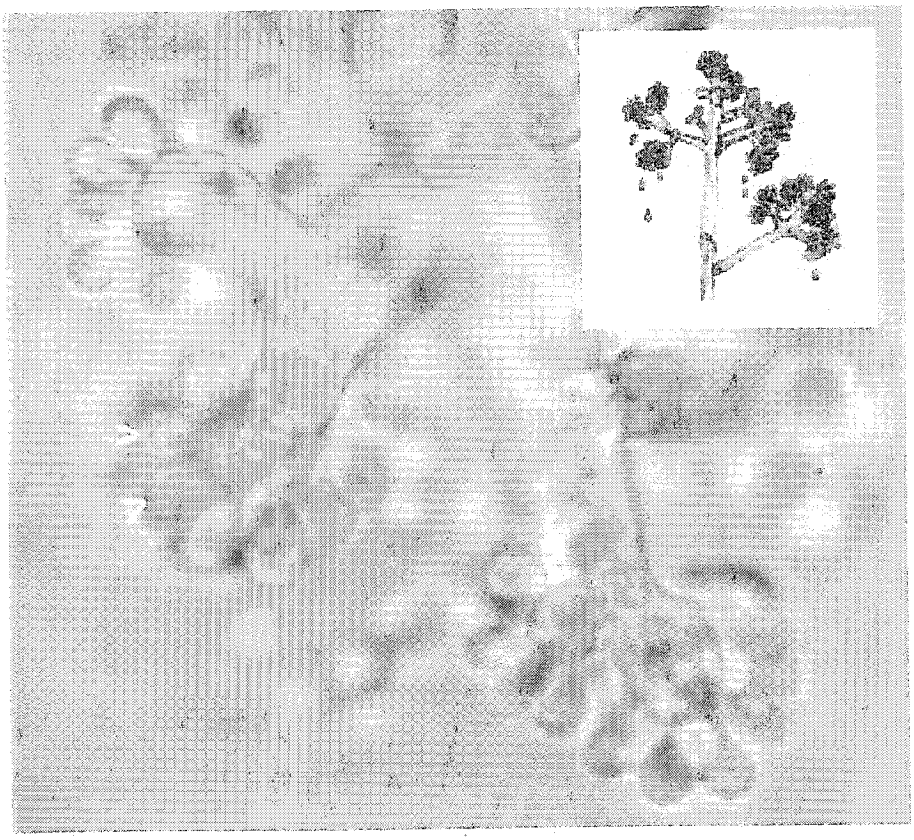


Figure 7.2. The black rind hypha (with light interior composted of a dense mass) of Botrytis cinerea (Deacon, 2004).

began to sporulate after a 6h period of continuous wetness and 12 h incubation, whereas at 10 °C they required a minimum of 24 h incubation to sporulate regardless of the wetness period. Rachides also sporulated at 30°C, but required a minimum of 24 h incubation and wetness (Whiteman and Stewart, 1998). Spores can be disseminated by air, water or by infested plant or greenhouse equipments. The suitable pH values range between 3.0 and 6.0, with an optimum value of 5.0. Self-inhibition of germination is a commonly observed characteristic of conidia of many fungi when crowded together. Conidia of Botrytis cinerea typically will not germinate at concentrations of $10^6$ $ml^{-1}$ or more (Sharrock et al., 1992).

## 7.11 Pesticide

Pesticides are potentially present in agriculturally based composting materials. Although all pesticides are hazardous chemicals, insecticides are the most hazardous to humans due to their inhibition of nervous system enzymes (Büyüksönmez et al. 1999). According to Abu-Jawdah (1986), Actellic, Carbofuran, Methidathion, Permethrin and Malathion are the most recommended insecticides in greenhouses in Saudi Arabia. However, pirimiphos-methyl (Actellic) is one of the most popular insecticides used in greenhouses in Saudi Arabia (Abo-El-Saad et al., 2001). Antonious and Snyder (1994) reported that Pirimiphos-methyl residues on the leaves of greenhouse tomato plants one hour after spraying was 225 mg/kg, which decreased to 112.5, 56.25, 28.13 and 12 mg/kg after 3, 6, 9 and 14 days, after application, respectively (Figure 7.3). The disappearance rate (K) was 0.23 $day^{-1}$ with a half-life of 3.1 days.

Since insecticides are only applied once when there is insect infection and trimming usually take place two weeks after spaying, a minimum concentration of 12 mg/kg is expected to be on greenhouse tomato trimmings. Therefore, three concentrations (12, 24 and 36 mg/kg) were chosen for this study to account for the minimum, double and triple the expected concentration of insecticide on greenhouse tomato leaves. Tomato trimmings in each composting mixture used during this study is 600 g at 13 % MC

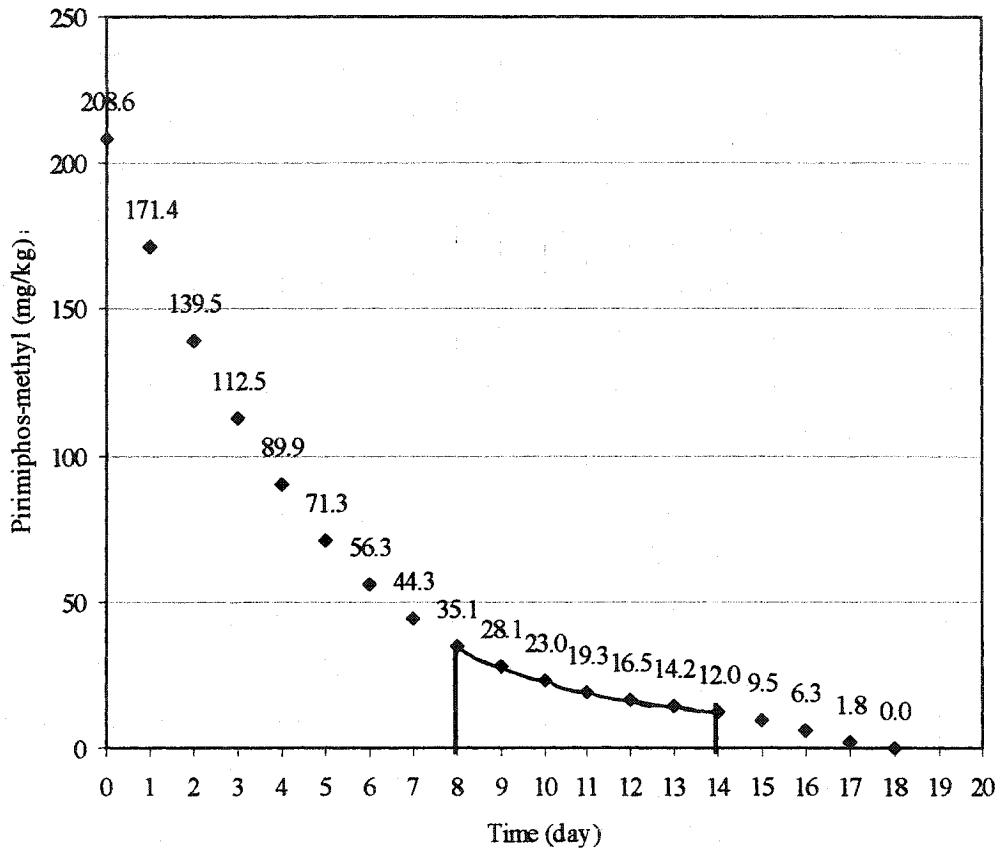



Figure 7.3. Pirimiphos-methyl concentration on tomato leaf with time after single application (Antonious and Snyder, 1994).

(originally 5.22 kg at 90 % MC). Consequently, 62.64, 125.28 and 187.92 mg active ingredient of pirimiphos-methyl with a specific gravity of 1.157 were applied to three identical composting mixtures. Since the final mixture (3.5 kg) consists of tomato trimming: wood shavings: MSW (0.36: 0.54: 10 %) at 60 % MC. The initial concentration of pesticide after mixing other ingredients inside the bioreactor was 15.8, 31.6 and 47.4 mg/kg, respectively.

An analytical grade (240 µL) of Pirimiphos-methyl (Actellic) [O-(2-diethylamino-6-methylpirimidin-4-yl) O, O-dimethyl phosphoro-thioate], with 99.0% purity (Cat No. PS644, Sigma-Aldrich Canada Ltd, Oakville, Ontario) was used in this study. The molecular weight of pirimiphos-methyl is 305.3 with an empirical formula of $C_{11}H_{20}N_3O_3PS$, and its structural form of pirimiphos-methyl and its major degradation products are shown in Figure 7.5 (IPCS INCHEM, 2002). The pure substance is a weak alkaline straw-colored liquid, which has a melting point of >15 to 18 °C and freezes to a white solid at 15 °C. The ultra violet spectrum is a strong absorption band at 248 nm and a weaker band at 300 nm. It is very soluble in most organic solvents, and its solubility in water is 5 mg/l at room temperature (30° C). Pirimiphos-methyl can cause cholinesterase, an enzyme produced in the liver, inhibition in humans, which at high doses results in nausea, dizziness, confusion, and high exposures (accidents, major spills) respiratory paralysis and death.

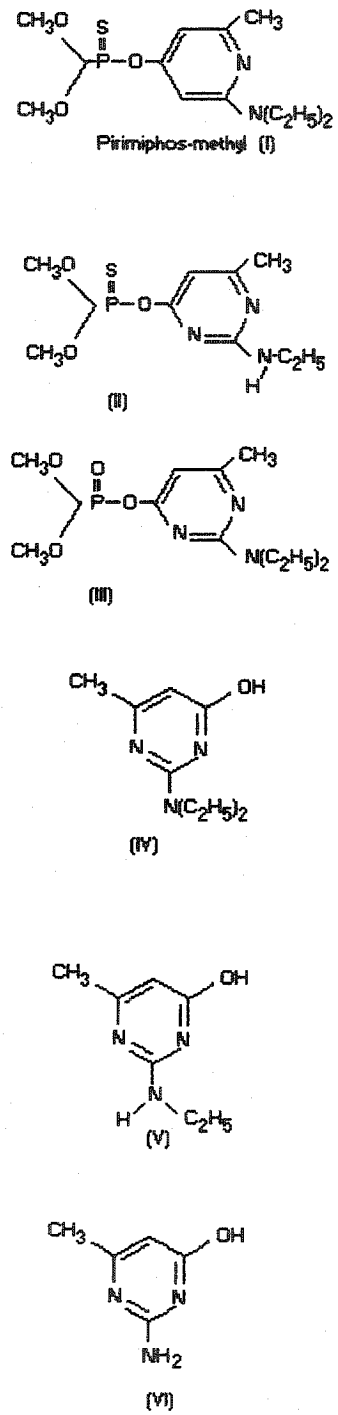



Figure 7.4. Structural forms of pirimiphos-methyl and its major products (IPCS INCHEM, 2002).

# 8. EXPERIMENTAL PROCEDURE

## 8.1 System Preparation

The temperature sensors (Thermocouples type T) were calibrated using ice and boiling deionized distilled water baths. The thermocouples, including the fittings, were immersed into the ice bath and connected up to the data acquisition system individually. The thermocouple reading, as temperature in degree centigrade, was corrected to read zero °C (offset) and then into the boiling water to correct the upper limit. The calibration equation is a linear relationship as follows:

$$T_{Corrected} = a \times T_{Actual} \pm b \quad (8.1)$$

Where:

$T_{Corrected}$ = corrected temperature reading ( °C)

$T_{Actual}$ = actual temperature reading ( °C)

a = the slope of the linear line, constant (-)

b = the intercept (offset), constant (°C)

Table 8.1 presents the calibration constants (a and b) for each thermocouple wire used in the system.

## 8.2 Mixtures Preparation and Experimental Protocols

### 8.2.1 Inoculum Size Study

Wood shavings were used as a bulking agent in this set of experiments. The tomato remains were first mixed with wood shavings at a ratio of 1: 1.5 on dry wieght basis (the most suitable ratio for the chopping process). An amount of 3 kg (wb) of the tomato remains-wood shavings mixture was mixed with different amounts of municipal compost to achieve a tomato remains-woodshavings mixture: municipal solid compost ratios (weight basis) of 100:00, 90:10, 80:20, 70:30, 60:40, and 50:50, given final tomato remains: woodshavings: municipal compost ratios of 1.0: 1.5: 0, 1.0: 1.5: 0.28, 1.0:

Table 8.1. Thermocouples calibration constant.

| Channel | a | b |
|---|---|---|
| B1 T1 | 1.0315 | -0.4000 |
| B1 T2 | 1.0340 | -0.4000 |
| B1 T3 | 1.0320 | -0.4100 |
| B1 T4 | 1.0290 | 0.0000 |
| B2 T1 | 1.0350 | -0.5000 |
| B2 T2 | 1.0350 | -0.6000 |
| B2 T3 | 1.0340 | -0.2200 |
| B2 T4 | 1.0350 | -0.2000 |
| B3 T1 | 1.0300 | -0.1000 |
| B3 T2 | 1.0325 | +0.0050 |
| B3 T3 | 1.0310 | -0.1000 |
| B3 T4 | 1.0300 | +0.1900 |
| $T_{air_in}$ | 1.0200 | -0.6000 |
| $T_{Room}$ | 1.0130 | -0.4000 |

B Bioreactor.

T Thermocouple.

1,2,3,4 = Locations.

1.5: 0.63, 1.0: 1.5: 1.07, 1.0: 1.5: 1.67 and 1.0: 1.5: 2.50. The moisture contents of these mixtures were adjusted to approximately 60 %. The C:N ratio of each mixture was adjusted to approximately 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement. Table 8.2. shows the various constituents of the final mixtures used in the inoculum experiments.

The final mixture used in each experiment was mixed well and then placed in the bioreactor. Six bioreactors were used in this experiment. The mixture occupied 75% of the total volume of the bioreactor (or 0.012 $m^3$). The plexiglas side wall was put in place. Visual inspection of each bioreactor was done to detect any leakage before placing the insulation cover on the side wall. The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperatures were continuously monitored. Samples were collected at the end of the experiments for moisture content, solids (total, volatile and ash), total carbon (TC), total kjeldahl nitrogen (TKN), ammonium nitrogen ($NH_4$) and C: N ratio analyses.

### 8.2.2 Sugar Addition Study

Tomato remains were mixed with wood shavings at a ratio of 1: 1.5 on dry weight basis. The mixture of tomato remains-wood shavings was then mixed with municipal solid compost at a ratio of 90:10, given a final tomato remains: wood shavings: municipal compost ratio of 1: 1.5: 0.28. The C:N ratio was determined for the mixture and corrected to 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement. The moisture content of the mixture was also adjusted to approximately 60 %. Table 8.3 shows the constituents of the final mixture used in these experiments.

The final miture was mixed well and then placed in the bioreactor. The mixture occupied 75% of the total volume of the bioreacter (or 0.012 $m^3$). The plexiglas side wall of each bioreactor was put in place and visual inspection was done to detect any leakage before placing the insulation cover on the side wall.The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperatures were continueously monitored.

Table 8.2. The constituents of the mixtures used in the inoculum study.

| Parameter | Mixture: Compost Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 100: 00 | 90: 10 | 80: 20 | 70: 30 | 60: 40 | 50: 50 |
| Tomato remains[A] (%) | 40.0 | 36.0 | 32.0 | 28.0 | 24.0 | 20.0 |
| Wood shavings (%) | 60.0 | 54.0 | 48.0 | 42.0 | 36.0 | 30.0 |
| Municipal solid compost (%) | 0.0 | 10.0 | 20.0 | 30.0 | 40.0 | 50.0 |
| Moisture content (%) | 61.7 | 61.1 | 60.6 | 61.0 | 61.1 | 60.9 |
| Total dry weight [B] (g) | 1149.0 | 1167.0 | 1182.0 | 1170.0 | 1167.0 | 1173.0 |
| Initial C: N ratio | 33.2:1 | 32.0:1 | 30.9:1 | 29.9:1 | 28.9:1 | 28.0:1 |
| Urea required (g) | 3.3 | 2.2 | 1.0 | 0.0 | 0.0 | 0.0 |
| Final C: N ratio | 30:1 | 30:1 | 30:1 | 29.9:1 | 28.9:1 | 28:1 |

A Tomato Remains = tomato leaves, stems and fruits.
B Total mixture wet weight = 3 kg.

Table 8.3. The constituents of the mixture used in the sugar addition study.

| Parameter | Value |
|---|---|
| Tomato remains[A] (%) | 36.0 |
| Wood shavings (%, v/v) | 54.0 |
| Municipal solid compost (%) | 10.0 |
| Mixture moisture content (%, wet basis) | 61.1 |
| Mixture total dry weight[B] (g) | 1167.0 |
| Mixture initial C:N ratio | 32:1 |
| Urea required (g) | 2.2 |
| Mixture final C:N ratio | 30:1 |

A Tomato remains = tomato leaves, stems and fruits.
B Total mixture wet weight ~ 3 kg.

Four bioreactors were used in this experiment. The first reactor was used as a control (no sugar addition). A volume of 150 ml of sugar solution (666.7 g sugar/ L) was added to each of the second, third and fourth bioreactors before the temperatures started to decline (after 24 h). Another 150 ml of the sugar solution was added to each of the third and fourth bioreactors before the temperature started to decline (after 36 h). Finally, a third sugar application of 150 ml was added to the fourth bioreactor before the temperature started to decline (after 48 h).

### 8.2.3 Manure Addition Study

Dairy cow manure was used as a substitute for municipal compost, both as an inoculum and as a source of bioavailable carbon at six levels (0, 0.28, 0.63, 1.07, 1.67 and 2.50 on dry weight basis) as shown in Table 8.4. The tomato remains were first mixed with wood shavings at a ratio of 1: 1.5 on dry wieght basis. An amount of 3-kg of the tomato remains-wood shavings mixture was mixed with different amounts of dairy cow manure to achieve a tomato remains-woodshavings mixture: manure ratios of 100:00, 90:10, 80:20, 70:30, 60:40, and 50:50, given final tomato remains: woodshavings: manure ratios of 1.0: 1.5: 0, 1.0: 1.5: 0.28, 1.0: 1.5: 0.63, 1.0: 1.5: 1.07, 1.0: 1.5: 1.67, and 1.0: 1.5: 2.50. The moisture contents of the mixtures were adjusted to approximately 60 %. The C:N ratio of each mixture was adjusted to 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement.

Each of the final mixture was mixed well and 3-kg were placed in the bioreactor. The mixture occupied 75% of the total volume of the bioreacter (or 0.012 $m^3$). The plexiglas side wall was put in place and visual inspection of each bioreactor was done to detect any leakage before placing the insulation cover on the side wall.

The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperatures were continuously monitored. Carbon dioxide and oxygen concentration in the inlet and outlet

Table 8.4. The constituents of the mixtures used in the manure addition study.

| Parameter | Mixture: Manure Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 100: 00 | 90: 10 | 80: 20 | 70: 30 | 60: 40 | 50: 50 |
| Tomato remains[A] (%) | 40.0 | 36.0 | 32.0 | 28.0 | 24.0 | 20.0 |
| Wood shavings (%) | 60.0 | 54.0 | 48.0 | 42.0 | 36.0 | 30.0 |
| Dairy cow manure (%) | 0.0 | 10.0 | 20.0 | 30.0 | 40.0 | 50.0 |
| Moisture content (%) | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 |
| Total dry weight [B] (g) | 1200.0 | 1200.0 | 1200.0 | 1200.0 | 1200.0 | 1200.0 |
| Initial C: N ratio | 33.2:1 | 31.9:1 | 30.7:1 | 29.6:1 | 28.6:1 | 27.7:1 |
| Urea required (g) | 3.3 | 2.1 | 0.9 | 0.0 | 0.0 | 0.0 |
| Final C: N ratio | 30:1 | 30:1 | 30:1 | 29.6:1 | 28.6:1 | 27.7:1 |

A Tomato Remains = tomato leaves, stems and fruits.
B Total mixture wet weight = 3 kg.

gases were measured during each experiment every 8 hours. Sample were collected at the end of the experiments for moisture content, solids (total, volatile and ash), total carbon (TC), total kjeldahl nitrogen (TKN), ammonium nitrogen ($NH_4$) and C: N ratio analyses.

### 8.2.4 Used Cooking Oil and Cheese Whey Addition Study

Three sources of bioavailable carbon were initially considered in this study. Cheese whey, used cooking oil and slaughte house wastewater. The choice of these three sources was based on their availability in the local area. Preliminery analyses were first performed on these wastes to determine their energy contents. Based on the results, slaughter house wastewater was disregarded in this study due to its low energy content (<0.2 g fat/L), whereas cheese whey (5 g fat /L and 50 g Lactose/L) and used cooking oil (908 g fat /L) were used because of their higher energy contents.

A volume of 1.92 L of cheese whey was added to a 1.8 kg mixture of tomato residues: wood shavings: municipal solid compost (1:1.5: 0.28 ratio) to adjust the moisture content to 60%. The mixture had an energy content of 2243.5 kJ, which was determined from the composition of the whey using the following Equation:

$$\text{EnergyContent}(\text{kcal}/100\text{g}) = \text{Carbohydrates}(\%)\times 4 + \text{Proteins}(\%)\times 4 + \text{Fat}(\%)\times 9 \quad (8.2)$$

The used cooking oil had an energy content of 35 kJ/mL. About 64.1 mL of used cooking oil was initially added to a 1.8 kg mixture of tomato residues: wood shavings: municipal solid compost (1:1.5: 0.28 ratio). Water was used to adjust the moisture content to 60%.

Both mixtures (whey and used cooking oil containing mixtures) were designed to have identical energy contents (614.5 kJ/kg). A control mixture of tomato residues: wood shavings: municipal solid compost (without whey or used cooking oil addition) was used in these experiments. The C:N ratio of each mixture was adjusted to 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement. The compositions of the three mixtures are shown in Table 8.5.

Table 8.5. The constituents of the mixtures used in used oil and cheese whey addition study.

| Parameter | Mixture with Cheese Whey | Mixture with Used Cooking Oil | Control Mixture [A] |
|---|---|---|---|
| Tomato remains[B] (%) | 36.0 | 36.0 | 36.0 |
| Wood shavings (%) | 54.0 | 54.0 | 54.0 |
| Municipal solid compost (%) | 10.0 | 10.0 | 10.0 |
| Moisture content (%) | 60.0 | 60.0 | 60.0 |
| Total dry weight [C] (g) | 1400.0 | 1400.0 | 1400.0 |
| Initial C: N ratio | 30.5:1 | 38.3:1 | 35.8:1 |
| Urea required (g) | 0.8 | 10.3 | 7.2 |
| Final C: N ratio | 30.0:1 | 30.0:1 | 30.0:1 |
| Energy Content (kJ/kg) | 614.5 | 614.5 | -- |

A No whey or oil added.
B Tomato Remains = tomato leaves, stems and fruits.
C Total mixture wet weight = 3.5 kg.

Each of the final mitures was mixed well and 3.5 kg were placed in the bioreactor. The mixtures occupied 75% of the total volume of the bioreactor (or 0.012 $m^3$). The plexiglas side wall was put in place and visual inspection of each bioreactor was done to detect any leakage before placing the insulation cover on the side wall. The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperatures were continueously monitored. Small samples were collected every 12h for monitoring the pH of the mixtures and larger samples were collected at the end of the experiments for moisture content, solids (total, volatile and ash), fat, carbohydrates, proteins, total kjeldahl nitrogen (TKN), ammonium nitrogen ($NH_4$) and C: N ratio analyses.

### 8.2.5 Heat Analyses Study

#### 8.2.5.1 Heat of Mixing.

A 3.5-kg mixture of tomato remains-wood shavings-municipal solid compost: used cooking oil (at approximately 60 % moisture content and a C: N ratio of 30: 1) was prepared. The mixture, bioreactor, and mixing unit were completely sterilized to insure that the composting experiment is free of microorganisms. The mixture was placed in several 1-L Griffin beakers, covered with double sheets of aluminum foil and then autoclaved (Market Forge Co., Sterilizer. Model STM-E, NY.) at a temperature of 121°C and a pressure of 98.1 kpa for one hour. The bakers were then left to cool down for 24 hours. The sterilization process was repeated three times to insure all microorganisms and spores were inactivated. A solution was made from the sterilized mixture (4 grams of the sterilized mixture in 400 mL of sterilized distilled water) and plated on a standard plate agar in replicates according to the procedure described by Benson (1998). The plates were then incubated at 35 °C for 48 hours to determine the effectiveness of the sterilization.

All air inlet and outlet ports in the bioreactor were sealed and the bioreactor and the mixing shaft were chemically sterilized using 2% potassium metabisulfite solution. As a precaution, the laboratory exhaust fan was turned off, and laboratory doors were closed to prevent any air current in the working area. Using the same chemical, a few sprays around the bioreactor to minimize any contamination during material loading.

The sterilized bioreactor was filled with the sterilized mixture of the composted material. The sterilized Plexiglas side wall was screwed in place and the mixing unit was turned on at 5 RPM. The temperature was recorded every 5 minutes. The power consumption was also recorded using a sensitive power meter (EXTECH, True RMS Power Multimeter (Model 382860, Walthaw, Massachusetts, USA). The power consumption of the mixing shaft was also measured without the tomato remains: wood shavings: municipal solid compost mixture. The bioreactor mixing shaft was left to run in the empty bioreactor while collecting the measurements for 13 hours.

8.2.5.2 Bioreactor Heat Analysis. Heat analysis was performed on the system using the data obtained from the used oil experiment in order to determine the amount of oil required as a source of bioavailable carbon and to develop a method of oil addition to the system in order to maintain the thermophilic temperature above 55 °C for at least 3 days.

### 8.2.6 Continuous Used Cooking Oil Addition Study

After the heat balance was performed on the bioreactor that operated on the used cooking oil, the total heat losses rate was determined to be 51.14 kJ/h. Used cooking oil has an energy content of 35 kJ/ml. Assuming 100% energy release, 1.46 mL of used cooking oil must be added every hour to compensate for the heat losses from the system. Since the sugar addition experiment indicated that the temperature will decline after 12h, 18 mL of used cooking oil was added every 12 h. Three experiments were conducted to investigate the influence of used cooking oil addition on maintaining the thermophilic temperature zone (> 55 °C) for three days. The used cooking oil was added staring at the peak temperature (at 31 h) and every 12 h thereafter. The first experiment was conducted with the addition of 18 mL of used cooking oil every 12 h, while the other two were conducted with the addition of 50 % of original amount (9 mL of used cooking oil every 12 h) and double the amount (36 mL of used cooking oil every 12 h).Three identical mixtures of tomato residues: wood shavings: municipal solid compost (1: 1.5: 0.28) were used. The moisture content and C: N ratio of each mixture were corrected to be 60 % and 30: 1, respectively.

Each of the final mitures was mixed well and 3.5-kg were placed in the bioreactor. The mixture occupied 75% of the total volume of the bioreacter (or 0.012 $m^3$). The plexiglas side wall was put in place and visual inspection of each bioreactor was done to detect any leakage before placing the insulation cover on the side wall. The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperatures were continueously monitored. Small samples were collected every 12 h for monitoring the pH of the mixtures and larger samples were collected at the end of the experiments for moisture content, solids, solids (total, volatile and ash), fat, proteins, total kjeldhel nitrogen (TKN), ammonium nitrogen ($NH_4$) and C: N ratio analyses.

### 8.2.7 Virus Study

Two batches of tomato plants were infected. The first batch had only Golden Boy variety whereas the second batch had Roma, Red Robin and Scotia varieties.

The first batch contained one hundred and twenty individually (Figure 8.1) grown tomato plants (4 weeks old Golden Boy Variety). Each plant was transferred into a large round plastic pot (12.5 cm) using Miracle-Gro-garden soil for flowers and vegetables as a potting media (Scotts Company, Marysville, Ohio). The hydroponic system was divided into six compartments. Each compartment was divided into three separate trays and had its independent light system. Ten pots of tomato plants were placed in each tray. Thirty tomato plants were placed in each compartment (Figure 8.2). The tomato plants were irrigated weekly with a solution of Miracle-Gro, all Purpose water soluble plant fertilizer (Scotts Company, Marysville, Ohio) at the recommended rate of 4 mL/L. Tomato leaves were wetted and soil was soaked with the Miracle-Gro solution (~300 mL/pot). Fresh water was added when needed due to the water loss by evaporation. The photoperiod was kept at 12 hour and the room temperature was in the range of 20-25°C. By the end of the first week of planting, tomato plant looked healthier and new leaves were developed.

The *Tobacco mosaic virus* (PV-1) used in the first batch was obtained from the American Type Culture Collection (ATCC, Manassas, VA). The inoculation process is

Figure 8.1. An individual tomato plant from the first batch (Golden Boy variety).

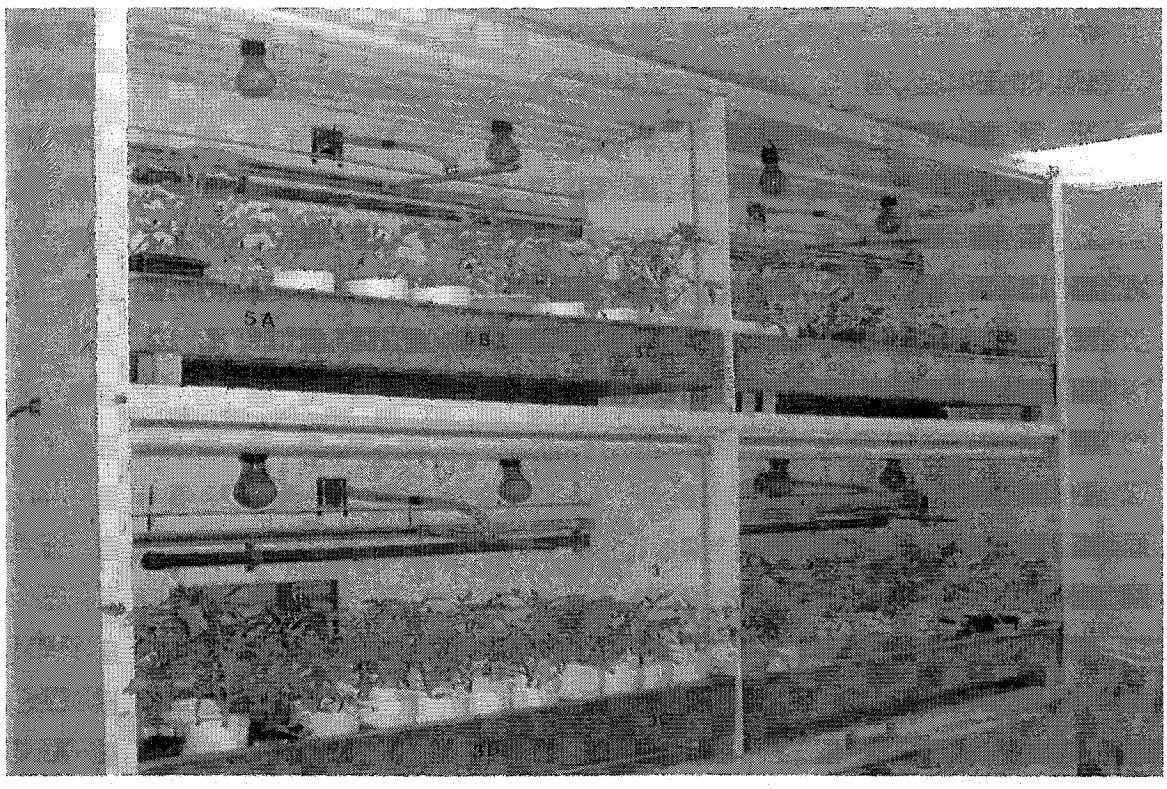
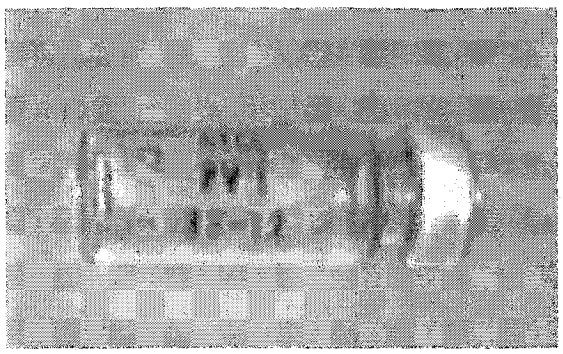



Figure 8.2. First batch of tomato plants (Golden Boy variety).

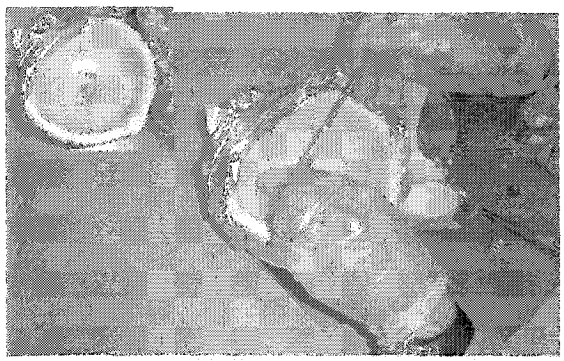
illustrated in Figure 8.3. The sealed TMV vial (which contained the freeze dried infected tissue) was carefully opened and the contents of the vial (infected tobacco plant tissue) were placed in a pre-cooled (4 °C) mortar. A volume of 9 mL of the inoculation buffer (0.1% peptone water, prepared by dissolving 1 g bacto-peptone in 1 L deionized distilled water and then autoclave at 121 °C, 103.4 kPa for 45 minutes) was added. Sterile pestle was used to thoroughly triturate the tissue. Young-healthy tomato plants were selected to proceed with the inoculation procedure. A few leaves on each plant were selected and marked. While one hand was used to support the leave to avoid over pressing, the other hand was used to mechanically damage some of the cells using abrasive cloth (240-J). Then, TMV inoculum was lightly rubbed onto the systemic host plants (Tomato) using a sterile cotton swab.

The infected tomato plants were labeled and left in their own individual containers under a 12 h light period in the hydroponic system for the virus infection process to take place (incubation period). After ten days, the symptoms of infection started to develop (mosaic-like). The infected tomato plants were collected for virus identification according to the procedure illustrated in Figure 8.4. Three infected tomato plants were selected and newly developed leaves (~1 g) were removed from each plant. Each sample was homogenized with the buffer solution in a mortar and then left aside (few minutes) to settle. The positive and negative controls, supplied with the ELISA kit, were prepared according to the manufacturer (Neogen Europe Ltd., Auchincruive, Scotland, UK) procedure and kept in a freezer (-10 °C) for later analyses. Volumes of 100 µL of each sample and controls were transfered into a microtitre (microwells). After the addition of probe, antigen and color substrate, the plate was scanned using a Bio-Rad ELISA plate reader (Bio-Rad Laboratories, Hercules, CA).

The second batch included three varieties of tomatoes (Roma, Red Robin and Scotia). The tomato plants were sprayed with End.Al (a new formula by Safer Ltd., Scarborough, Ontario used as a miticide, insecticide or an acaricide) before planting in the hydroponic system to avoid possible spider mites manifestation. The plants were transplanted into the hydroponic system using gravels as a medium. The hydroponic system was divided into six compartments. Each compartment was divided into three

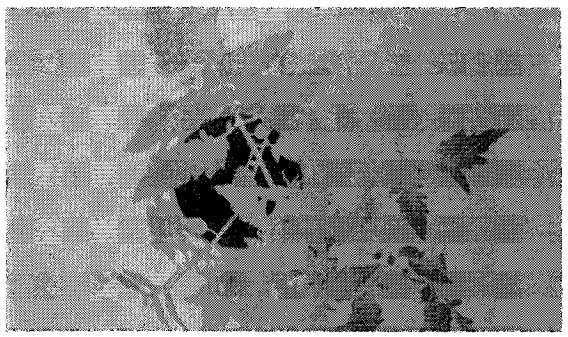


(a) A sealed TMV vial



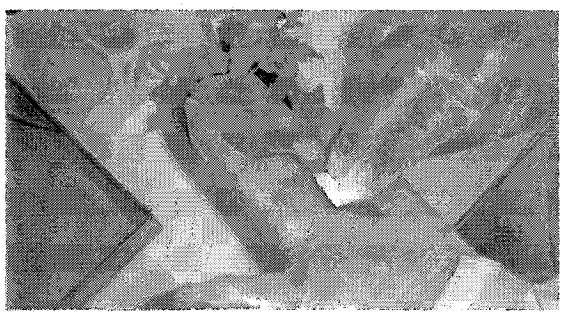
(b) The content of the vial and buffer were place in a pre-cooled mortar.

(c ) The content and buffer were homogenized.



(d) A healthy tomato plant was selected

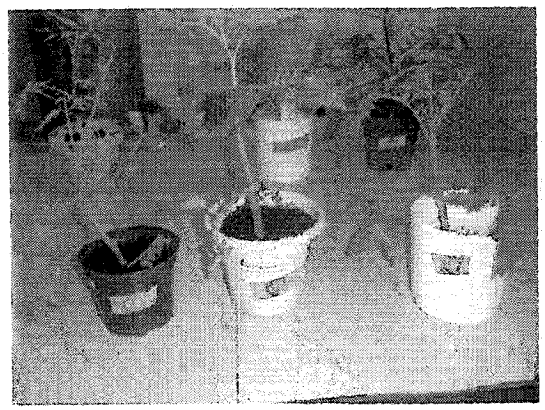
(e) One hand was used to support the leaf.



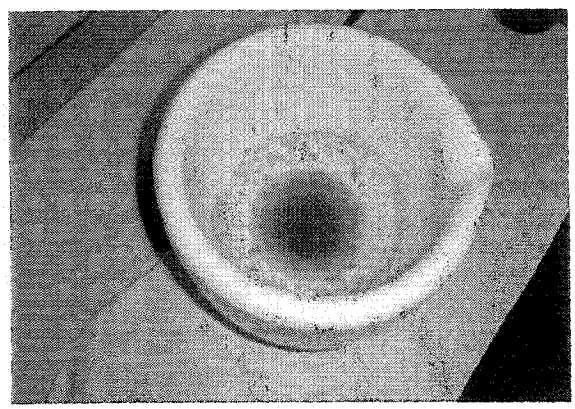
(f) A leaf was lightly sanded.

(g) The inoculum was applied onto the leaf

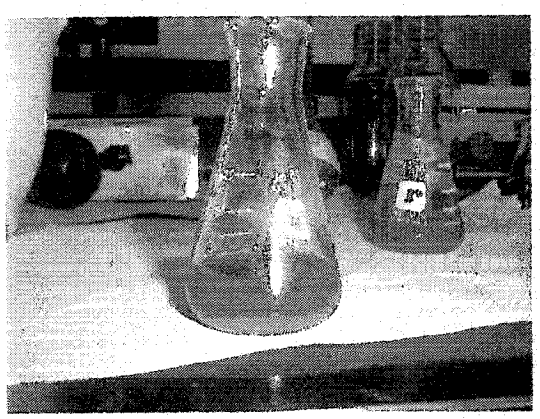
Figure 8.3. The TMV inoculation procedure for the first batch of tomato plants (Golden Boy variety).



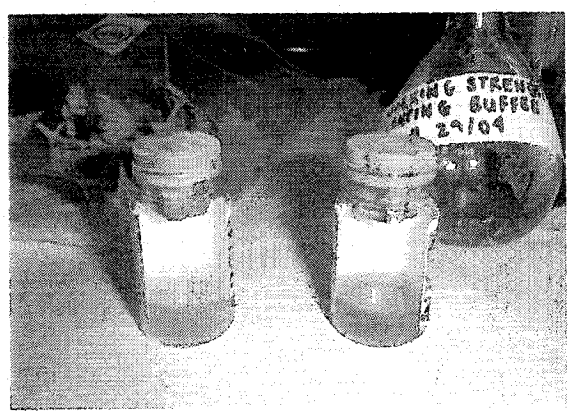
(a) Plants that showed symptoms.



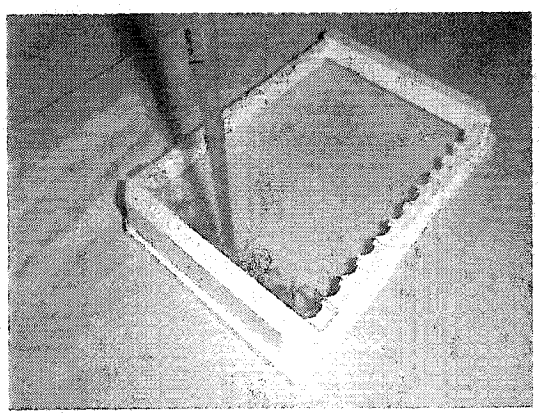
(b) A gram of plant leaves was homogenized with buffer.



(c) The homogenized liquid was left to settle.



(d) Negative and positive controls were prepared.



(e) Microwells were filled with samples and controls.

(f) A plate reader was used.

Figure 8.4. ELISA test procedure.

separate trays and had its independent light and aeration systems. Eight Tomato plants were planted in each tray. Forty eight tomato plants were grown from each variety (Figure 8.5). Hydroponic fertilizer (Table 8.1) was used to formulate the plant growth solution at the recommended rate (2 mL/L). The trays were filled with the solution and the aeration system and light were continuously running. Fresh water was added when needed due to the water loss by evaporation. Each week, the plant growth solution was drained and a new plant growth solution was added. By the end of the first week of planting, tomato plant looked healthier and new leaves were developed.

The *Tobacco mosaic virus* (PVAS-931) used in the second batch was obtained from the American Type Culture Collection (ATCC, Manassas, VA). The inoculation process is illustrated in Figure 8.6. The TMV sealed vial (which contains the freeze dried infected tissue) was carefully opened and the contents of the vial (infected tobacco plant tissue) were placed in a pre-cooled (4 °C) mortar with 9 mL of deionized distilled water. Sterile pestle was used to thoroughly triturate the tissue. Carborundum (500 mesh) was added to the inoculum at a rate of 50-100 mg/mL as recommended by ATCC to avoid the over pressing damage which was noticed after the first inoculation procedure. A young-healthy tomato plant was selected (Figure 8.7) from each variety for the virus infection process. A few leaves on each plant were selected and marked. The TMV inoculum was lightly rubbed onto the tomato leaves using a sterile cotton swab. The inoculated leaves were washed with tap water for a few minutes after application to remove salt residues. The infected tomato plants were then incubated in the hydroponic system for 10 days for the virus symptoms to develop. Leaves of infected tomato and tobacco plants were also provided by the Potato Research Centre in New Brunswick, Canada. Samples (~1 g) of the infected tomato plants from the second batch and the infected leaves received from the Potato Research Centre were collected for virus identification according to the procedure illustrated in Figure 8.4.

After the confirmation of the infection by TMV, a mixture of the tested plants (~160 g) was mixed with 500 g of the final compost mixture. Tap water (163-mL) and urea (5-g) were added to the mixture to adjust the moisture content and C: N ratio to 60 % and 30: 1, respectively. All ingredients were throughly mixed and divided into small

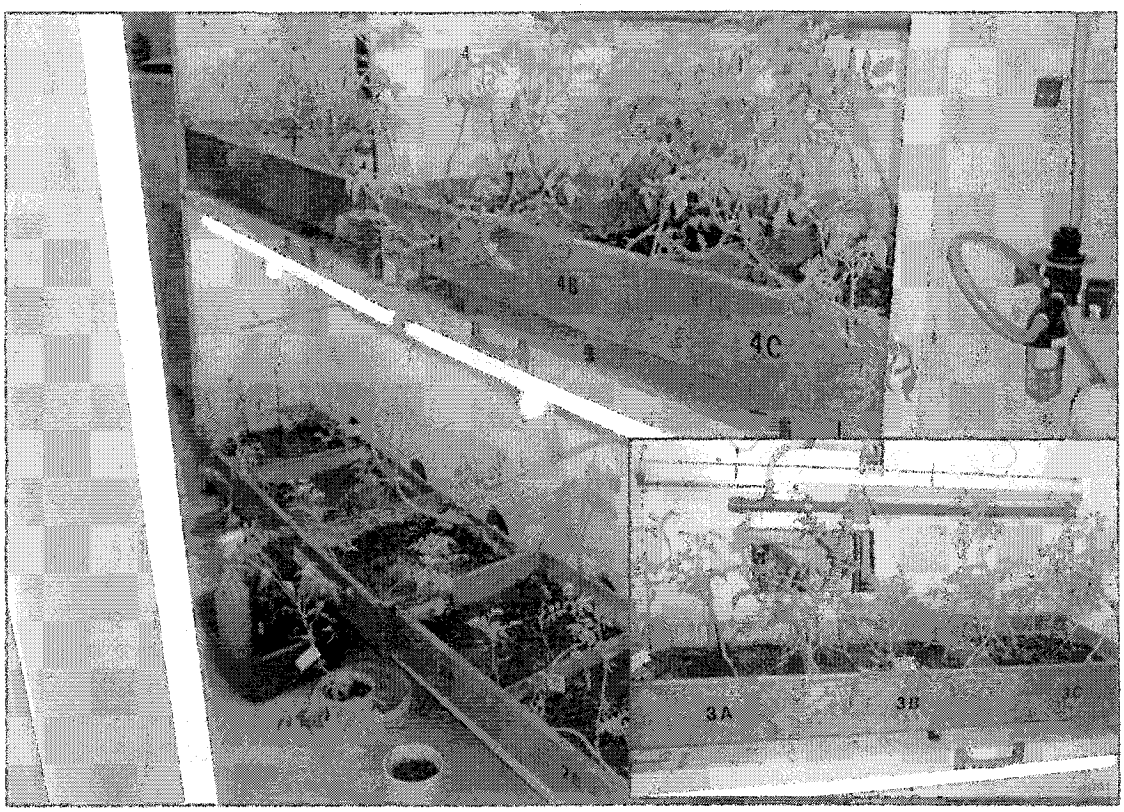
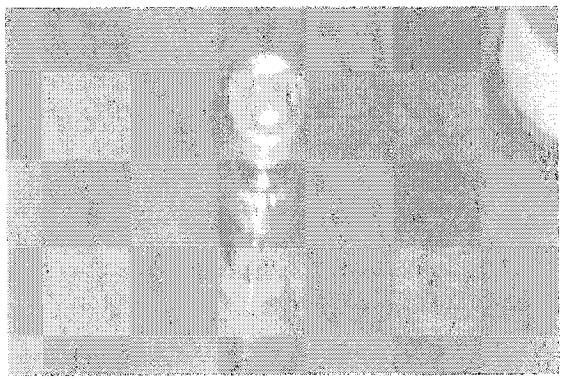


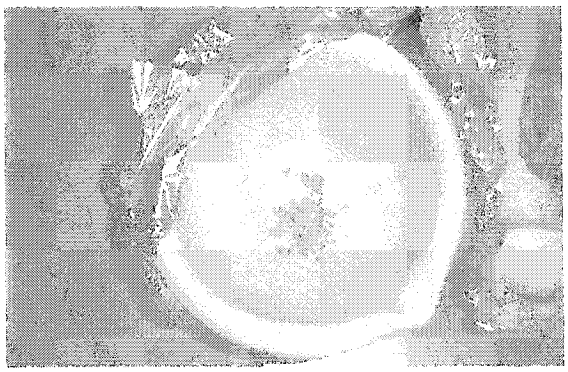

Figure 8.5. Second batch of tomato plants in the stoneponic system (forty eight plants each from Roma, Red Robin and Scotia varieties).

Table 8.6. Hydroponic fertilizer (Plant Products Co. Ltd., Brampton, Ontario, Canada).

| Nutrient | Value |
|---|---|
| Macronutrient Content (%) | |
| N | 10.0 |
| $P_2O_5$ | 6.0 |
| $K_2O$ | 16.0 |
| Ca | 7.2 |
| Mg | 2.2 |
| S | 2.9 |
| Micronutrient Content (%) | |
| Fe | 0.3000 |
| Cu | 0.0052 |
| Mn | 0.1042 |
| Zn | 0.0052 |
| B | 0.0157 |
| Mo | 0.0105 |



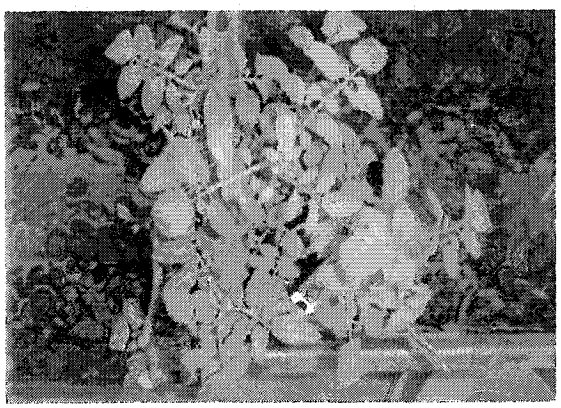
(a) A sealed TMV vial.



(b) The contents of the vial were placed in a pre-cooled mortar.

(c) The content and deionized distilled water were homogenized.

(d) The inoculum and carborundum powder were mixed together.



(e) A young-healthy plants from each variety were selected.

(f) One hand was used to support the leaf as virus inoculum was applied.

Figure 8.6. The TMV inoculation procedure for the second batch of tomato plants (Roma, Red Robin and Scotia varieties).

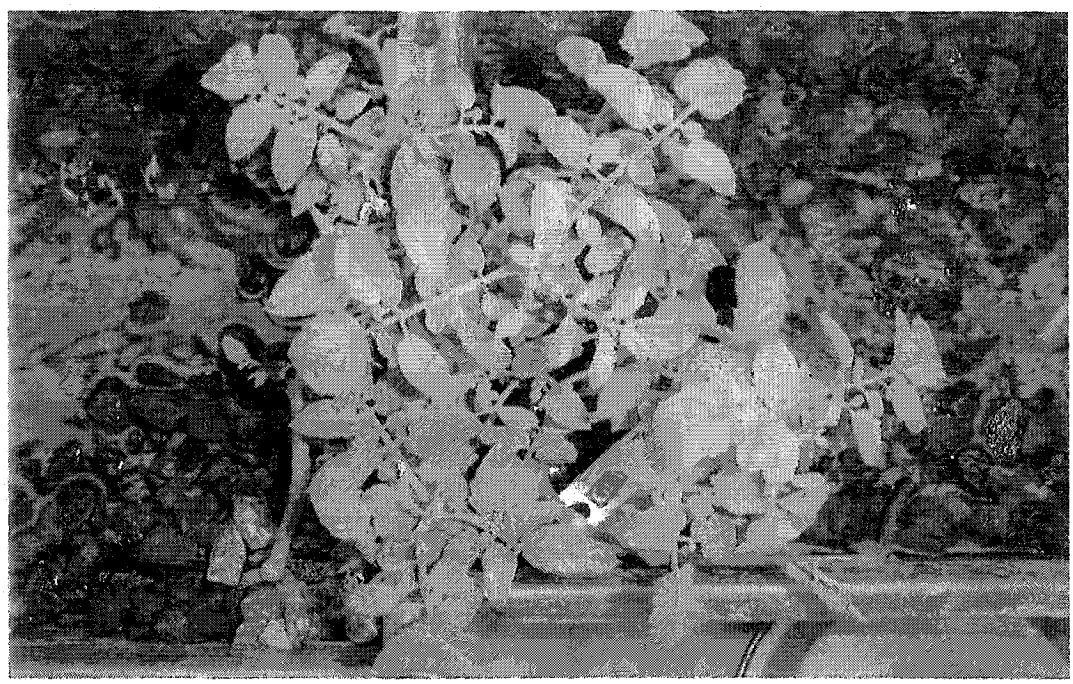


Figure 8.7. A young-healthy tomato plant from the second batch (after 10 days of inocultion).

portions of 40 g each and placed in sachets (7 X 12 cm) made of porous fabric (muslin mesh). An effort was made to have the same pathogen size distribution in each sachet. They were individually placed in zip-lock bags and kept in a frigerator at 4 °C until required for the composting experiment.

About 64.1 mL of used cooking oil was initially added to each 1.8 kg mixture of tomato residues: wood shavings: MSW (1:1.5: 0.28 ratio). Water was used to adjust the moisture content to 60%. The C:N ratio was adjusted to 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement. The final miture was mixed well and 3.5-kg were placed in a container. A single inoculum sachet of the plant pathogen *TMV* was securely fixed to the mixing rod as shown in Figure 8.8. The final compost mixture was then placed in the bioreactor. It occupied 75% of the total volume of the bioreacter (or 0.012 $m^3$). The plexiglas side wall was put in place and visual inspection of the bioreactor was done to detect any leakage before placing the insulation cover on the side wall. The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperature was continueously monitored. Once the temperature peaked (after 31 h), a volume of 36 mL of the used cooking oil was added every 12 h in order to maintain the temperature above 55 °C and the samples were collected every 24 hours to assess the inactivation of the TMV.

### 8.2.8 Mold Study

The mold *Botrytis cinerea* used in this study was obtained from the American Type Culture Collection (ATCC, Manassas, VA). The mold preparation procedure is illustrated in Figure 8.9. *Botrytis cinerea* was revived by carefully breaking the double vial and adding about 5-mL sterile water to the inner vial, which was then left to rehydrate for 2 h. The entire contents were transferred into a test tube containing 9-mL sterile potato dextrose broth (PDB), which contained infusion from 200 g potatoes (4 g/L) and 20 g/L Bacto Dextrose. The tube was incubated for 3 days at room temperature (~25 °C). One loopful of the rehydrated mold was used to streak each of the 100 plates containing potato dextrose agar (PDA) prepared according to the manufacturer's instructions (Difco, Detroit, Michigan). The plates were incubated at room temperature

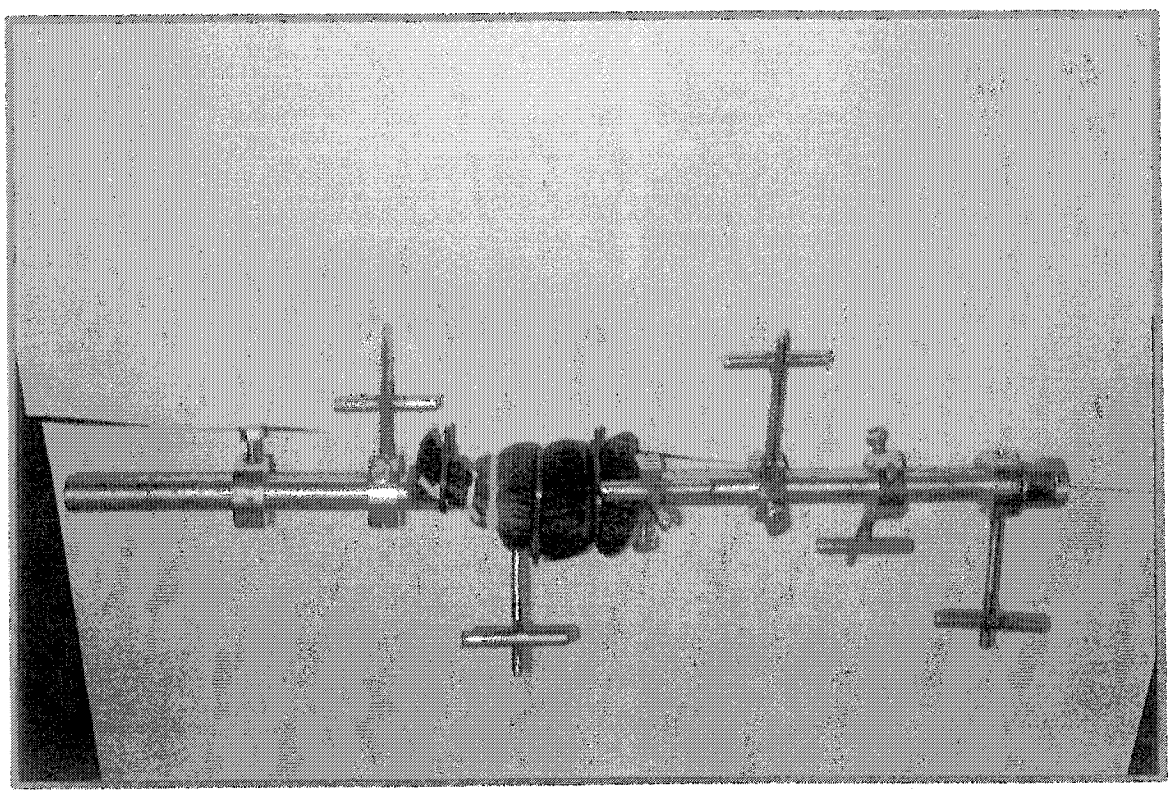
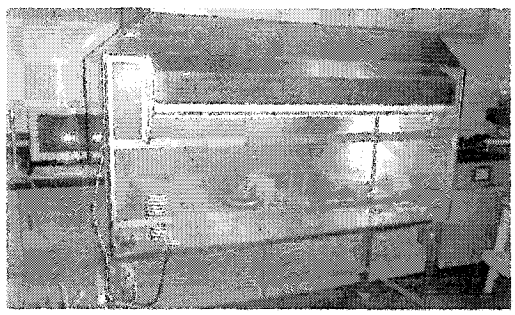
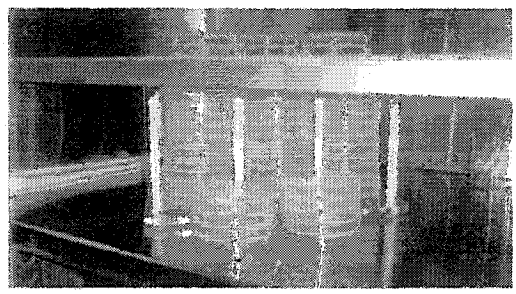


Figure 8.8. Inoculum sachet position in the bioreactor.

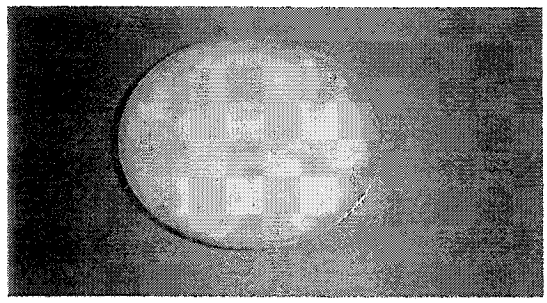


(a) Freeze dried culture was left to rehydrate in 5-mL sterile water for 2 h and content was added into 9-mL sterile PDB and incubated at room temperature for 3 days.

(b) One loopful of the culture was used to streak plates containing PDA.

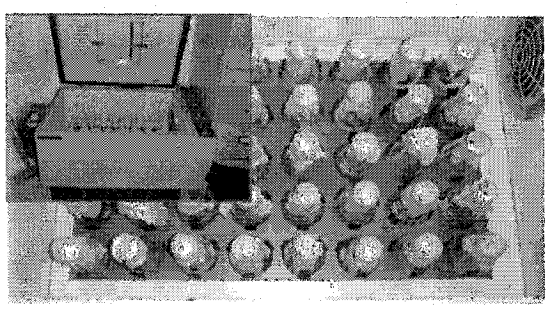


(c) 100 Plates were prepared and incubated at room temperature in total darkness for 6 days.

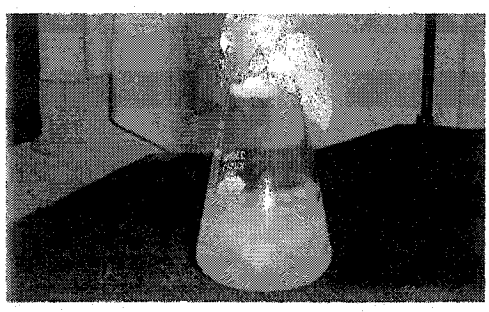


(d) Dense growth was observed after 6 days

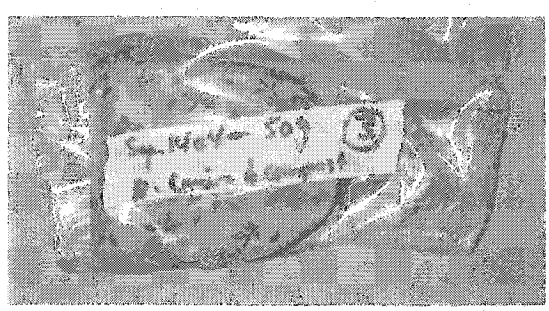
(e) Two plates were scrubbed into a 250-ml flask containing 150-ml PDB.



(f) All flasks were covered and placed in the shaker (150 rpm) in dark at 20°C for 6 days.



(g) After 6 days, intensive growth was observed, all flasks were mixed together and then divided into 30 lots each was placed in a container



(h) 250-mL of the liquid inoculum was used to prepare the final inoculum mixture, 50 g of which was placed in small sachets.

Figure 8.9 *Botrytis cinerea* culture preparation procedure.

(20-23 °C) in total darkness for 6 days, at which time the *B. cinerea* isolate had developed abundant hyphal swellings. Two plates of the culture (*Botrytis cinerea*) were scooped into a presterile 250 mL erlenmeyer flask contaning a 150 mL PDB. The flasks were stopperred and placed on a shaker (150 rpm) at room temperature in dark for 6 days. All flask contents (~ 6 L) and the rest of the plates were combined toghether after blending (to have a uniform inocula) and to ensure that all growth stages (spores, sclerotia and mycelium) are present. The prepared liquid inoculum was then divided into 30 lots and each was placed in small container (200 mL) and kept in a frigerator at 4 °C until required.

The final inoculum was prepared by mixing 250-mL of the prepared liquid inoculum with approximately 500 g of the final compost mixture. Tap water (163-mL) and urea (5-g) were added to the mixture to adjust the moisture content and C: N ratio to 60 % and 30: 1, respectively. All ingredients were throughly mixed and left in dark in an incubator at 18 °C for three days before use. Extensive growth of *Botrytis cinerea* was noticed in the prepared inoculum after three days. The mixture was then removed from the incubator and mixed throughly again and divided into small portions of 50 g each and placed in sachets (7 X 12 cm) made of porous fabric (muslin mesh). An effort was made to have the same pathogen size distribuation in each sachet. They were individually placed in zip-lock bags in a frigerator at 4 °C until required for the composting experiment.

About 64.1 mL of used cooking oil was initially added to each 1.8 kg mixture of tomato residues: wood shavings: MSW (1:1.5: 0.28 ratio). Water was used to adjust the moisture content to 60%. The C:N ratio was adjusted to 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement. The final mitures was mixed well and 3.5-kg were placed in a container. A single inoculum sachet of the plant pathogen *Botrytis cinerea* was securely fixed to the mixing rod as shown in Figure 8.8. The final compost mixture was then placed in the bioreactor. It occupied 75% of the total volume of the bioreacter (or 0.012 $m^3$). The plexiglas side wall was put in place and visual inspection of the bioreactor was done to detect any leakage before placing the insulation cover on the side wall. The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The

temperature was continuously monitored. Once the temperature peaked (after 31 h), a volume of 36 mL of the used cooking oil was added every 12 h in order to maintain the temperature above 55 °C and the samples were collected every 24 hours to assess the inactivation of the *Botrytis cinerea.*

### 8.2.9 Pirimiphos-methyl Study

The specific gravity of pirimiphos-methyl is 1.157. Three different concentrations of pirimiphos-methyl were prepared: 62.64, 125.28 and 187.92 mg active ingredent. Since the analitical form of pirimiphos-methyl is not soluble in water but disolved well in oil (Ussary, 1978), the required amount of pesticide was blended with the amount of used cooking oil required for each experiment.

The used cooking oil-insecticide mixture was then added to each 1.8 kg mixture of tomato residues: wood shavings: municipal solid compost (1:1.5: 0.28 ratio). Water was used to adjust the moisture content to 60%. The C:N ratio was adjusted to 30:1 by the addition of Urea (46% nitrogen) as a nitrogen supplement. The final mixtures was mixed well and 3.5-kg were placed in the bioreactor. It occupied 75% of the total volume of the bioreacter (or 0.012 $m^3$). The plexiglas side wall was put in place and visual inspection of the bioreactor was done to detect any leakage before placing the insulation cover on the side wall. The mixing unit was started at 5 RPM and the system was operated at a constant aeration rate of 0.15 $m^3/h$ (0.17 vvm) during all experiments. The temperature was continuously monitored. Once the temperature peaked (afer 31 h), a volume of 36 mL of the used cooking oil was added every 12 h in order to maintain the temperature above 55 °C and samples were collected every 24 hours to assess the destruction of the insecticide pirimiphos-methyl.

## 8.3 Analyses and Measurement

### 8.3.1 Moisture Content

Moisture content was performed using oven-drying method following ASTM (D 3173-73) procedure (ASTM, 2001). Three physical samples were removed from the system and each sample (5 – 10 grams) was weighted using a Mettler Scientific Scale

(AE 200S, Mettler Instrumente AG. Greifensee-Zurich. Switzerland). The weight was recorded to the nearest 0.0001 gram. Wet sample was oven dried at 105 °C for 24 hours in an air forced drying oven (Isotemp Oven, Model No. 655F, Fisher Scientific, Toronto, Ontario). The moisture content was then determined using the following formula:

$$M_c = \frac{WW - DW}{WW} \times 100 \tag{8.3}$$

Where:

$M_c$ =Moisture content in percent (%)

WW =Wet Weight (g)

DW =Dry Weight (g)

### 8.3.2 pH Measurements

The composted materials pH was measured using Fisher Accumet pH meter (Model 805 MP. Fisher Scientific. Pittsburgh, PA, USA). A 50 to 100 $cm^3$ sample of the composted material was diluted 1:10 (v:v) with distilled-deionized water and placed in a mechanical shaker at 230 rpm for 30 minutes prior to pH measurement.

### 8.3.3 Proximate Analysis

The proximate analysis was performed to determine the weight faction of volatiles and ash in the compost mixture (tomato remains, wood shavings and MSW). The ASTM Standard Method for Proximate Analysis of Coal and Coke was used (ASTM, 2001). The volatiles and ash values were determined on dry basis.

### 8.3.4 Elemental Analysis

The ultimate analysis was performed to determine the elemental composition of the composting mixture. The weight fractions of carbon, hydrogen, nitrogen, sulfur, chlorine, and ash were determined, and the weight fraction of oxygen in the composting mixture was estimated by subtracting the sum of carbon, hydrogen, nitrogen, sulfur, chlorine and ash content from 100. Carbon, Hydrogen, Iron, Potassium, Magnesium, Manganese, Chlorine, Sulfur, Zinc, Boron, Chromium, and Cadmium weight fractions were determined at the Materials Engineering Center (MEC) of Dalhousie University. All

elements were determined by flame atomic absorption spectrometer (Spectr AA 55B, Varian Australia Ply Ltd. Mulgrave, Victoria. Australia) with detection limit of 1 ppm except for Carbon, Sulfur, and Chlorine. Carbon dioxide and non-carbonate carbon were determined with Leco carbon analyzer (Model 516-000. Leco Corporation. St. Joseph, MI. USA) and sulfur was determined with Leco sulfur analyzer (Model 332-500. Leco Corporation. St. Joseph, MI. USA) along with an induction furnace (Leco $HF_2$ O Furnace, Leco Corporation. St. Joseph, MI. USA). Chlorine was determined by titration. Nitrogen analyses were done using a KjelTech Auto Analyzer (Tecator, Model 1030. Herndon, VA. USA) available at the Biological Engineering Laboratory. Ash content in the composting mixture was determined by following the procedure given in the ASTM Standard Test Method for Ash in Wood (D-1102-84) (ASTM, 2001).

### 8.3.5 Total Carbon Analysis

Total carbon of the composted sample was determined at the Materials Engineering Center (MEC) of Dalhousie University. Carbon dioxide and non-carbonate carbon were determined with Leco carbon analyzer (Model 516-000. Leco Corporation. St. Joseph, MI. USA) along with an induction furnace (Leco $HF_2$ O Furnace, Leco Corporation. St. Joseph, MI. USA).

### 8.3.6 Total Kjeldahl Nitrogen, Ammonium Nitrogen and Crude Protein

Both total kjeldahl nitrogen (TKN) and ammonium nitrogen ($NH_4$-N) were determined using a KjelTech Auto Analyzer (Tecator, Model 1030. Herndon, VA. USA). One gram sample of the composted material was diluted with 20 mL distilled water for $NH_4$-N analysis. For TKN analysis, a gram sample of the composted material was digested with 4 mL concentrated sulphuric acid ($H_2SO_4$) and 20 mL distilled water, then was placed in the digester at 420 °C for 60 minutes under vacumed ventilator. The analyte was then automatically titrated by the analyzer. Crude protein was calculated as follows:

$$\text{Crude Protein} = \text{ON} \times 6.25 \tag{8.4}$$

Where:

ON = the organic nitrogen (=TKN - $NH_4$)

### 8.3.7 Fat Analysis

Total fat and grease was analyzed following EPA method 1664 procedure where sample is acidified to pH <2 and serially extracted three times with hexane in a separatory funnel. The extract is quantified by gravimetric analysis (EPA, 1999).

### 8.3.8 *Tobacco Mosaic Virus*

The sachets of TMV inoculum were retrieved from the bioreactors at a pre-determined times (24, 48, 72, 96, 120 and 144 hours after the peak temperature). Testing was performed on the initial and the treated mixtures of the first tomato batch using the Enzyme-linked immunosorbent assay (ELISA). The ELISA kit (Adegen Ltd, Nellies Gate, Auchincuive, AYR, UK) utilized antibody designed to recognize a specific TMV protein. All positive, negative controls and buffers required to carry out the test were supplied with the kit. The TMV protein was extracted from the infected material by mixing a gram of the sample with the coating buffer. Then, the extracted protein was added to a microwell and incubated at 4 °C over night. The procedure was followed until a colored solution was formed that could be visually identified as positive or negative depending on its color intensity (negative color or lighter-color is considered a negative result, while positive color or darker-color is considered a positive result). The optical density of the developed color was read at 650 nm. Only double the reading value of the negative control or higher was considered a positive result.

ELISA tests have been used as a preliminary test due to its accuracy and time saving (Christensen et al., 2001; Suárez-Estrella et al., 2002). However, since ELISA assay does not distinguish between living and dead TMV proteins (Christensen et al., 2001; and Chitarra and Van den Bulk, 2003), local lesions host (bean) bioassay was utilized to provide information about the virus ability to infect a host plant. Inoculated mixtures with TMV (before and after composting) were sent to the Potato Research Centre (AAFC, Fredericton, New Brunswick) for testing. Generally, this bioassay is preformed by applying the extract of the virus onto a leaf of a local lesions host to determine if the virus loses its ability to induce lesions (small, 1 mm, reddish-brown local lesions). The number of the developed lesions is proportional to the

concentration of the active virus particles in the extract. The virus is restricted to the mesophyll cells of the bean's leaf tissue, and the tissue surrounding the point of entry dies, thus creating local lesions (APS, 2004).

### 8.3.9 *Botrytis Cinerea*.

The sachets of *Botrytis cinerea* inoculum were retrieved from the bioreactors at a pre-determined times (24, 48, 72, 96, 120 and 144 hours after the peak temperature). Samples were tested using Enzyme-linked immunosorbent assay (ELISA) and plating assay. The ELISA kit (Adegen Ltd, Nellies Gate, Auchincuive, AYR, UK) utilized antibody designed to recognize *B. cinerea* and provided quantitative information on the mold. All positive, negative controls and buffers required to carry out the test were supplied with the kit. The *Botrytis cinerea* protein was extracted from the infected mixtures by mixing a gram of the sample with the coating buffer. Then, the extracted protein was added to a microwell and incubated at 4 °C over night. The procedure was followed until a colored solution was formed. The optical density value measured at 450 nm was proportional to the concentration of mycelium in the sample. Pre-coated standard strips were supplied along with the kit and were used to create the standard curve according to the procedure described by the manufacturer (Figure 8.10). The standard curve was generated to provide a means of quantifying the amount of *B. cinerea* antigen present in the initial sample and monitor fungus in the retrieved samples from each experiment.

Since the ELISA test cannot distinguish between viable and dead mold cells (Christensen et al., 2001; and Chitarra and Van den Bulk, 2003), a plating assay was utilized to provide information about the viable cells. The diluted plating assay is a conformational step that determines if a viable mycelium of *B. cinerea* is present in samples. The plating assay was necessary to verify the result of the ELISA test and determine the time at which *Botrytis cinerea* was eradicated from the infected mixtures. Samples of 5-g each of the infected untreated and treated (24, 48, 72, 96, 120 and 144 h of thermophilic temperatures) mixtures were thoroughly shaken in 5-mL of deionized distilled water according to the procedure described by Paul and Clark (1988) and

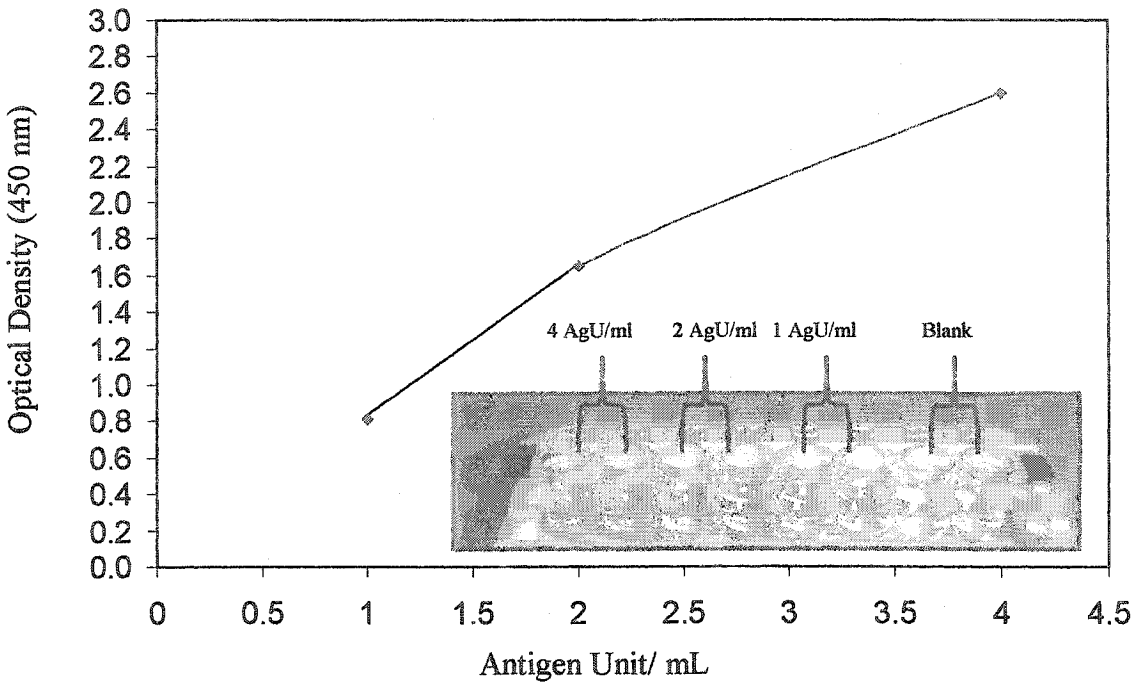



Figure 8.10. Standard curve of *Botrytis cinerea*.

Harrigan and McCance (1990). A volume of 1-mL of the prepared slurry was transferred into a test tube having 9-mL of sterilized distilled water ($10^{-1}$) and diluted serially stepwise to $10^{-5}$ dilution. A volume of 0.1 mL of the supernatant of each dilution ($10^{-3}$, $10^{-4}$ and $10^{-5}$) was transferred onto freshly prepared PDA plates and spread with a sterile bent glass rod. The dilution of $10^{-4}$ was chosen for further plating because the dilution of $10^{-3}$ gave a confluent growth and $10^{-5}$ gave fewer colonies. The inoculated plates were inverted and incubated at 16-18 °C for 48 hours after which the plates were examined for growth. The incubation temperature was chosen because it is within the range of optimum temperature for *B. cinerea* growth (15-22 °C) and due to the fact that compost microorganisms experience a long lag period when incubated at temperature less than 20 °C (Haug, 1993). All plates were visually and microscopically (at 40 magnification) inspected for the target mold (*B. cinerea*).

### 8.3.10 Pesticide Residue

The pesticide residue in the contaminated composting mixture was determined using a gas chromatograph, GC (Model No. 5890-SII, Hewlett Packard, Atlanta, Georgia). The GC was calibrated by injecting 10.0 µL of the hexane extracted pesticide of different concentrations onto a 25 m X 0.2 mm, 0.33 µm film thickness, 5 % diphenyl siloxane megabore capillary column to establish a standard curve for the target pesticide (Figure 8.11). The injection port was set at 180 °C and the flame ionization detector was set at 250 °C. The oven containing the column was first held isothermally at 40 °C for 4 minutes and then increased at a rate of 10 °C/min until a final temperature of 350 °C was reached. The final temperature was held for 5 minutes. The carrier gas was helium and was held at a constant flow rate of 1.2 ml/min. The pesticide residue was calculated with the aid of the computer program using the peak area method and results were saved as output files.

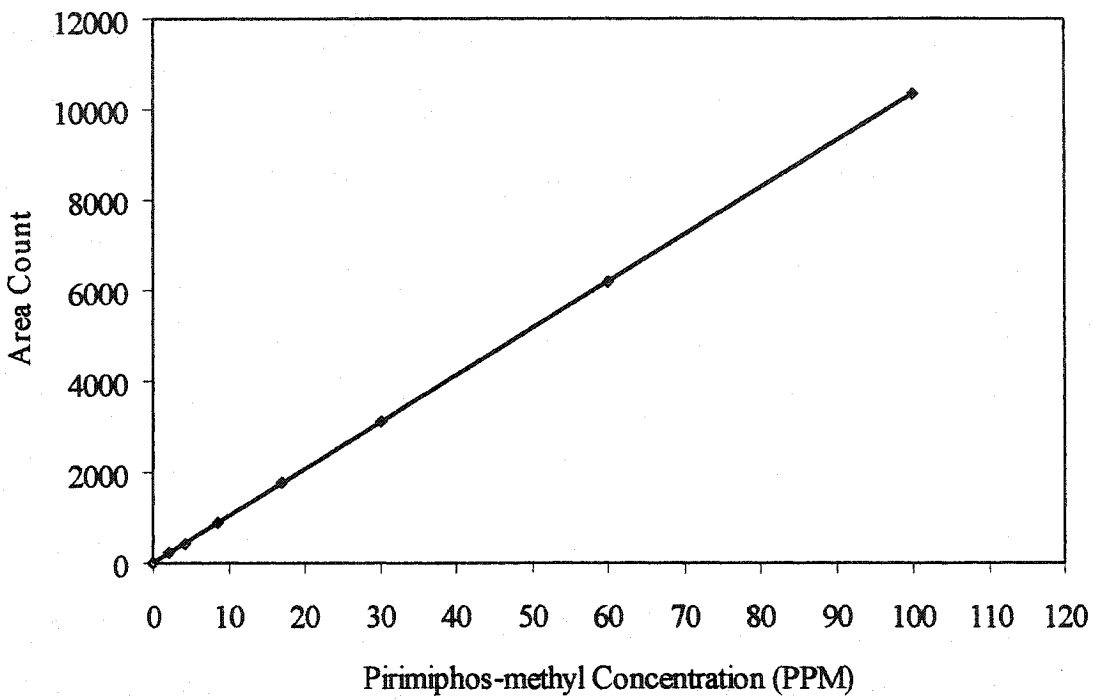



Figure 8.11. Standard curve of pirimiphos-methyl.

# 9. HEAT BALANCE

During composting, heat energy is produced as a result of the microbial conversion of chemical energy into thermal energy as generally described by the following equation (USEPA, 1993):

$$\text{Organic Material} + O_2 \longrightarrow CO_2 + H_2O + NH_3 + \text{Energy (heat)} + \text{Humus (compost)} + \text{New Cells} \qquad (9.1)$$

The composting process is governed by the basic principals of heat and mass transfer, and by the biological constrains of living microorganisms (Keener et al., 1993). Several researchers have reported the rate of heat production by organic material decomposition (Carlyle and Norman, 1941; Wiley, 1957; Walker and Harrison, 1960; and Mote and Griffis, 1982). Published data suggest that there are wide variations in the rate of heat released by compost because the rate of heat production is a function of chemical, physical and biological properties of the composted material.

Continuous mixing is often used to help maintain a homogeneous temperature distribution within the bioreactor. In a bioreactor with continuous mixing, heat energy is produced by compost as a result of the microbial conversion of chemical energy into thermal energy as well as by friction between the composed material and the mixing shaft (Ashbolt and Line, 1982; Mote and Griffis, 1979; Whang and Meenaghan, 1980; Nakasaki et. al., 1985; and Kubota and Nakasaki, 1991). However, when composting a sterilized material, microbial heat generation is eliminated and heat input by mixing shaft can be measured by conducting an energy balance on the bioreactor.

To perform heat balance on a bioreactor with a mixing unit, the heat produced in the unit, the heat lost from the unit (sensible and latent), and the heat accumulated in the unit must be considered (Haug, 1993). The heat produced (evolved) during the process is either stored in the compost mass or removed via a combination of several different thermal energy transfer mechanisms , radiation, conduction, evaporative cooling, and sensible heating of air (Miller, 1993). A heat (energy) balance was performed on the

composting system as shown in Figure 9.1. The heat balance on the entire system includes: (a) the heat generated as a result of microbial metabolism of organic substrate, (b) the heat added by the mixing unit, (c) the heat required to raise the temperature of the medium, (d) the heat losses through the system horizontal body (cylinder), (e) the heat losses through the system PVC side wall, (f) the heat losses through the system plexiglas side wall, (g) the heat losses with the exhaust gas, and (h) the heat losses by radiation.

Mathematically, the energy balance equation can be written in a simple form as follows:

$$q_p + q_m = q_s + q_c + q_{pvc} + q_{plexi} + q_e + q_r \quad (9.2)$$

Where :

$q_p$ = the rate of heat generated by the organic substrate metabolism (kJ/h)

$q_m$ = the rate of heat added by the mixing unit (kJ/h)

$q_s$ = the rate of total heat required to raise the temperature of the medium, system components (kJ/h)

$q_c$ = the rate of heat loss through the main body of the cylinder (kJ/h)

$q_{pvc}$ = the rate of heat loss through the PVC side wall (kJ/h)

$q_{plexi}$ = the rate of heat loss through the Plexiglas side wall (kJ/h)

$q_e$ = the rate of heat loss with the exhaust gas (kJ/h)

$q_r$ = the rate of heat loss by radiation (kJ/h)

The rate of heat loss in the form of radiation from laboratory scale bioreactor is usually negligible (Finstein et al., 1980). As a result, equation (9.2) can be rewritten as follows:

$$q_p + q_m = q_s + q_c + q_{pvc} + q_{plexi} + q_e \quad (9.3)$$

The rate of total heat required raising the temperature of the medium and the bioreactor components can be calculated as follows:

$$q_s = q_{compost} + q_{pvc\text{-}c} + q_{fiber\text{-}c} + q_{Alumi\text{-}c} + q_{pvc\text{-}w} + 2*q_{styro\text{-}w} + q_{plexi\text{-}w} + q_{mixing} \quad (9.4)$$

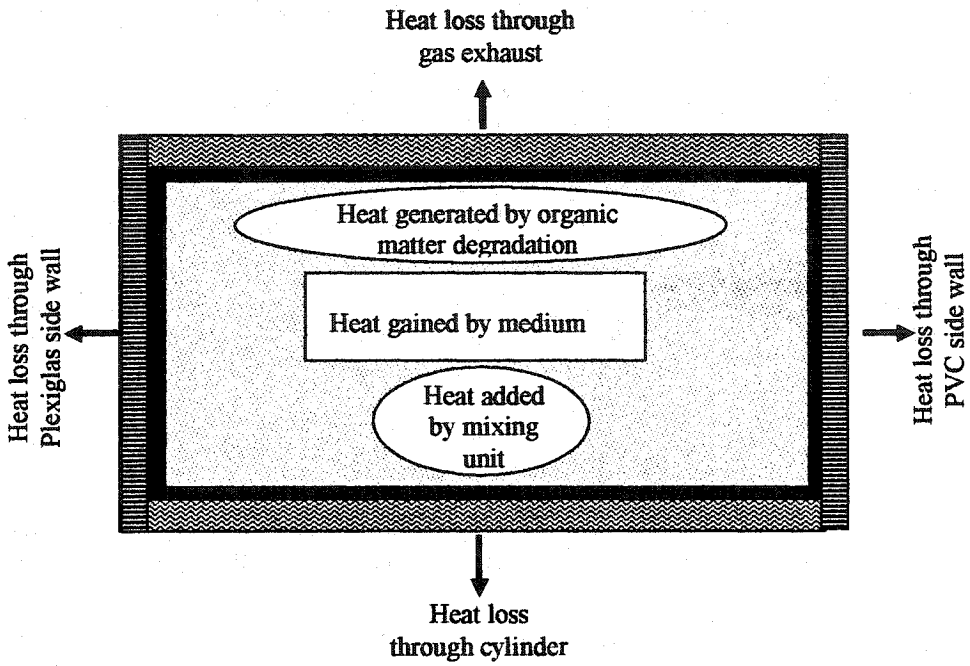



Figure 9.1. Heat balance of the entire system.

Where:

$q_{compost}$ = the rate of heat required to raise the temperature of the medium (kJ/h)

$q_{pvc-c}$ = the rate of heat required to raise the temperature of the horizontal PVC cylinder (kJ/h)

$q_{fiber-c}$ = the rate of heat required to raise the temperature of the horizontal fiberglass around the cylinder (kJ/h)

$q_{Alumi-c}$ = the rate of heat required to raise the temperature of the aluminum cover of the cylinder (kJ/h)

$q_{pvc}$ = the rate of heat required to raise the temperature of the PVC side (kJ/h)

$q_{pvc-w}$ = the rate of heat required to raise the temperature of the Styrofoam insulation of the side wall (kJ/h)

$q_{plexi-w}$ = the rate of heat required to raise the temperature of the Plexiglas side wall (kJ/h)

$q_{mixing}$ = the rate of heat required to raise the temperature of the mixing shaft (kJ/h)

The rate of heat transfer on the entire system is shown in Figure 9.2, the values of $q_{compost}$, $q_{pvc-c}$, $q_{fiber-c}$, $q_{Alumi-c}$, $q_{pvc-w}$, $q_{styro-w}$, $q_{plexi-w}$, $q_{mixing}$, $q_c$, $q_{pvc}$, $q_{plexi}$ and $q_e$, can be calculated from the following equations: (Holman, 1997; and Lemus and Lau, 2002)

$$q_{compost} = M_{compost}\, Cp_{compost}\, (T_f - T_i) / \Delta t \quad (9.5)$$

$$q_{pvc-c} = M_{cylinder}\, Cp_{pvc}\, (\Delta T_1) / \Delta t \quad (9.6)$$

$$q_{fiber-c} = M_{fiber} Cp_{fiber}\, (\Delta T_2) / \Delta t \quad (9.7)$$

$$q_{Alumi-c} = M_{Alumi}\, Cp_{Alumi}\, (\Delta T_3) / \Delta t \quad (9.8)$$

$$q_{pvc-w} = M_{pvc_side}\, Cp_{pvc}\, (\Delta T_4) / \Delta t \quad (9.9)$$

$$q_{styro-w} = M_{styro}\, Cp_{styro}\, (\Delta T_5) / \Delta t \quad (9.10)$$

$$q_{plexi-w} = M_{plexi}\, Cp_{plexi}\, (\Delta T_6) / \Delta t \quad (9.11)$$

$$q_{mixing} = M_{mixing_shaft}\, Cp_{ss}\, (\Delta T_7) / \Delta t \quad (9.12)$$

$$q_c = U_c\, A_c\, (T_v - T_s) \quad (9.13)$$

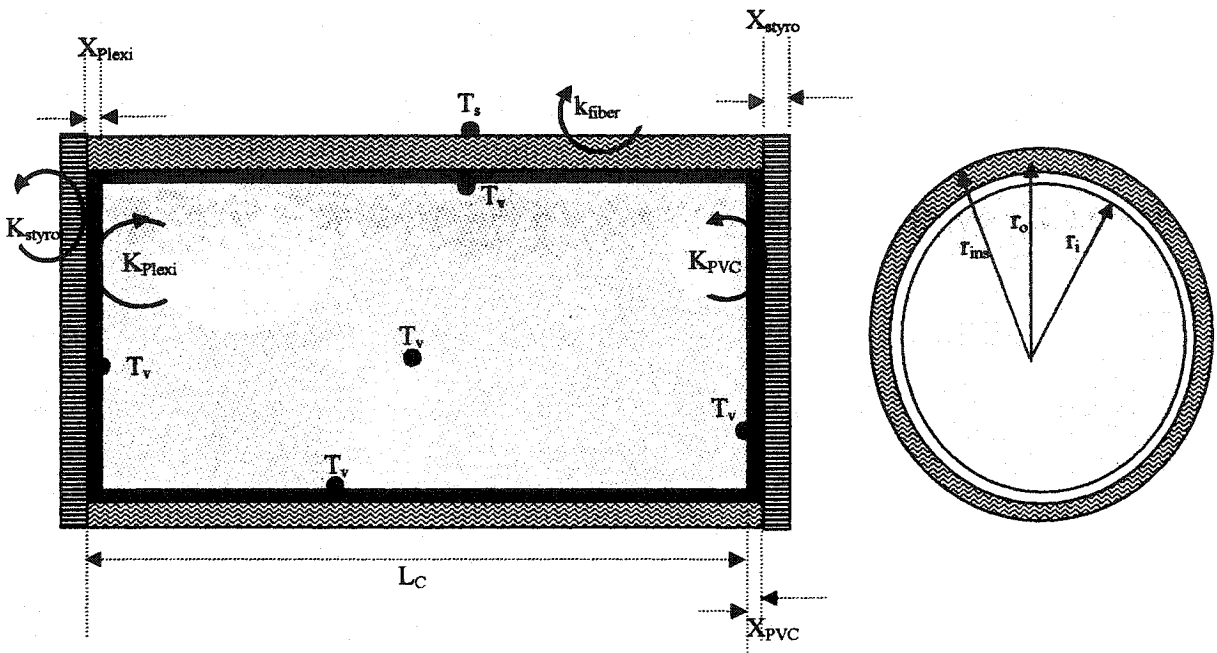



Figure 9.2. The heat transfer on the entire system.

$$q_{pvc} = U_{pvc} A_{pvc} (T_v - T_s) \quad (9.14)$$

$$q_{plexi} = U_{plexi} A_{plexi} (T_v - T_s) \quad (9.15)$$

$$q_e = Q_{air} \rho (h_o - h_i) \quad (9.16)$$

Where:

$A_{plexi}$ = the surface area of the Plexiglas side wall ($m^2$)

$A_{PVC}$ = the surface area of the PVC side wall ($m^2$)

$A_c$ = the surface area of the cylinder ($m^2$)

$Cp_{compost}$ = the specific heat of the compost (kJ/kg. °K)

$Cp_{pvc}$ = the specific heat of the cylinder material (PVC) (kJ/kg. °K)

$Cp_{fiber}$ = the specific heat of the fiberglass (kJ/kg. °K)

$Cp_{Alumi}$ = the specific heat of the cover (Aluminum) (kJ/kg. °K)

$Cp_{styro}$ = the specific heat of the Styrofoam (kJ/kg. °K)

$Cp_{plexi}$ = the specific heat of the Plexiglas side wall (kJ/kg. °K)

$Cp_{ss}$ = the specific heat of the stainless steel mixing shaft (kJ/kg. °K)

$Cp_a$ = the specific heat of the air (kJ/kg. °K)

$M_{compost}$ = the mass of the compost (kg)

$M_{cylinder}$ = the mass of the cylinder (kg)

$M_{fiber}$ = the mass of the fiberglass (kg)

$M_{Alumi}$ = the mass of the Aluminum sheet (kg)

$M_{styro}$ = the mass of the Styrofoam (kg)

$M_{plexi}$ = the mass of the Plexiglas side wall (kg)

$M_{ss}$ = the mass of the stainless steel mixing shaft (kg)

$M_{pvc}$ = the mass of the PVC side wall (kg)

$Q_{air}$ = the inlet airflow rate ($m^3/h$)

$T_f$ = the final temperature of the compost at the end of a time interval (°K)

$T_i$ = the initial temperature of the compost at the beginning of a time interval (°K)

$T_{in}$ = the air inlet temperature (°K)

$\Delta T_{1\text{-}7}$ = the temperature changes in the material of the cylinder, fiber, aluminum, pvc side wall, styrofoam, plexiglas side wall, and mixing shaft within a time interval respectively (°K)

$T_v$ = the average temperature of the compost within a time interval (°K)

$T_a$ = the laboratory ambient temperature (°K)

$T_s$ = the temperature of the outside surface of the bioreactor within a time interval (°K)

$T_o$ = the exhaust gas temperature within a time interval (°K)

$\Delta t$ = the time interval (h)

$U_c$ = the overall heat loss coefficient of the cylinder ($kJ/m^2$ h °K)

$U_{PVC}$ = the overall heat loss coefficient of the PVC side wall ($kJ/m^2$ h °K)

$U_{Plexi}$ = the overall heat loss coefficient of the Plexiglas side wall ($kJ/m^2$ h °K)

$\rho$ = the air density ($kg/m^3$)

$h_o$ = the enthalpy at $T_a$ (kJ/ kg d.a)

$h_i$ = the enthalpy at $T_{in}$ (kJ/ kg d.a)

Assuming the bioreactor components temperature differences are equal to the temperature difference in the composted material in each interval of time, that is $\Delta T_1 = \Delta T_2 = \Delta T_3 = \Delta T_4 = \Delta T_5 = \Delta T_6 = \Delta T_7 = T_f - T_i$, in each interval of time.

# 10. RESULTS

## 10.1 Inoculum Size Study

### 10.1.1 Moisture

The initial moisture contents of all mixtures were adjusted to approximately 60% (61.1 ± 0.4%). The final moisture content was approximately 59.6 ± 1.7% as shown in Table 10.1. Little changes were observed in the moisture content of the material. The reduction in moisture content ranged from 0.0 to 3% with an average value of 1.5 %.

### 10.1.2 Volatile Solids

The volatile solids results are presented in Table 10.2. The initial volatile solids varied from 798 to 868 g VS/kg DM depending on the inoculum content in the mixture. The percent reduction of the volatile solids range from 16.8 to 44.7 %.

### 10.1.3 Total Carbon

Table 10.3 shows the initial and final concentrations of total carbon and the percent reduction for the different mixtures used in these experiments. The initial total carbon content (TC) varied from 437 to 391 g/kg DM as the inoculum size increased from 0 to 50% due to the different TC contents of the different sources (tomato remains, wood shavings and MSW). The percent reductions of the total carbon ranged from 9.4 to 28.4 % depending on the inoculum size.

Table 10.1. Moisture content changes during the inoculum composting study.

| Mixture[1] : MSW Compost ratio | Moisture Content (%) | | |
|---|---|---|---|
| | Initial | Final | Change |
| 100: 00 | 61.7 | 61.3 | 0.4 |
| 90: 10 | 61.1 | 59.1 | 2.0 |
| 80: 20 | 60.6 | 57.0 | 3.6 |
| 70: 30 | 61.0 | 61.0 | 0.0 |
| 60: 40 | 61.1 | 61.0 | 0.0 |
| 50: 50 | 60.9 | 57.9 | 3.0 |
| Average | 61.1 | 59.6 | 1.5 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by dry weight).

Table 10.2. Volatile solids changes during the inoculum composting study.

| Mixture[1] : MSW Compost ratio | Volatile Solids[2] | | | |
|---|---|---|---|---|
| | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) |
| 100: 00 | 868 | 722 | 146 | 16.8 |
| 90: 10 | 858 | 667 | 191 | 22.3 |
| 80: 20 | 835 | 620 | 215 | 25.8 |
| 70: 30 | 830 | 598 | 232 | 27.9 |
| 60: 40 | 806 | 506 | 300 | 37.2 |
| 50: 50 | 798 | 441 | 357 | 44.7 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 on dry weight basis).
2- Calculated based on the dry matter basis.

Table 10.3. Total carbon and total kjeldahl nitrogen changes during the inoculum composting study.

| Mixture[1] : MSW Compost ratio | Total Carbon | | | | Total Kjeldahl Nitrogen (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial | Final | Reduction | | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) | (g/kg) | (g/kg) | (g/kg) | (%) |
| 100: 00 | 437 | 396 | 41 | 9.4 | 14.6 | 14.1 | 0.5 | 3.4 |
| 90: 10 | 432 | 389 | 43 | 10.0 | 14.4 | 13.9 | 0.5 | 3.5 |
| 80: 20 | 422 | 368 | 54 | 12.8 | 14.1 | 13.3 | 0.8 | 5.7 |
| 70: 30 | 411 | 358 | 53 | 12.9 | 13.7 | 12.8 | 0.9 | 6.6 |
| 60: 40 | 401 | 309 | 92 | 23.0 | 13.4 | 10.7 | 2.7 | 20.2 |
| 50: 50 | 391 | 280 | 111 | 28.4 | 13.0 | 9.7 | 3.3 | 25.4 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by dry weight).

### 10.1.4 Total Kjeldahl Nitrogen

Table 10.3 shows the initial and final concentrations of the kjeldahl nitrogen content (TKN) and the percent reduction for the different mixtures used in these experiments. The initial TKN of the mixtures also decreased as the inoculum size increased. Increasing the inoculum size from 0 to 50% decreased the TKN from 14.6 to 13.0 g/kg DM. The percent reductions of the TKN range from 3.4 to 25.4 %, depending on the inoculum size.

### 10.1.5 C: N Ratio

The C: N values for the mixtures used in these sets of experiments are presented in Table 10.4. At the start of all experiments, the C: N ratios were adjusted to the optimum range of 30: 1, which were slightly reduced to 28:1 - 29: 1 at the end of the experiments.

### 10.1.6 Temperature

The profiles of the average temperatures ($T_{ave}$) of the bioreactors, and the inlet air temperature (Ti) are presented in Figure 10.1. The maximum temperatures and their peak times are presented in Table 10.5. The average temperature in the bioreactors containing 0%, 10%, 20%, 30%, 40% and 50% inoculum reached 37.8, 50.8, 51.5, 52.2, 53.2 and 61.8° C after 24, 27, 38, 40, 45 and 48 hours respectively. Temperatures higher than 50 ° C (thermophilic) were observed in all bioreactors containing inoculum (10, 20, 30, 40 and 50%), and were maintained for 7, 8, 10, 15, and 29 hours, respectively. Temperature above 55 ° C was only observed in the bioreactor containing 50 % inoculum and lasted only for 20 hours.

Table 10.4. C: N ratio changes during the inoculum composting study.

| Mixture[1] : MSW Compost ratio | C: N | | |
|---|---|---|---|
| | Initial | Final | Change |
| 100: 00 | 30: 1 | 28.0: 1 | 2.0 |
| 90: 10 | 30: 1 | 28.0: 1 | 2.0 |
| 80: 20 | 30: 1 | 28.0: 1 | 2.0 |
| 70: 30 | 30: 1 | 28.0: 1 | 2.0 |
| 60: 40 | 30: 1 | 29.0: 1 | 1.0 |
| 50: 50 | 30: 1 | 29.0: 1 | 1.0 |
| Average | 30: 1 | 28.3: 1 | 1.7 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by weight).

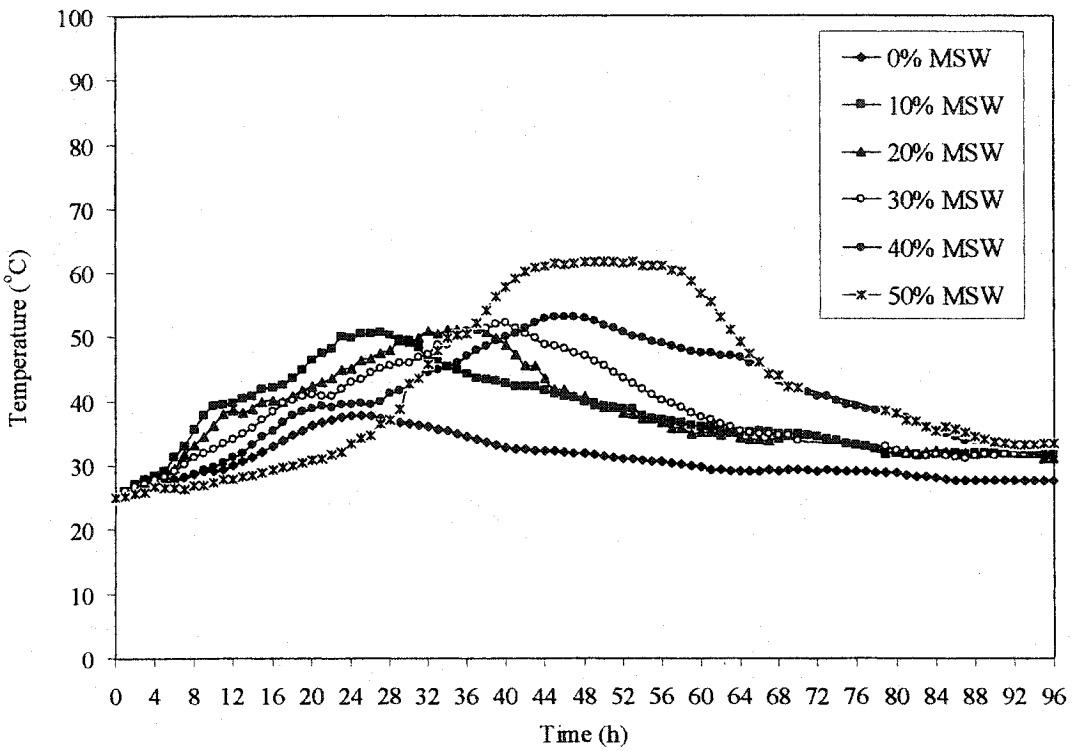



Figure 10.1. The temperature profile of the composting process of tomato remains-wood shaving-municipal solid waste compost mixture.

Table 10.5. The maximum temperature, time of peak time, and duration of temperature above 50 °C during the inoculum study.

| Mixture[1] : MSW Compost ratio | Maximum Temperature (°C) | Time of Peak (h) | Temperature above 50°C | Duration of Temperature above 50°C (h) |
|---|---|---|---|---|
| 100: 00 | 37.8 | 24 | No | 0 |
| 90: 10 | 50.8 | 27 | Yes | 5 |
| 80: 20 | 51.5 | 38 | Yes | 8 |
| 70: 30 | 52.2 | 40 | Yes | 10 |
| 60: 40 | 53.2 | 45 | Yes | 15 |
| 50: 50 | 61.8 | 48 | Yes | 29 |

1- Mixture consists of tomato remains and wood shavings mixed at a ratio of 1:1.5 by dry weight basis.

## 10.2 Addition of Sugar (as Carbon Source) Study

The profiles of the average bioreactors temperatures ($T_{ave}$), and the inlet air temperature (Ti) are presented in Figure 10.2. The compost temperatures level and duration are presented in Table 10.6. The average bioreactor temperature peaked after 27, 34, 43 and 57 hours reaching 50.8, 57.5, 62.3 and 64.3 °C in the bioreactors with control, one, two and three sugar applications. Temperatures higher than or equal to 50 were maintained in bioreactors with control, one, two and three sugar applications and lasted for 5, 18, 35 and 47 hours, respectively. Temperatures higher than 55 were observed in bioreactor with sugar addition and lasted for 8, 24 and 35 hours for bioreactor receiving one, two and three sugar applications, respectively. Only the bioreactor with two and three sugar applications had a temperature above 60° C which lasted 7 and 20 hours, respectively. The average temperature of the control bioreactor (without sugar addition) never reached 55 °C.

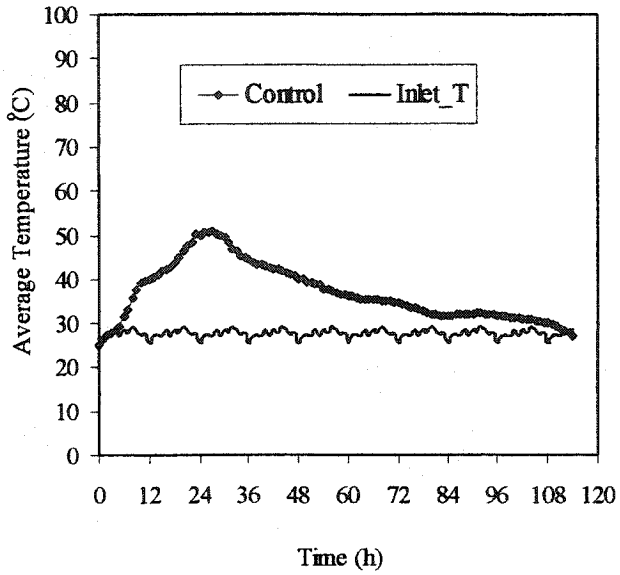
## 10.3 Dairy Manure Study

### 10.3.1 Moisture

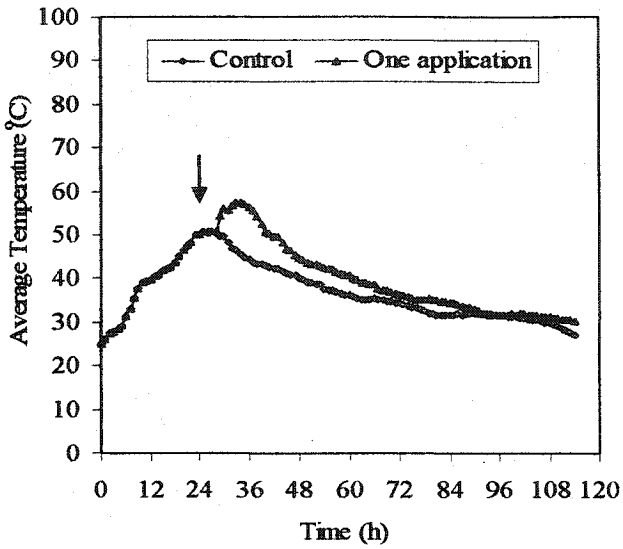
The initial moisture contents of all mixtures were adjusted to approximately 60 % (60.66 ± 1.27 %). The final moisture content was approximately 58.82 ± 1.17 % as shown in Table 10.7. Little changes were observed in the moisture content of the material during composting process. The reduction in the moisture content ranged from 0.40 to 3.99 % with an average value of 1.84 %.

### 10.3.2 Volatile Solids

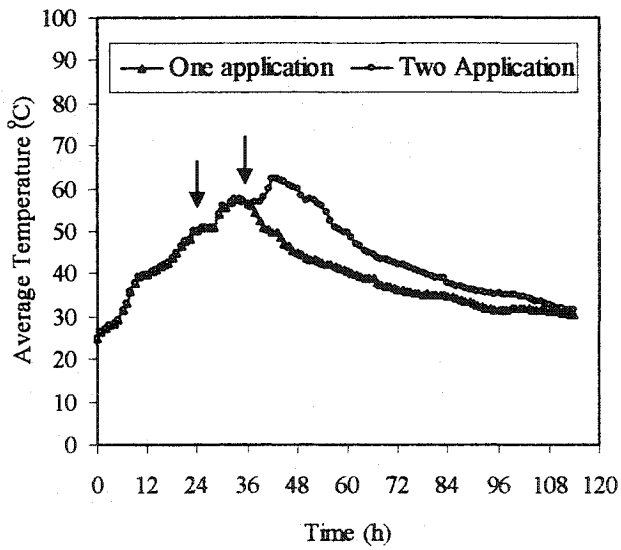
The volatile solids results are presented in Table 10.8. The initial volatile solids varied from 841 to 872 g VS/kg DM depending on the manure content in the mixture. The percent reduction of the volatile solids range from 16.8 to 32.7 %.



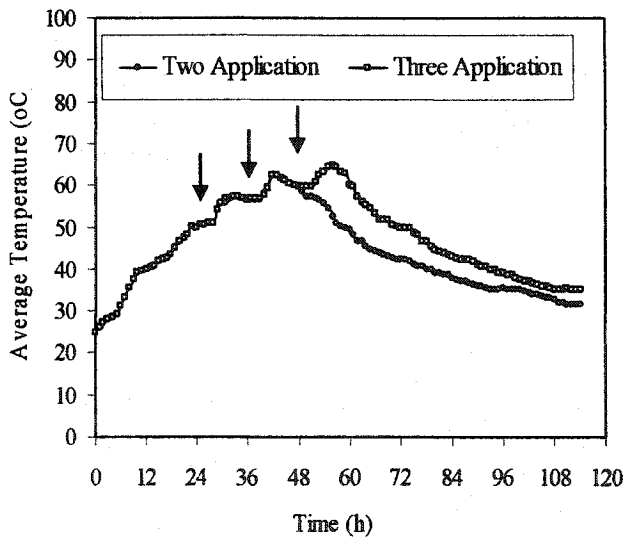

(a) Control




(b) One application




(c) Two applications




(d) Three applications

Figure 10.2. Temperature profile of the composting process of tomato remain-wood shaving-municipal solid waste compost mixture with sugar addition.

Table 10.6. Temperature ranges and duration (h) reached during the sugar addition experiments.

| Treatment | Maximum Temperature | Time of Peak | Duration of the Temperature ≥ (h) | | |
|---|---|---|---|---|---|
| | (°C) | (h) | 50°C | 55°C | 60°C |
| Without Sugar | 50.8 | 27 | 5 | 0 | 0 |
| With Sugar | | | | | |
| One Application | 57.5 | 34 | 18 | 8 | 0 |
| Two Applications | 62.3 | 43 | 35 | 24 | 7 |
| Three Applications | 64.3 | 57 | 47 | 35 | 18 |

Table 10.7. Moisture content changes during the dairy manure composting study.

| Mixture[1] : Manure ratio | Moisture Content (%) | | |
|---|---|---|---|
| | Initial | Final | Change |
| 100: 00 | 61.70 | 61.30 | 0.40 |
| 90: 10 | 59.53 | 58.43 | 1.10 |
| 80: 20 | 59.45 | 58.40 | 1.05 |
| 70: 30 | 60.62 | 58.88 | 1.74 |
| 60: 40 | 60.03 | 57.30 | 2.73 |
| 50: 50 | 62.60 | 58.61 | 3.99 |
| Average | 60.66 | 58.82 | 1.84 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by dry weight).

Table 10.8. Volatile solids changes during the dairy manure composting study.

| Mixture[1] : Manure ratio | Volatile Solids[2] | | | |
|---|---|---|---|---|
| | Initial | Final | Reduction | |
| | (g /kg) | (g /kg) | (g /kg) | (%) |
| 100: 00 | 868 | 722 | 146 | 16.8 |
| 90: 10 | 870 | 695 | 175 | 20.1 |
| 80: 20 | 872 | 675 | 197 | 22.6 |
| 70: 30 | 851 | 637 | 214 | 25.2 |
| 60: 40 | 846 | 603 | 243 | 28.7 |
| 50: 50 | 841 | 566 | 275 | 32.7 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 on dry weight basis).
2- Calculated based on the dry matter basis.

### 10.3.3 Total Carbon

Table 10.9 shows the initial and final concentrations of total carbon and the percent reduction for the different mixtures used in these experiments. The initial total carbon content (TC) decreased slightly from 437 to 416 g/kg DM as the manure size increased from 0 to 50% due to the variation of the TC contents of the different sources (tomato remains, wood shavings and manure). The percent reduction of the total carbon ranged from 9.4 to 10.8 %, depending on the amount of manure added to the mixture.

### 10.3.4 Total Kjeldahl Nitrogen

Table 10.9 shows the initial and final concentrations of total kjeldahl nitrogen and the percent reduction for the different mixtures used in these experiments. The initial total kjeldahl nitrogen content (TKN) of the mixture also increased as the manure size increased. Increasing the manure size from 0 to 50% increased the TKN from 14.6 to 15.1 %. The percent reductions of the TKN range from 3.4 to 6.0 %, depending on the amount of manure added to the mixture.

### 10.3.5 C: N Ratio

The C: N values for the mixtures used in these sets of experiments are presented in Table 10.10. At the start of all experiments, the C: N ratios were within the optimum ranging from 27.6: 1- 29.9: 1 with an average value of 28.4: 1, which were slightly reduced to 26.2: 1 - 28: 1 with an average value of 26.9: 1 at the end of the experiments.

### 10.3.6 Temperature

The profiles of the average temperatures ($T_{ave}$) of the bioreactors are presented in Figure 10.3. The maximum temperatures and their peak times are presented in Table 10.11. The average temperature in the bioreactors containing 0%, 10%, 20%, 30%, 40% and 50% manure reached 37.8, 39.0, 39.5, 39.0, 39.1 and 41.2 °C after 24, 11, 11, 10, 10 and 10 hours respectively. Temperatures higher than 35°C were observed in bioreactors

Table 10.9. Total carbon and total kjeldahl nitrogen changes during the dairy manure composting study.

| Mixture[1] : Manure ratios | Total Carbon | | | | Total Kjeldahl Nitrogen | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial | Final | Reduction | | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) | (g/kg) | (g/kg) | (g/kg) | (%) |
| 100: 00 | 437 | 396 | 41 | 9.4 | 14.6 | 14.1 | 0.5 | 3.4 |
| 90: 10 | 425 | 384 | 41 | 9.6 | 14.8 | 14.1 | 0.7 | 4.3 |
| 80: 20 | 422 | 380 | 42 | 10.0 | 14.9 | 14.2 | 0.7 | 4.5 |
| 70: 30 | 420 | 379 | 41 | 9.8 | 15.0 | 14.1 | 0.9 | 5.4 |
| 60: 40 | 417 | 375 | 42 | 10.1 | 15.1 | 14.2 | 0.9 | 6.0 |
| 50: 50 | 416 | 371 | 45 | 10.8 | 15.1 | 14.2 | 0.9 | 6.0 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by dry weight).

Table 10.10. C: N ratio changes during the dairy manure composting study.

| Mixture[1] : Manure ratio | C: N | | |
|---|---|---|---|
| | Initial | Final | Change |
| 100: 00 | 29.9: 1 | 28.0: 1 | 1.9 |
| 90: 10 | 28.8: 1 | 27.2: 1 | 1.6 |
| 80: 20 | 28.4: 1 | 26.7: 1 | 1.7 |
| 70: 30 | 28.1: 1 | 26.8: 1 | 1.3 |
| 60: 40 | 27.7: 1 | 26.5: 1 | 1.2 |
| 50: 50 | 27.6: 1 | 26.2: 1 | 1.4 |
| Average | 28.4: 1 | 26.9: 1 | 1.5 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by weight).

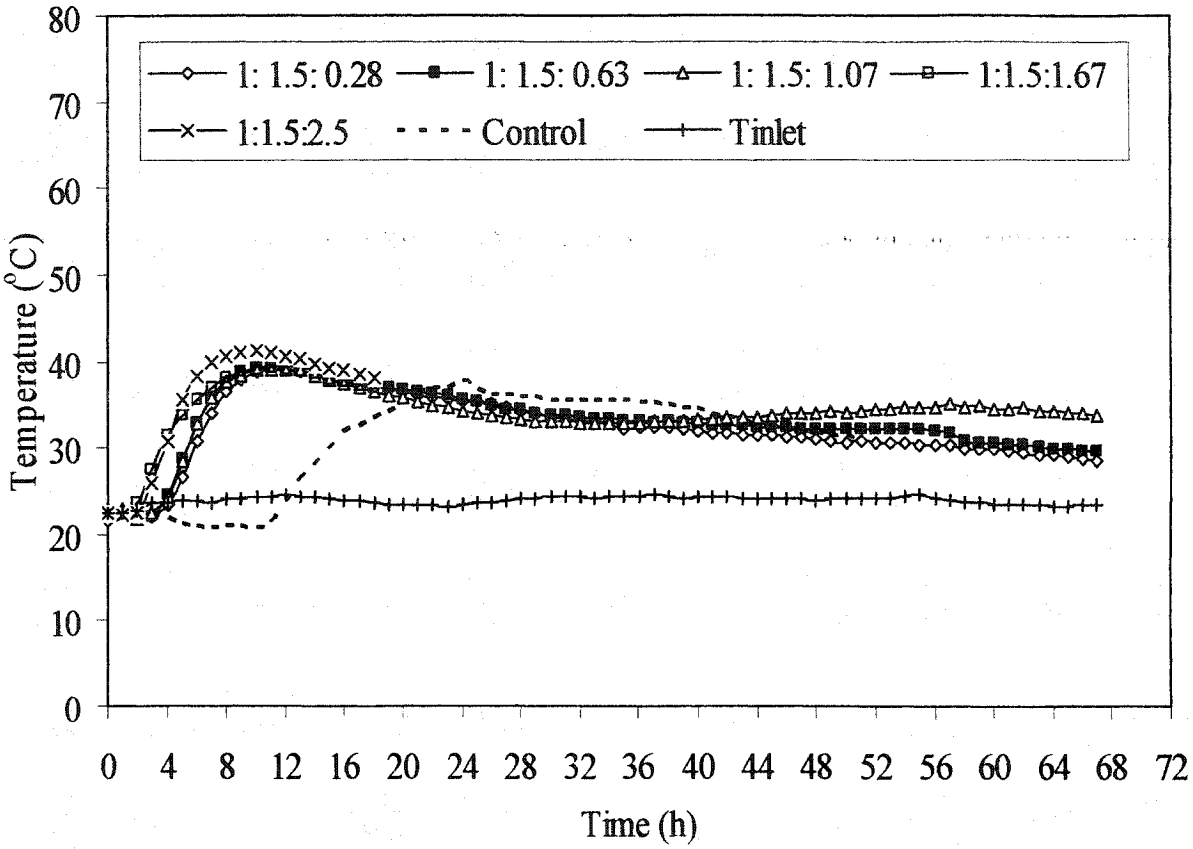



Figure 10.3. The temperature profile during the composting process of tomato remain-wood shaving- dairy manure mixture.

Table 10.11. Maximum temperatures, time of peak and ranges of temperatures during the dairy manure study.

| Mixture[1] : Manure ratio | Maximum Temperature | Time of Peak | Duration (h) of the Temperature ≥ | | |
|---|---|---|---|---|---|
| (%) | (°C) | (h) | 35°C | 40°C | 45°C |
| 100: 00 | 37.8 | 24 | 21 | 0 | 0 |
| 90: 10 | 39.0 | 11 | 19 | 0 | 0 |
| 80: 20 | 39.5 | 11 | 19 | 0 | 0 |
| 70: 30 | 39.0 | 10 | 19 | 0 | 0 |
| 60: 40 | 39.1 | 10 | 20 | 0 | 0 |
| 50: 50 | 41.2 | 10 | 21 | 7 | 0 |

1- Mixture consists of tomato remains and wood shavings mixed at a ratio of 1:1.5 by dry weight basis.

containing manure (10, 20, 30, 40 and 50%), and were maintained for 19, 19, 19, 20, and 21 hours, respectively. Temperatures higher than 40° C were only observed in the bioreactor containing 50 % manure and was maintained for 7 hours. Temperatures higher than 45°C were not observed in any of the bioreactors.

## 10.4 Used Oil and Cheese Whey Study

### 10.4.1 Moisture

The initial moisture contents of all mixtures were adjusted to approximately 60% (61.0 ± 0.70 %). The final moisture content was approximately 59.6 ± 0.61 % as shown in Table 10.12. Little changes were observed in the moisture content of the material during composting process. The reduction in moisture content ranged from 0.3 to 2.0 % with an average of 1.4 %.

### 10.4.2 Volatile Solids

The volatile solids results are presented in Table 10.13. The initial volatile solids were identical (872 g VS/kg DM) for the three mixtures. The percent reduction of the volatile solids range from 18.5 to 29.1 % depending on the type of carbon source being used in the mixture.

### 10.4.3 Total Kjeldahl Nitrogen and Ammonium Nitrogen

Table 10.14 shows the initial and final concentrations of total kjeldahl nitrogen content (TKN) and ammonium nitrogen contents as well as the percent reduction for the different mixtures used in these experiments. The initial TKN of the mixture varied from 14.3 to 18.7 g/kg DM, depending on the type of carbon source being used. The percent reduction of the TKN also was related to the carbon source; 3.5, 17.7, 11.0 % for control, cheese whey and used cooking oil experiments, respectively. The initial and final

Table 10.12. Moisture content changes during the cheese whey and used cooking oil study.

| Treatment | Moisture Content (%) | | |
|---|---|---|---|
| | Initial | Final | Change |
| Control | 61.7 | 59.9 | 1.8 |
| Cheese Whey | 60.3 | 60.0 | 0.3 |
| Used Cooking Oil | 61.0 | 59.0 | 2.0 |
| Average | 61.0 | 59.6 | 1.4 |

Table 10.13. Volatile solids changes during the cheese whey and used cooking oil study.

| Treatment | Volatile Solids[1] | | | |
|---|---|---|---|---|
| | Initial | Final | Reduction | |
| | (g /kg) | (g /kg) | (g /kg) | (%) |
| Control | 872 | 711 | 162 | 18.6 |
| Cheese Whey | 872 | 678 | 194 | 22.2 |
| Used Cooking Oil | 872 | 618 | 254 | 29.1 |

1- Calculated based on the dry matter basis.

Table 10.14. Total kjeldahl nitrogen and ammonium nitrogen during cheese whey and used cooking oil addition study.

| Treatment | Total Kjeldahl Nitrogen | | | | Ammonium Nitrogen | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial | Final | Reduction | | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) | (g/kg) | (g/kg) | (g/kg) | (%) |
| Control | 14.3 | 13.8 | 0.5 | 3.5 | 3.3 | 3.4 | -0.1 | - 3.0 |
| Cheese Whey | 18.7 | 15.4 | 3.3 | 17.7 | 3.5 | 3.4 | 0.1 | 2.9 |
| Used Cooking Oil | 14.5 | 12.9 | 1.6 | 11.0 | 3.4 | 3.5 | -0.1 | -2.9 |

ammonium nitrogen values in all mixtures were similar (3.3-3.5 g/kg DM), indicating insignificant changes (-2.9 to 2.9 %) in the concentration of ammonium nitrogen as a result of the composting process.

### 10.4.4 Total Carbohydrates

Table 10.15 shows the initial and final concentrations of total carbohydrates and the percent reduction for the different mixtures used in theses experiments. The initial total carbohydrates content of the control, cheese whey and oil mixtures were 775, 735.0 and 738.6 g/kg, respectively. The carbohydrates contents were reduced by 21.5, 24.2 and 31.7 % for control, cheese whey and oil experiments, respectively.

### 10.4.5 Crude Proteins

Table 10.15 shows the initial and final concentrations of crude proteins and the percent reduction for the different mixtures used in these experiments. The initial crude proteins content of the mixtures were 82.3, 109.9 and 80.6 g/kg for the control, cheese whey and oil experiments, respectively. The percent reductions of crude proteins were 12.4, 25.3 and 17.8 % for control, cheese whey and oil experiments, respectively.

### 10.4.6 Total Fat and Grease

The total initial and final fat and grease contents and the percent reduction for the mixtures used in these experiments (control, cheese whey and oil) are presented in Table 10.15. The mixture used in the control experiment had a low oil and grease content (14.7 g/kg). The addition of whey increased the oil and grease content of the mixture to 23.7 g/kg, and the mixture used in the oil experiment had the most oil and grease content (56.3 g/kg). The percent reductions of oil and grease were 64.6, 76.4 and 88.8 % for control, cheese whey and oil experiments, respectively.

Table 10.15. Total carbohydrates, crude proteins and total fat and grease changes during the cheese whey and used cooking oil study.

| Treatment | Total Carbohydrates | | | | Crude Proteins | | | | Total Fat and Grease | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Initial | Final | Reduction | | Initial | Final | Reduction | | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) | (g/kg) | (g/kg) | (g/kg) | (%) | (g/kg) | (g/kg) | (g/kg) | (%) |
| Control | 775.0 | 608.7 | 166.3 | 21.5 | 82.3 | 72.1 | 10.2 | 12.4 | 14.7 | 5.2 | 9.5 | 64.6 |
| Cheese Whey | 738.6 | 560.0 | 178.6 | 24.2 | 109.0 | 82.1 | 26.9 | 25.3 | 23.7 | 5.6 | 18.1 | 76.4 |
| Used Oil | 735.0 | 502.1 | 232.9 | 31.7 | 80.6 | 66.3 | 14.3 | 17.8 | 56.3 | 6.3 | 50 | 88.8 |

1- Total Carbohydrate =100- Proteins % - Fat % - Mc % - Ash %.
2- Protein Content = Organic Nitrogen X 6.25.

### 10.4.7 Temperature

The profiles of the average temperatures ($T_{ave}$) of the bioreactors are presented in Figure 10.4. The maximum temperatures and their peak times are presented in Table 10.16. The average maximum temperature in the control bioreactor and bioreactors containing cheese whey and oil reached 50.8, 63.4 and 63.3 °C after 27, 60, and 31 hours, respectively. Temperatures higher than 55 °C were observed only in the bioreactors containing cheese whey and used cooking oil, and were maintained for 14 and 17 hours in the bioreactor receiving cheese whey and used oil, respectively. Temperatures higher than 60 °C were also observed in these bioreactors and were maintained for 9 hours.

## 10.5 Heat Analysis Study

In a bioreactor with continuous mixing, heat energy is produced by compost as a result of microbial conversion of chemical energy into thermal energy as well as by friction between the composted material and the mixing shaft (Ashbolt and Line, 1982; Mote and Griffis, 1979; Whang and Meenaghan, 1980; Nakasaki et al., 1985 and Kubota and Nakasaki, 1991). A heat (energy) balance equation for the entire system (equation 9.3), which included all possible heat losses was given in section 9.

### 10.5.1 Heat of Mixing

During the 48 hours incubation period of the sterile mixture samples, there was no growth noticed on any of the plates of the three replicates indicating that the mixture was free of microorganisms. Therefore, it was safe to assume that the heat generated in the bioreactor was completely due to friction force created by the mixing process.

The power consumptions for the empty and filled bioreactors measured during the composting of sterilized tomato remains- wood shavings- municipal compost mixture (1: 1.5: 2.5) are shown in Table 10.17. The average power value of 5 readings taking while the mixing shaft operated in an empty bioreactor was 36 kJ/h (10 W), while the

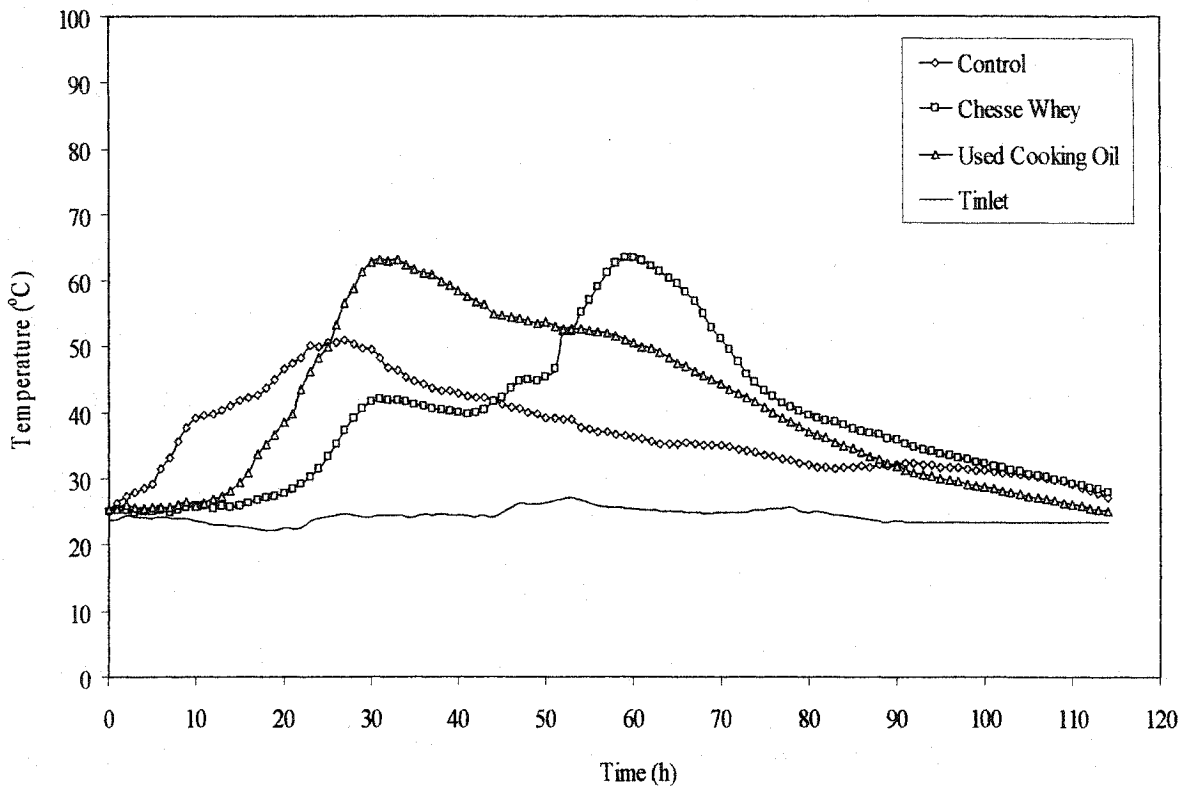



Figure 10.4. The temperature profile of the composting process of tomato remain-wood shaving mixture with cheese whey and used cooking oil.

Table 10.16. Maximum temperatures, time of peak and ranges of temperatures during the oil and cheese whey study.

| Treatment | Maximum Temperature | Time of Peak | Duration (h) of the Temperature ≥ | | |
|---|---|---|---|---|---|
| | (°C) | (h) | 50°C | 55°C | 60°C |
| Control | 50.8 | 27.0 | 5 | 0 | 0 |
| Cheese Whey | 63.4 | 60.0 | 19 | 14 | 9 |
| Used Oil | 63.3 | 31.0 | 36 | 17 | 9 |

1- Mixture consists of tomato remains and wood shavings mixed at a ratio of 1:1.5 by dry weight basis.

Table 10.17. Power consumption of the bioreactor.

| Reading | Empty Bioreator | | | Filled Bioreactor | | |
|---|---|---|---|---|---|---|
| | mA | V | W | mA | V | W |
| 1 | 387.15 | 25.83 | 10 | 389.11 | 28.27 | 11.0 |
| 2 | 362.10 | 27.62 | 10 | 445.89 | 24.67 | 11.0 |
| 3 | 404.86 | 24.70 | 10 | 424.22 | 25.93 | 11.0 |
| 4 | 362.10 | 27.62 | 10 | 386.40 | 25.88 | 10.0 |
| 5 | 403.23 | 24.80 | 10 | 359.45 | 27.82 | 10.0 |
| Average | 383.87 | 26.11 | 10 | 401.01 | 26.51 | 10.6 |

average power value of 5 readings taking while the mixing shaft operated in a filled bioreactor with the sterilized material was 38.16 kJ/h (10.6 W). Therefore, the energy required for mixing was 2.16 kJ/h (0.6 W).

The profiles of the average temperatures inside ($T_{average}$) and on the outside surface ($T_{surface}$) of the bioreactor are presented in Figure 10.5. The average bioreactors temperatures ($T_{average}$) of the sterilized compost increased with time due to heat generated by particle friction reaching the steady state (constant temperature) after 3 h, at which the heat generated by mixing was equivalent to the heat losses from the bioreactor. Initially, before reaching steady state, a portion of the heat generated by mixing was used to heat the compost material and the body of the bioreactor while the other portion was lost through the bioreactor body.

Since the experiment was run without aeration and sterilized material was used, the heat lost with the exhaust gas ($q_e$) and the metabolic heat production ($q_p$) can all be set to zero. At the steady state, heat accumulation within the material and the bioreactor body ($q_s$) is zero. Therefore, equation (10.3) can be rewritten as follows:

$$q_m = q_c + q_{pvc} + q_{plexi} \tag{10.1}$$

The overall heat transfer coefficients of the sidewalls ($U_{PVC}$ and $U_{Plexi}$) of the composting system can be calculated as follows (Cengel, 2003; and Holman, 1997):

$$U_{PVC} = \frac{1}{\left[\frac{1}{h_{si}} + \frac{X_{PVC}}{k_{PVC}} + \frac{X_{Styro}}{k_{Styro}} + \frac{1}{h_o}\right]} \tag{10.2}$$

$$U_{Plexi} = \frac{1}{\left[\frac{1}{h_{si}} + \frac{X_{Plexi}}{k_{Plexi}} + \frac{X_{Styro}}{k_{Styro}} + \frac{1}{h_o}\right]} \tag{10.3}$$

Where:

$X_{PVC}$ = the thickness of the PVC sidewall (m)

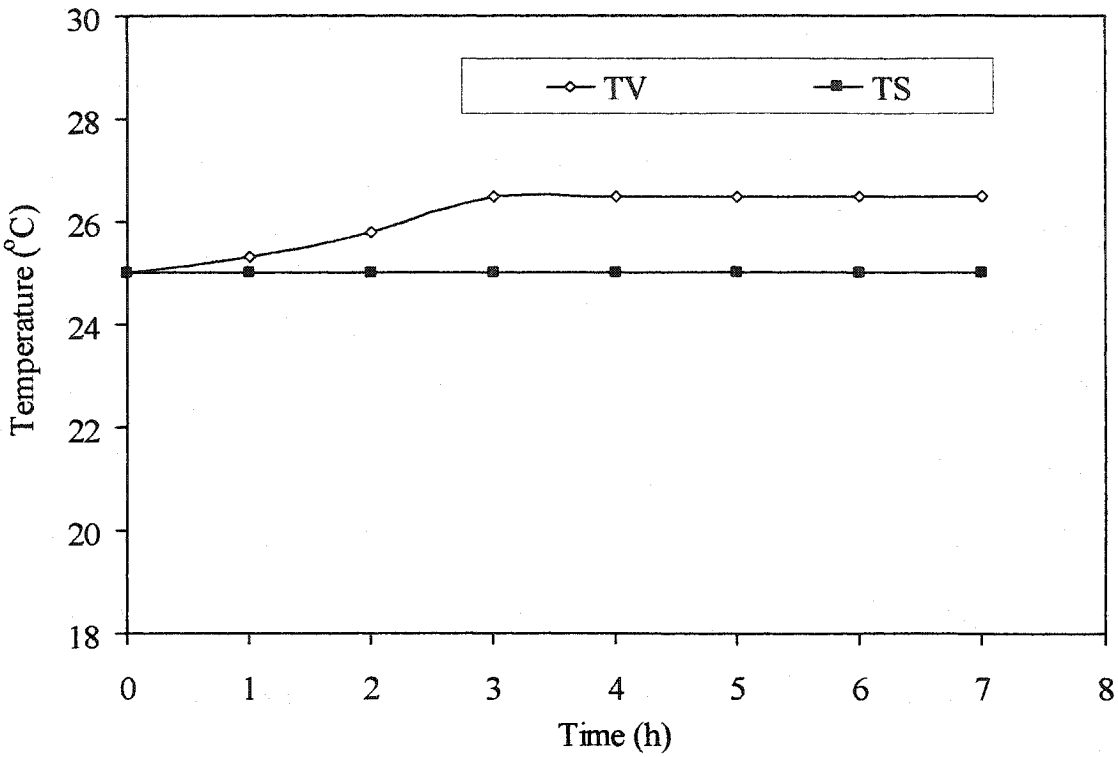



Figure 10.5. Recorded temperatures during the heat of mixing study.

$X_{Plexi}$ = the thickness of the Plexiglas sidewall (m)

$X_{Styro}$ = the thickness of the Styrofoam insulation (m)

$h_{si}$ = the convective heat transfer coefficient between the compost and the surface of the inside wall of the system (kJ/ $m^2$ h °K)

$h_o$ = the convective heat transfer coefficient between the out side surface of the system and the room (kJ/ $m^2$ h °K)

$k_{PVC}$ = the thermal conductivity of the PVC material (kJ/ m h °K)

$k_{Plexi}$ = the thermal conductivity of the Plexiglas material (kJ/ m h °K)

$K_{Styro}$ = the thermal conductivity of the Styrofoam material (kJ/ m h °K )

Since mixing provided homogenous distribution of temperature, the bioreactor inside surface temperature was assumed to be equal to the average temperature inside the bioreactor. Therefore, equations (10.2) and (10.3) can be rewritten as follows:

$$U_{PVC} = \frac{1}{\left[\frac{X_{PVC}}{k_{PVC}} + \frac{X_{Styro}}{k_{Styro}}\frac{1}{h_o}\right]} \tag{10.4}$$

$$U_{Plexi} = \frac{1}{\left[\frac{X_{Plexi}}{k_{Plexi}} + \frac{X_{Styro}}{k_{Styro}}\frac{1}{h_o}\right]} \tag{10.5}$$

The overall heat transfer coefficient of the cylinder ($U_c$), based on its outside area ($A_o$) can be calculated as follow (Cengel, 2003; and Holman, 1997):

$$U_c = \frac{1}{\left[\frac{A_{CO}}{A_{Ci}}\frac{1}{h_{Ti}} + A_{Co}\ln(\frac{r_o}{r_i})/(2\pi\, k_{PVC}L_c) + A_{Cins}\ln(\frac{r_{ins}}{r_o})/(2\,\pi\, k_{fiber}L_c) + \frac{1}{h_o}\right]} \tag{10.6}$$

Where:

$A_{Co}$ = the outside surface area of the cylinder ($m^2$)

$A_{Ci}$ = the inside surface area of the cylinder ($m^2$)

$A_{Cins}$ = the outside surface area of the insulation ($m^2$)

$h_{Ti}$ = the convective heat transfer coefficient between the compost and the inside surface of the cylinder ($kJ/m^2$ h °K)

$r_i$ = the inner radius of the cylinder (m)

$r_o$ = the outer radius of the cylinder (m)

$r_{ins}$ = the radius of the insulation material (m)

$L_c$ = the characteristic length of the cylinder (m)

Based on the assumption that the bioreactor inside surface temperature is equal to the average temperature inside the bioreactor, equation (10.6) can be rewritten as follows:

$$U_c = \frac{1}{\left[ A_{Co}\ln(\frac{r_o}{r_i})/(2\pi\ k_{PVC}L_c) + A_{Cins}\ln(\frac{r_{ins}}{r_o})/(2\ \pi\ k_{fiber}L_c) + \frac{1}{h_o} \right]} \qquad (10.7)$$

Equations (10.4), (10.5) and (10.7) were used to determine the overall heat transfer coefficients of the PVC side wall, the Plexiglas side wall and the cylindrical body of the bioreactor, respectively. Then, the conductive heat losses were calculated using equations (9. 13), (9. 14) and (9.15). Finally, the sum of all heat losses were set equal to the heat generated by the mixing shaft and was calculated using equation (10.1). The values of the constants used in these calculations are summarized in Table 10.18.

The heat production rate and the cumulative heat content of the sterilized tomato remains-wood shavings-municipal compost mixture are presented in Figure 10.6. The values of the various heat losses are shown in Table 10.19. The heat resulting from the mixing was 2.16 kJ/h. The heat lost through the bioreactor body was found to be 1.795 kJ/h. This is only 83.1 % of the energy required for mixing measured using a multimeter.

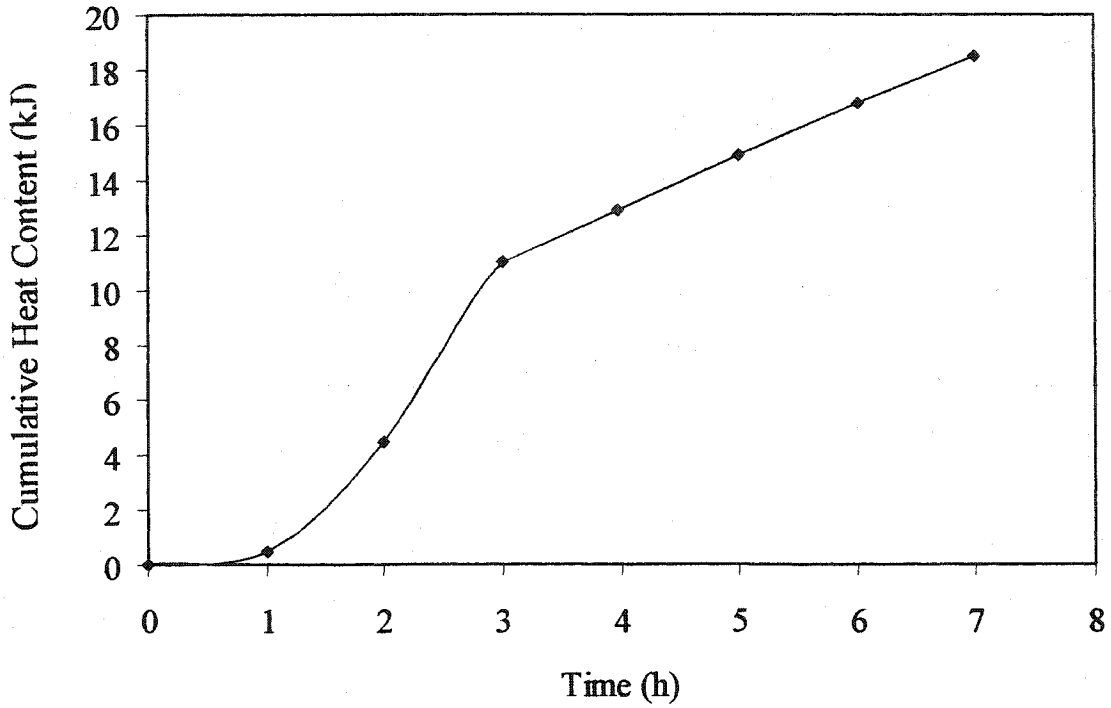
## 10.5.2 Bioreactor Heat Analysis

The overall heat transfer coefficients of the sidewalls and the cylindrical body ($U_{PVC}$, $U_{Plexi}$ and $U_C$) of the composting system can be calculated using equations 10.4, 10.5 and 10.7, respectively.

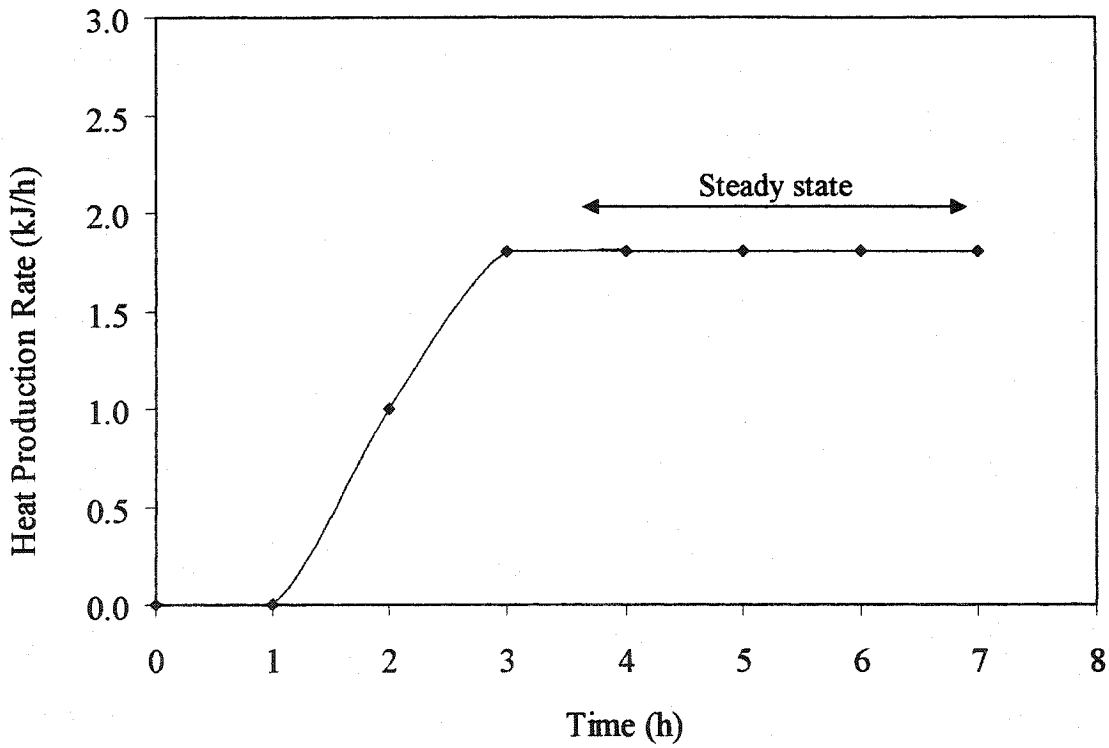
Table 10.18. Values of various parameters (Holman, 1997).

| Parameter | | Unit | Value |
|---|---|---|---|
| PVC cylinder | | | |
| | $r_i$ | m | 0.1015 |
| | $r_o$ | m | 0.1065 |
| | $k_{pvc}$ | kJ/h. m.°K | 0.3240 |
| | $L_C$ | m | 0.5200 |
| | $A_{Ti}$ | $m^2$ | 0.3320 |
| | $A_{To}$ | $m^2$ | 0.3480 |
| Fiberglass insulation | | | |
| | $k_{fiber}$ | kJ/h. m.°K | 0.1368 |
| | $r_{ins}$ | m | 0.1446 |
| | $A_{Tin}$ | $m^2$ | 0.4720 |
| PVC side wall | | | |
| | $r_i$ | m | 0.1015 |
| | Thickness | m | 0.0060 |
| Plexiglas side wall | | | |
| | $k_{plexi}$ | kJ/h. m.°K | 1.9440 |
| | $A_{PVC} = A_{Plexi}$ | $m^2$ | 0.0324 |
| Styrofoam insulation | | | |
| | $K_{styro}$ | kJ/h. m.°K | 0.1188 |
| | Thickness | m | 0.0380 |
| Aluminum cylinder | | | |
| | $M_{Alumi}$ | kg | 0.4950 |
| | $Cp_{Alumi}$ | kJ/kg. °K | 0.8960 |
| Mixing shaft | | | |
| | $M_{mixing_shaft}$ | kg | 1.1240 |
| | $Cp_{ss}$ | kJ/kg. °K | 0.4800 |
| Compost | | | |
| | $M_{compost}$ | kg | 3.5000 |
| | $Cp_{compost}$ | kJ/kg.°K | 0.8700 |

System volume = 0.017 $m^3$.




(a) Cumulative heat




(b) Heat Production Rate

Figure 10.6. Heat production by mixing.

Table 10.19. Calculated heat losses during the sterilized composting experiment.

| Energy Losses | Value | |
|---|---|---|
| | (kJ/h) | (%) |
| $q_c$ | 1.574 | 87.7 |
| $q_{pvc}$ | 0.108 | 6.0 |
| $q_{plexi}$ | 0.113 | 6.3 |
| $q_m$ | 1.795 | 100.0 |

$q_c$ = the heat loss through the main body of the cylinder.
$q_{pvc}$ = the heat loss through the PVC side wall.
$q_{plexi}$ = the heat loss through the Plexiglas side wall.
$q_m$ = the heat added by the mixing unit.

The amount of thermal energy in the exhaust gas leaving the system is equal to the latent and sensible heat gained as the air passes through the composting mass. The exhaust gas is considered to be a mixture of two independent perfect gases: dry air, and water vapor. Each component is assumed to obey the perfect gas law as follows (ASAE, 1999):

$$P_a V = m_a R_a T \qquad \text{for dry air} \qquad (10.8)$$

$$P_v V = m_v R_w T \qquad \text{for water vapor} \qquad (10.9)$$

Where:

$P_a$ = the partial pressure of the dry air ($N/m^2$)

$P_v$ = the partial pressure of the water vapor ($N/m^2$)

$V$ = the total volume of the gas mixture ($m^3$)

$m_a$ = the mass of dry air (kg)

$m_v$ = the mass of water vapor (kg)

$R_a$ = the gas constant (J/kg. °K)

$R_w$ = the water constant (J/kg. °K)

$T$ = the absolute temperature (°K)

Derived from the perfect gas law is the total energy, or enthalpy, of the mixture of perfect gases. The enthalpy of the exhaust gas equals the sum of the individual partial enthalpies of the mixture of dry air and water vapor and can be calculated as follows (ASAE, 1999):

$$h_m = h_a + w \times h_g \qquad (10.10)$$

Where:

$h_m$ = the specific enthalpy of the mixture (kJ /kg dry air)

$h_a$ = the specific enthalpy of dry air (kJ /kg dry air)

$w$ = the humidity ratio (kg water /kg dry air)

$h_g$ = the specific enthalpy for water vapor (kJ /kg water)

The humidity ratio (w) of the exhaust gas is defined as the ratio of the mass of water vapor to the mass of the dry air containing the water vapor, and can be determined

by the following equation (ASAE, 1999):

$$w = 0.622 * P_v / (P_{atm} - P_v) \quad (10.11)$$

Where:

$w$ = the humidity ratio (kg water /kg dry air)

$P_v$ = the partial pressure of water vapor (Pa)

$P_{atm}$ = the atmospheric pressure (Pa).

The partial pressure of water vapor can be defined by the relative humidity (RH) and the saturation vapor pressure ($P_s$) as follows (ASAE, 1999):

$$RH = P_v / P_s \quad (10.12)$$

And

$$\ln (P_s/R) = [(a+bT+cT^2+dT^3+eT^4)/(fT-gT^2)] \quad (10.13)$$

Where:

$R = 22105649.25$

$a = -27405.526$

$b = 97.5413$

$c = -0.146244$

$d = 0.12558X10^{-3}$

$e = -0.48502X10^{-7}$

$f = 4.34903$

$g = 0.39381X10^{-2}$

The temperature, T, is measured in Kelvin. In the temperature range 263.16 to 323.16 ° k, the specific enthalpies of the dry air and the saturated water vapor can be approximated with negligible error to (Cengel and Boles, 1989):

$$h_a \sim T \quad (10.14)$$

$$h_g \sim 2501 + 1.80\ T \quad (10.15)$$

Where:

$T$ = the dry bulb temperature of the mixture (°C).

The enthalpy for the exhaust gas can, therefore, be calculated by substituting equations (10.32) and (10.33) in equation (10.28) as follows:

$$h_m = T + w(2501 + 1.80\ T) \quad (10.16)$$

Due to the high rate of evaporative cooling during the composting process, the exhaust air is assumed to be 100% saturated. Therefore, the saturation pressure ($P_s$) equals the partial pressure of the water vapor ($P_v$) and the relative humidity (RH) = 1.0. Also, the saturation pressure ($P_s$) of the exhaust air was calculated based on the temperature directly inside the system, while the humidity ratio (w) of the inlet air calculation was based on the partial pressure of the water vapor and the relative humidity of the incoming air.

Equations (10.4), (10.5) and (10.7) were used to determine the overall heat transfer coefficients of the PVC-side wall, the Plexiglas-side wall and the main body of the bioreactor (cylinder), respectively. Then, the conductive heat losses were calculated using equations (9.13), (9.14) and (9.15). The energy stored within the composted material, that is responsible for raising the average temperature, was calculated using equation (9.4). The heat loss due to aeration (latent and sensible) was calculated using equation (9.16). Finally, the sum of all heat losses minus the heat produced by mixing shaft were set equal to the heat produced due to microbial metabolic activities and was calculated using equation (9.3). The result of the final calculations showed that the individual rate of heat produced varied significantly during the composting process (Figure 10.7). Table 10.20 shows the accumulative heat losses and production. Table 10.21 shows the heat losses at the peak temperature.

## 10.6 Continuous Addition of Used Cooking Oil Study

After the heat balance was performed on the data from used oil experiment, the rate of total heat losses at the peak temperature was determined to be 51.14 kJ/h (Table 10.21). Assuming 100% energy release from used cooking oil (36 kJ/mL), 1.46 mL/h (18-mL every 12 h) must be added to compensate for the heat losses from the system. Three experiments were conducted to investigate the influence of oil addition every 12 h staring at the peak temperature (at 31 h) on maintaining high thermophilic temperature (> 55 °C) for three days: 18-ml (required), 9-ml (50 % of the required) and 36-ml (double the required).

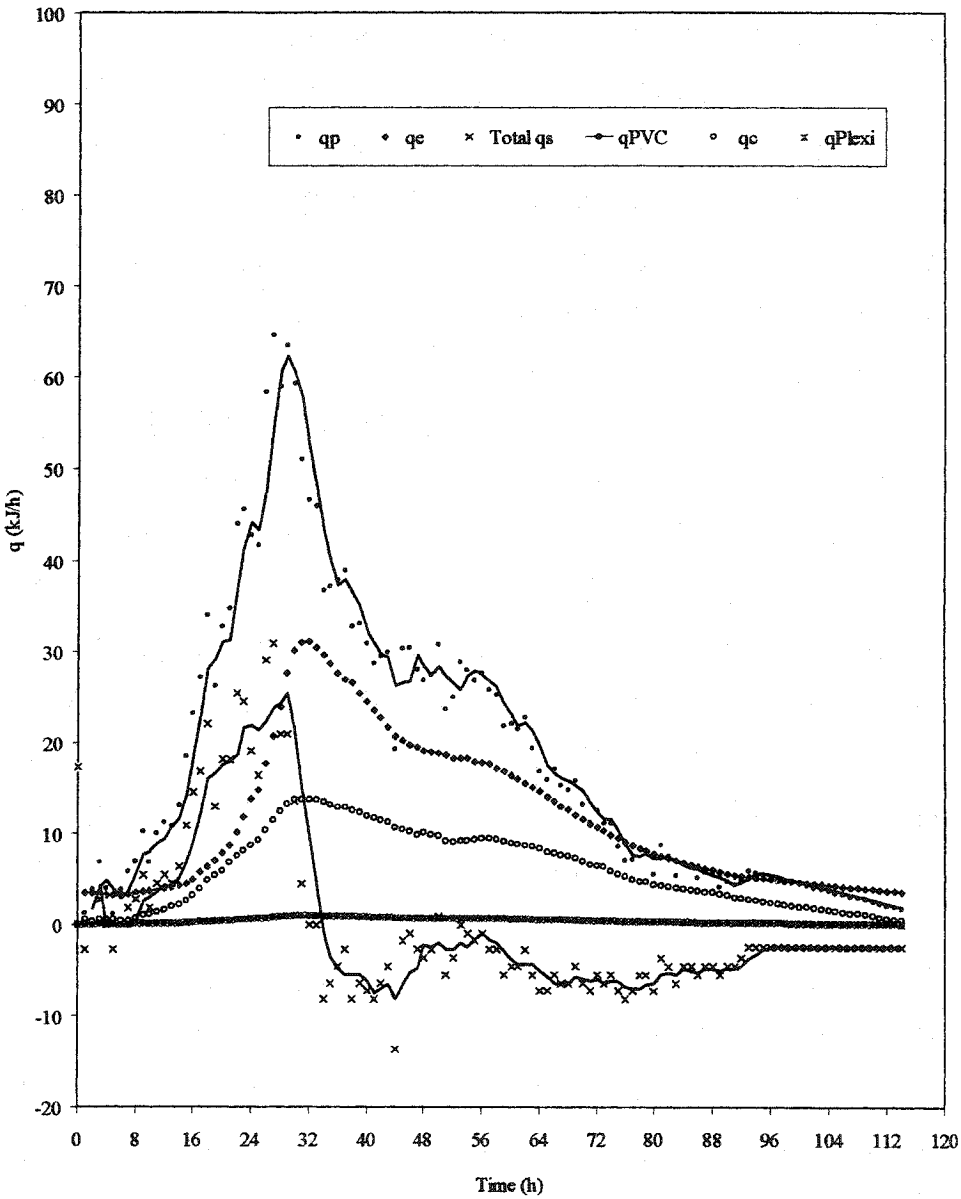



Figure 10.7. Calculated heat loss rates during the heat analysis study.

Table 10.20. Calculated cumulative heat generated and heat losses during heat balance study (114 h).

| Energy | Total Heat | | Average Heat Rate |
|---|---|---|---|
| | (kJ) | (%) | (kJ/h) |
| $q_c$ | 683.6 | 32.05 | 5.94 |
| $q_{pvc}$ | 46.7 | 2.18 | 0.41 |
| $q_{plexi}$ | 48.9 | 2.28 | 0.43 |
| $q_e$ | 1334.0 | 62.60 | 11.60 |
| $q_s$ | 19.1 | 0.90 | 0.17 |
| $q_m$ | 205.2 | 9.62 | 1.78 |
| $q_p$ | 1927.1 | 90.38 | 16.76 |
| Total heat produced/lost | 2132.3 | 100.00 | 18.54 |

% of the total heat produced/lost

$q_c$ = the heat loss through the main body.

$q_{pvc}$ = the heat loss through the pvc side wall.

$q_{plexi}$ = the heat loss through the plexiglas side wall.

$q_e$ = the heat loss through the exhaust gas.

$q_s$ = the heat gained by the compost and system materials.

$q_p$ = the metabolic heat produced.

$q_m$ = the heat generated due to mixing.

Table 10.21. Calculated heat generated and heat losses at the peak during heat balance study[+].

| Energy Losses | Heat Production Rate (kJ/h) |
|---|---|
| $q_c$ | 13.67 |
| $q_{pvc}$ | 0.93 |
| $q_{plexi}$ | 0.98 |
| $q_e$ | 31.02 |
| $q_s$ | 4.54 |
| Total heat losses | 51.14 |

[+] At the start of the steady state.

Total heat losses = $q_c + q_{pvc} + q_{plexi} + q_e + q_s$

$q_c$ = the heat loss through the main body.

$q_{pvc}$ = the heat loss through the pvc side wall.

$q_{plexi}$ = the heat loss through the plexiglas side wall.

$q_e$ = the heat loss through the exhaust gas.

$q_s$ = the heat gained by the compost and system materials.

### 10.6.1 Moisture

The initial moisture contents of all mixtures were adjusted to approximately 60% (61.5 ± 0.05 %). The final moisture content was approximately 57.0 ± 0.08 % as shown in Table 10.22. Little changes were observed in the moisture content of the material. The changes in moisture content varied from 1.6 to 8.9 %.

### 10.6.2 Volatile Solids

The volatile solids results are presented in Table 10.23. The initial volatile solids contents for all mixture were 887 g VS/kg DM (all mixtures contained same amounts of tomato, wood shavings and municipal solid compost). The percent reductions in the volatile solids were 2.8, 2.6 and 2.1 % for the mixture receiving 9, 18 and 36 mL used cooking oil, respectively.

### 10.6.3 Total Kjeldahl Nitrogen and Ammonium Nitrogen

Table 10.24 shows the initial and final concentrations of TKN and ammonium nitrogen as well as the percent reductions. The initial kjeldahl nitrogen content (TKN) of the mixtures was 14.8 g/kg DM. The percent reductions of the TKN were 57.1, 50.7 and 39.5 % for the mixture receiving 9, 18 and 36 mL used cooking oil, respectively. Initial ammonium nitrogen was 3.2 g/kg DM and decreased to 1.8, 1.9 and 1.5 g/kg DM for the mixture receiving 9, 18 and 36 mL used cooking oil, respectively.

### 10.6.4 Total Fat and Grease

The initial and final fat and grease contents for the mixtures used in these sets of experiments as well as the percent reductions are presented in Table 10.25. Initial total fats and grease contents were 33.0, 122.8 and 201.2 g/kg DM for the mixture receiving 9, 18 and 36mL used cooking oil, respectively. The percent reductions oil and grease were

Table 10.22. Moisture content changes during the continuous addition of used cooking oil study.

| Treatment | Moisture Content (%) | | |
|---|---|---|---|
| | Initial | Final | Change |
| Addition of 9-ml | 61.5 | 59.9 | 1.6 |
| Addition of 18-ml | 61.6 | 58.4 | 3.2 |
| Addition of 36-ml | 61.5 | 52.6 | 8.9 |
| Average | 61.5 | 57.0 | 4.5 |

Table 10.23. Volatile solids changes during the continuous addition of used cooking oil study.

| Treatment | Volatile Solids[1] | | | |
|---|---|---|---|---|
| | Initial | Final | Reduction | |
| | (g /kg) | (g /kg) | (g/kg) | (%) |
| Addition of 9-ml | 887 | 862 | 25 | 2.8 |
| Addition of 18-ml | 887 | 864 | 23 | 2.6 |
| Addition of 36-ml | 887 | 868 | 19 | 2.1 |

1- Calculated based on the dry matter basis.

Table 10.24. Total kjeldahl nitrogen and ammonium nitrogen during the continuous addition of used cooking oil study.

| Treatment | Total Kjeldahl Nitrogen | | | | Ammonium Nitrogen | | | |
|---|---|---|---|---|---|---|---|---|
| | Initial | Final | Reduction | | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) | (g/kg) | (g/kg) | (g/kg) | (%) |
| Addition of 9-ml | 14.8 | 6.5 | 8.3 | 56.1 | 3.2 | 1.8 | 1.4 | 43.8 |
| Addition of 18-ml | 14.8 | 7.3 | 7.5 | 50.7 | 3.2 | 1.9 | 1.3 | 40.6 |
| Addition of 36-ml | 14.8 | 8.9 | 5.9 | 39.5 | 3.2 | 1.5 | 1.7 | 53.1 |

Table 10.25. Total fat and grease changes during the continuous addition of used cooking oil study.

| Treatment | Total Fat and Grease | | | |
|---|---|---|---|---|
| | Initial | Final | Reduction | |
| | (g/kg) | (g/kg) | (g/kg) | (%) |
| Addition of 9-ml | 33.0 | 8.7 | 24.3 | 73.6 |
| Addition of 18-ml | 122.8 | 14.1 | 108.7 | 88.5 |
| Addition of 36-ml | 201.2 | 36.7 | 164.5 | 81.8 |

1- Mixture consists of tomato remains (leaves, stems and fruits) and wood shavings (1:1.5 by dry weight).

73.6, 88.5 and 81.8 % for the mixture receiving 9, 18 and 36 mL used cooking oil, respectively.

### 10.6.5 Temperature

The profiles of the average temperatures ($T_{ave}$) of the bioreactors are presented in Figure 10.8. The maximum temperatures and their peak times are presented in Table 10.26. The average temperature in the bioreactor receiving 9, 18 and 36 mL used cooking oil reached 62.5, 63.6 and 66.0 ˚C after 47, 34 and 47 hours, respectively. Temperatures higher than 55˚C were observed in all bioreactors, and were maintained for 37, 40 and 94 hours in the bioreactors receiving 9, 18 and 36 mL used cooking oil, respectively. Temperatures higher than 60˚C were also recorded in all bioreactors and were maintained for 8, 27 and 52 hours in the bioreactors receiving 9, 18 and 36 mL used cooking oil, respectively.

## 10.7 Virus Study

### 10.7.1 Tomato Infection Process

*Tobacco mosaic virus* is transmitted principally by mechanical inoculation. Virus has no true vectors, although there have been reports of incidental transmission by chewing insects, most probably by mechanical means (Lojek and Orlob, 1972). Two batches (different varieties) of tomato plants were inoculated in order to increase the inoculum size, so that enough material would be available to determine the fate of TMV during the thermophilic composting process.

10.7.1.1 First Tomato Batch. The first batch of tomato plants (Golden Boy Variety at 4 weeks old) started to develop mosaic-like symptoms a week after inoculation. The symptoms developed only on new leaves. Mosaic is characterized by intermingled patches of dark and light green color on the leaves of infected tomato plant (AVRDC, 2004). The symptoms in tomato plants vary greatly in intensity depending upon the variety, virus strain, time of infection, light intensity, and temperature (Zilter and Provvidenti, 1984). Samples of the newly developed leaves were, therefore, collected and

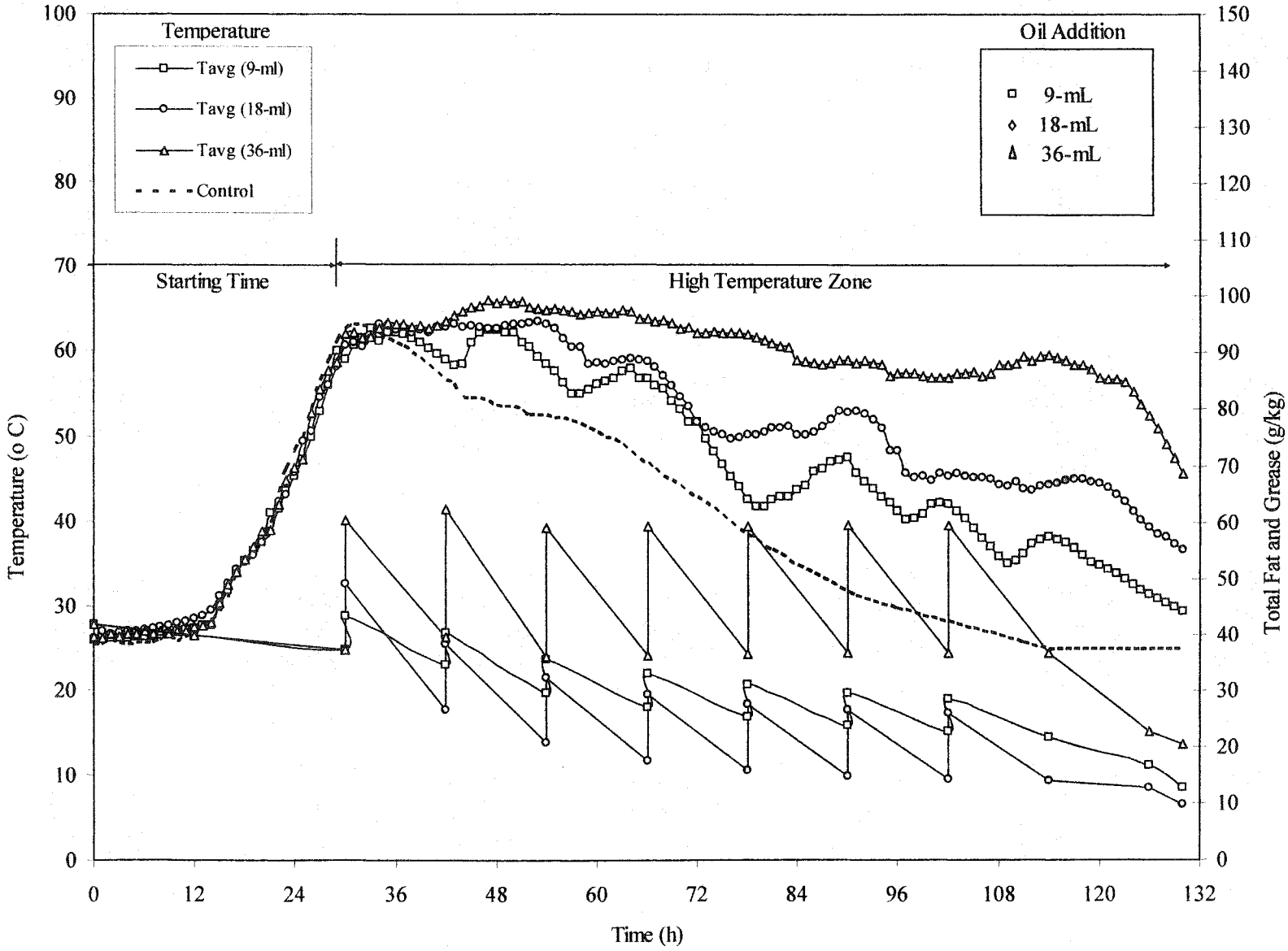



Figure 10.8. The temperature profile during the composting process of tomato remain-wood shaving-mixture and the addition of 9, 18 and 36-ml/12 h used cooking oil.

Table 10.26. Maximum temperatures, time of peak and duration during the continuous addition of used cooking oil study.

| Treatment | Maximum Temperature | Time of Peak | Duration (h) of the Temperature ≥ | | | | | |
|---|---|---|---|---|---|---|---|---|
| | (°C) | (h) | 35°C | 40°C | 45°C | 50°C | 55°C | 60°C |
| Addition of 9-ml | 62.5 | 47 | 99 | 81 | 67 | 45 | 37 | 8 |
| Addition of 18-ml | 63.6 | 34 | 112 | 103 | 82 | 67 | 40 | 27 |
| Addition of 36-ml | 66.0 | 47 | 114 | 110 | 104 | 99 | 94 | 52 |

tested for TMV using ELISA test a long with samples of the original stock of inoculum (Figure 10.9). The original inoculum showed positive results for the TMV, whereas tomato plants showed negative results for the TMV. Weekly observations and testing continued for 4 weeks after inoculation. Although symptoms of infection were visible and the health of the plants deteriorated rapidly (most of the plants died as shown in Figure 10.10), the test was still giving negative results for the TMV.

10.7.1.2 Second Tomato Batch. The second batch of tomato plants (Roma, Red Robin and Scotia) started to develop the TMV symptoms after 7-10 days. Samples of newly developed leaves of the inoculated tomato plants were tested for TMV infection along with the infected tomato and tobacco leaves received from Potato Research Center (AAFC, Fredericton, New Brunswick) using ELISA kit. The results shown in Figure 10.11 indicated that all sample were infected with TMV.

### 10.7.2 Temperature

The average temperatures profiles of TMV experiments are presented in Figure 10.12. During all experiments, the temperature increase gradually reaching a peak of 63.3 °C after 31 hours of operation. Thermophilic temperatures of 61.3 °C ± 0.92 %, 63.2 °C ± 0.96 %, 64.5 °C ± 2.0 %, 64.8 °C ± 1.9 %, 64.9 °C ± 1.7 % and 64.9 °C ± 1.7 % were maintained in the first, second, third, fourth, fifth and sixth bioreactors for 24, 48, 72, 96, 120 and 144 hours, respectively.

### 10.7.3 Local Lesion Bioassay

The sachets of TMV infected material were retrieved from the bioreactors on a pre-determined time (24, 48, 72, 96, 120 and 144 hours after the peak temperature). Bioassay was performed on a susceptible host to check the infectious ability of the TMV. The bioassay showed an initial concentration of 150 local lesions/leaf (LL/L), which was reduced to 35, 12, 2, 0, 0 and 0 LL/L after 24, 48, 72, 96, 120 and 144 hours of the thermophilic treatment at a temperature above 61.3, 63.2, 64.5, 64.8, 64.9 and 64.9 °C, respectively (Figure 10.13). TMV completely lost its ability to infect the leaf of the host after 4 days of thermophilic composting.

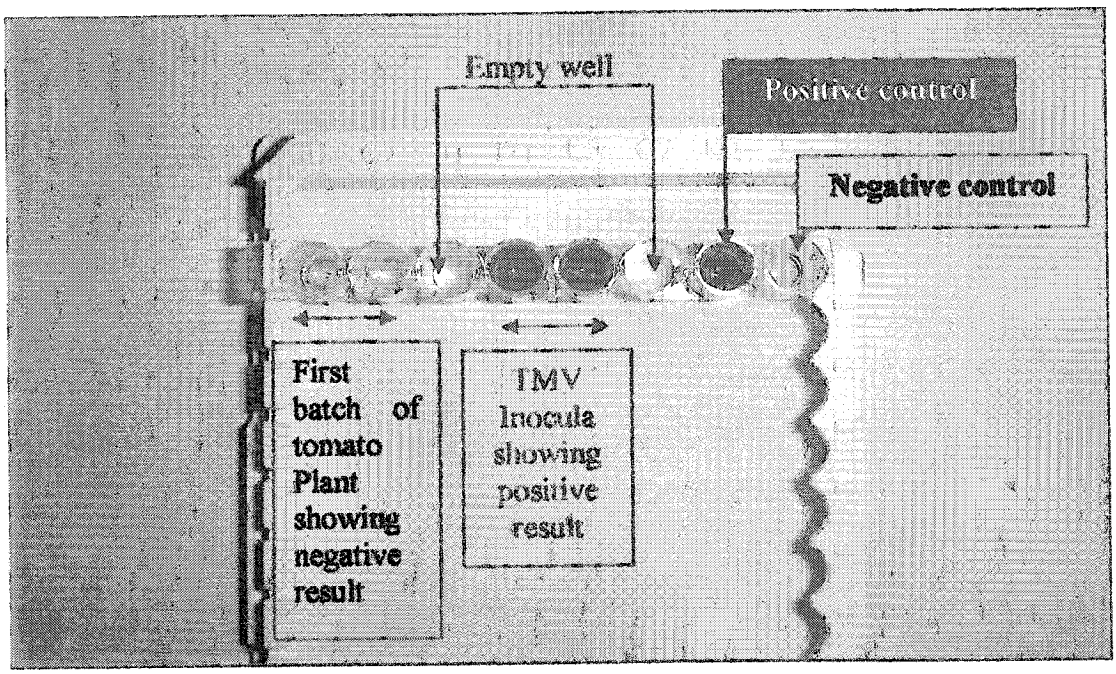



Figure 10.9. ELISA test results of the first tomato batch and stock inoculum of TMV.

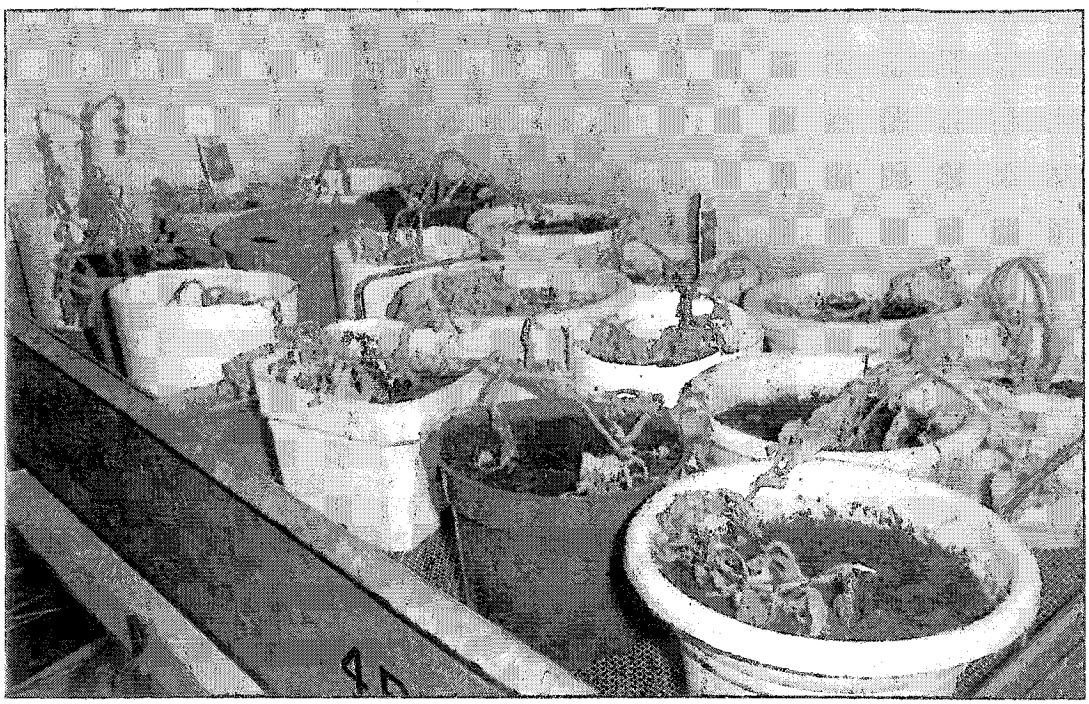


Figure 10.10. Most of the TMV inoculated tomato plants of the first batch died.

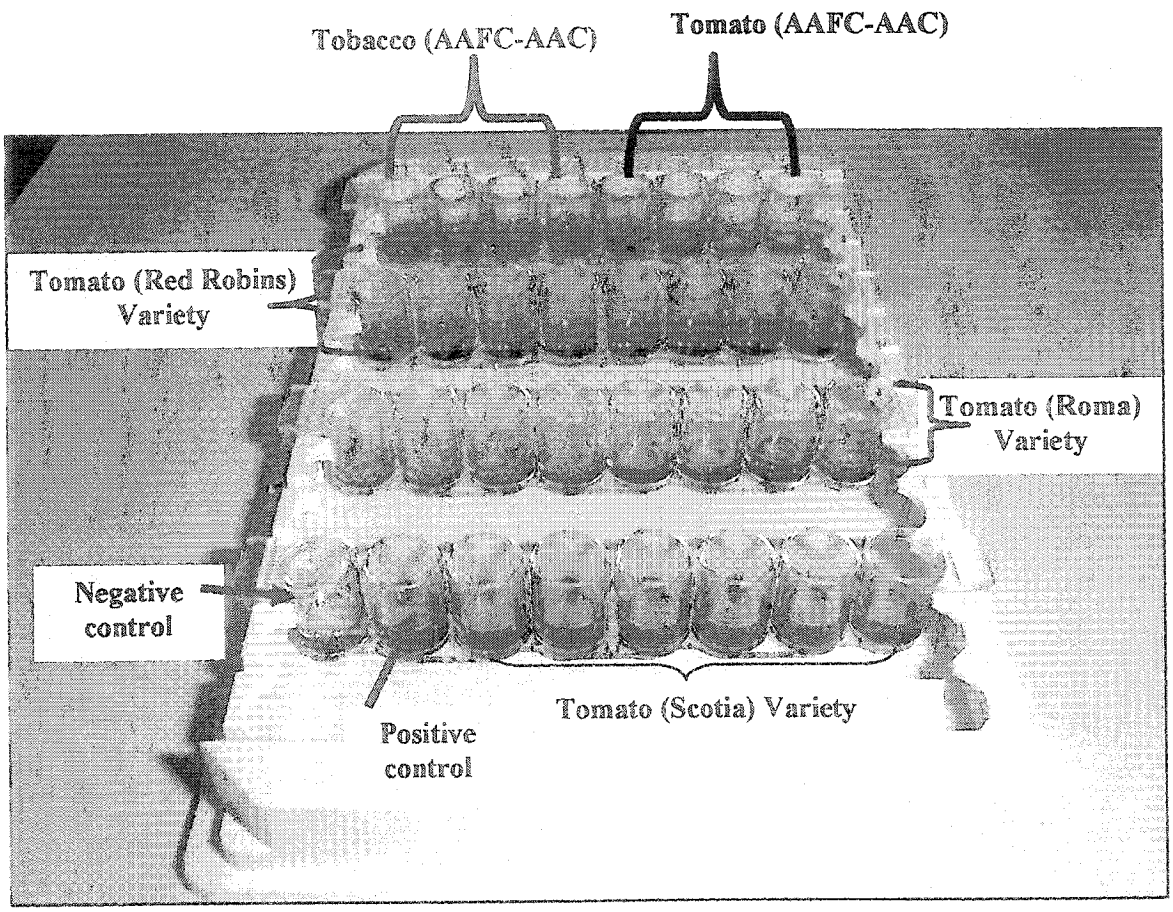



Figure 10.11. ELISA test results of the second tomato batch, controls and AAFC-AAC tomato and tobacco.

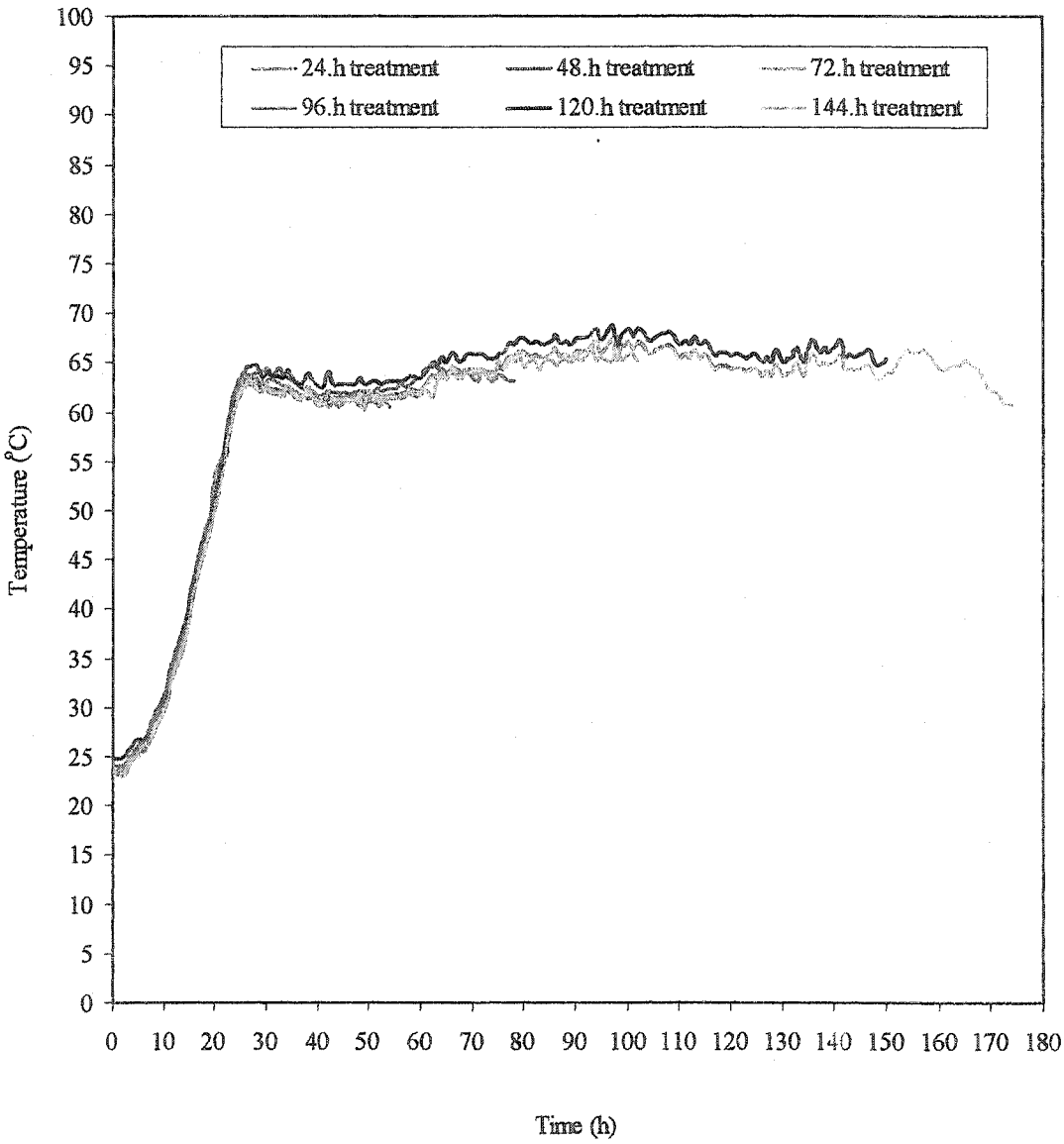



Figure 10.12. Temperature profile of the TMV composting experiments.

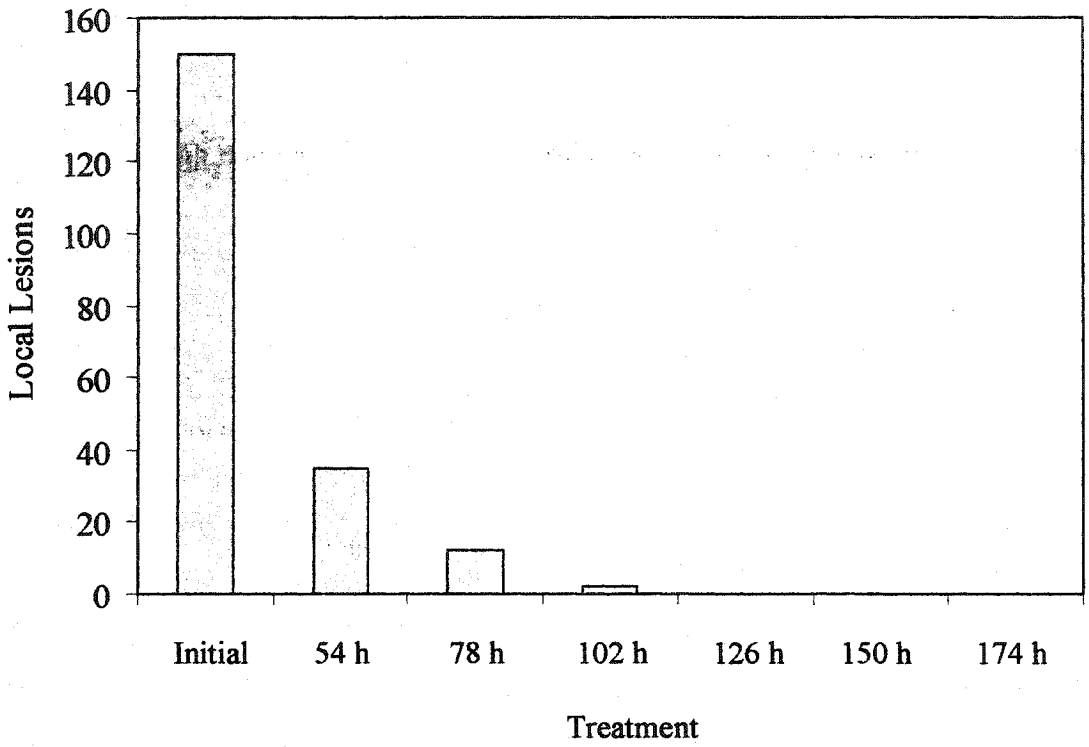



Figure 10.13. Effect of the duration of thermophilic composting on TMV local lesions count.

## 10.8 Mold Study

### 10.8.1 Temperature

The average temperatures profiles of the three experiments are presented in Figure 10.14. Average bioreactors temperatures similarly increased gradually reaching the peak of 63.3 °C after 31 hours of operation during all experiments. Average thermophilic temperatures of 63.9 ± 1.8°C, 63.5 ± 1.1 °C and 62.6 ± 1.5 °C were maintained in the first, second and third bioreactors for 24, 48 and 72 hours, respectively, during the three composting experiments.

### 10.8.2 ELISA Assay

The retrieved samples were immediately tested for the presence of *Botrytis cinerea* according to the ELISA test procedure. The variations in absorbance values ($O.D_{540nm}$) between samples on the same plate were 0.014 ± 0.12 %. Using the developed standard curve, the absorbance readings were converted into antigen units (AgU), which are equivalent to µg dried mycelium / mL of buffer (PBS). The final values are presented as µg dried mycelium per gram of compost mixture. The concentration of *Botrytis cinerea* in the compost samples obtained after 24, 48 and 72 hours of thermophilic composting are shown in Figure 10.15. The initial quantity of dried mycelium of 14.6 µg/g of compost was reduced to 12.9, 8.8 and 2.4 µg dried mycelium /g of mixture after 54, 78 and 102 hours (24, 48 and 72 hours of thermophilic composting), respectively. This amounted to reductions of 11.6, 39.9 and 83.4 % after 24 hours (at 63.9 ± 1.8°C), 48 hours (at 63.5 ± 1.1°C) and 72 hours (at 62.6 ± 1.5 °C), respectively.

### 10.8.3 Plating Assay

Due to the substantial reduction achieved from the ELISA assay and the fact that ELISA assay can not distinguish between viable and dead cells (Christensen et al., 2001, and Chitarra and Van den Bulk, 2003), plating assay was necessary to verify the result

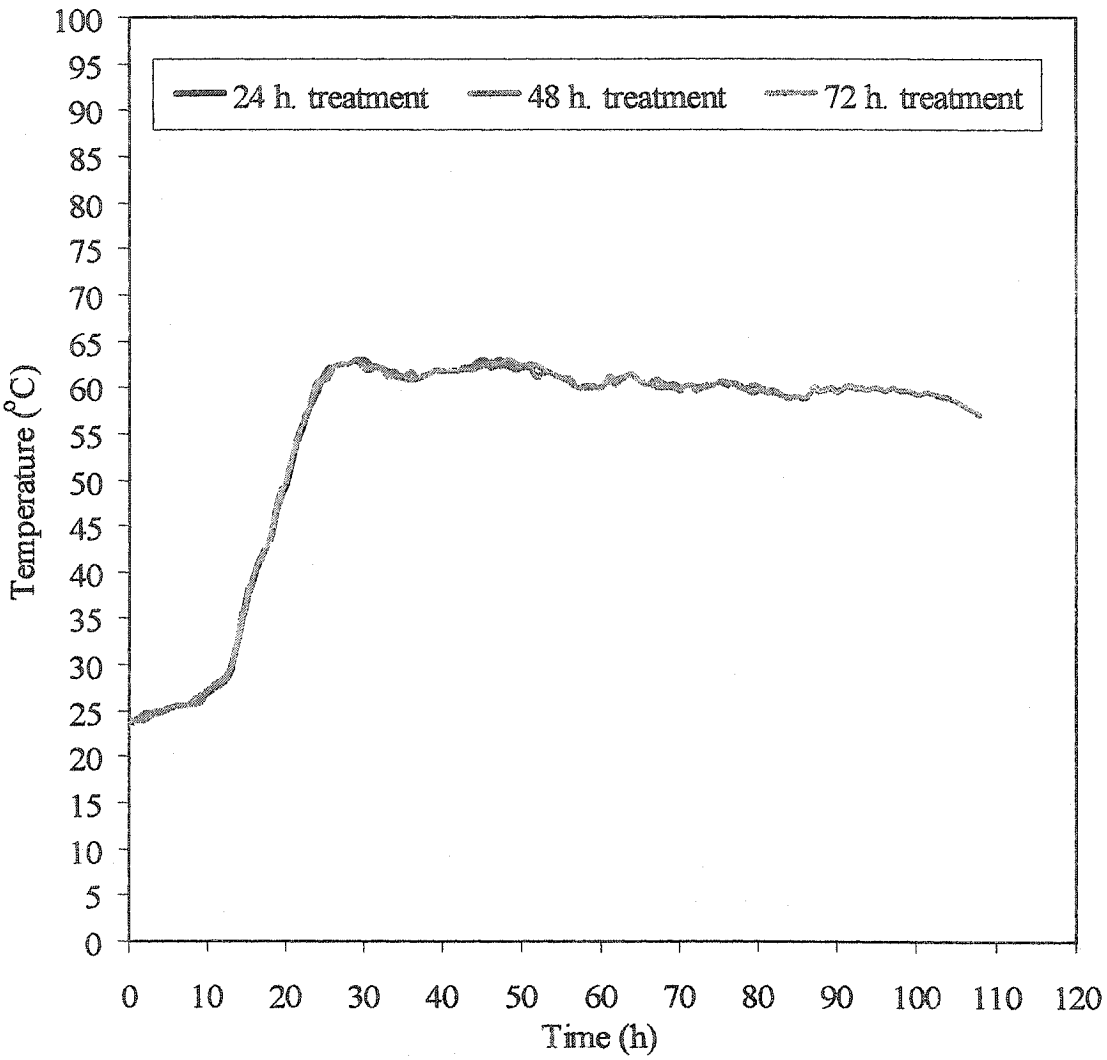



Figure 10.14. Temperatures profiles during the survival experiment of *Botrytis cinerea*.

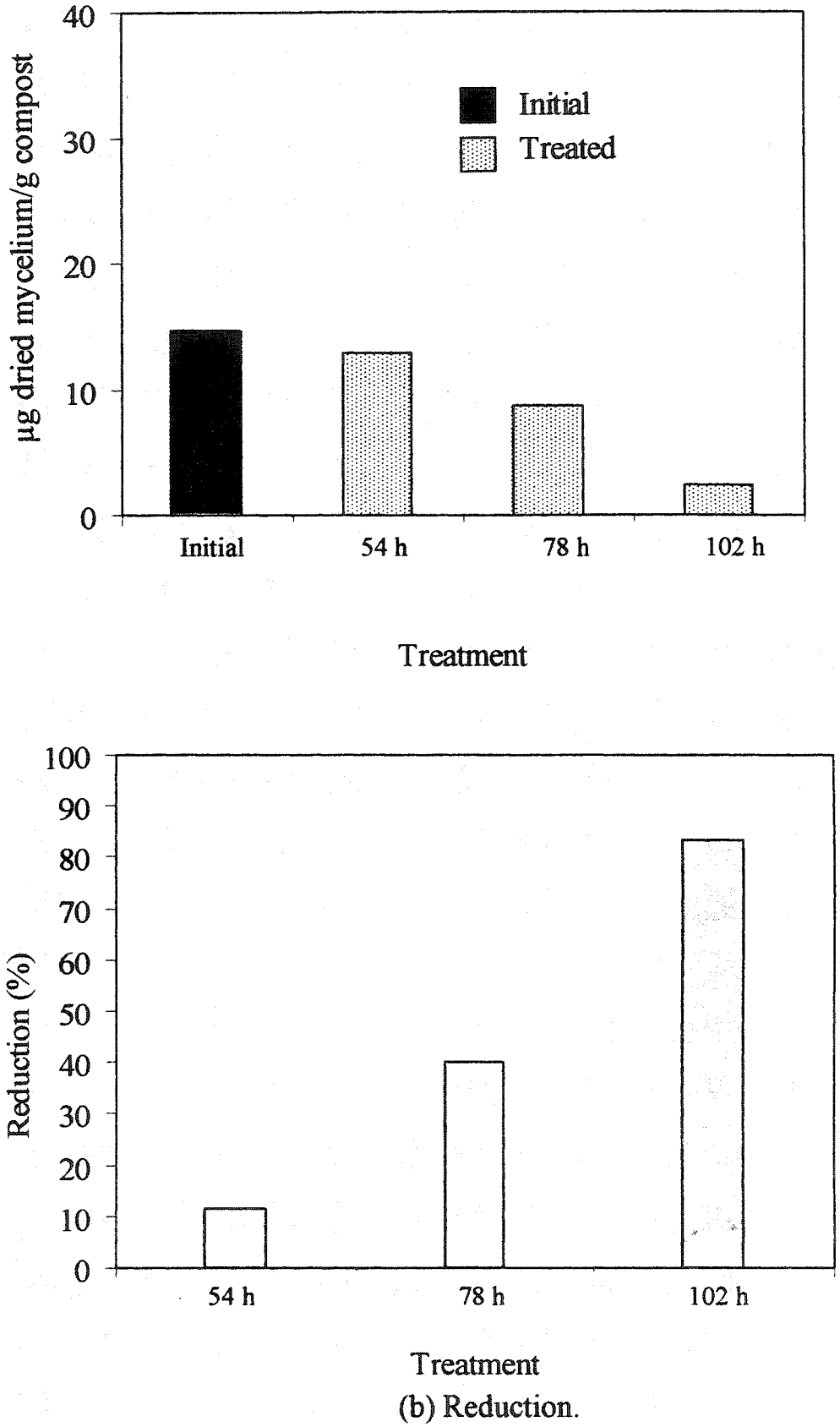



Figure 10.15. Effect of the duration of thermophilic stage on the survival of *Botrytis cinerea*.

of the ELISA test and determine the time at which *Botrytis cinerea* was inactivated. The pure culture of *Botrytis cinerea* (1/10000) is shown in Figures 10.16a. The developed gray colonies of *Botrytis cinerea* were circular filamentous in shape with raised elevation. The microscopic observation (Figure 10.16b) showed the gray mycelium of *Botrytis cinerea*. The condiophore is long and branched with rounded apical cells bearing grapelike clusters (Agrios, 1988; and Willetts, 1997).

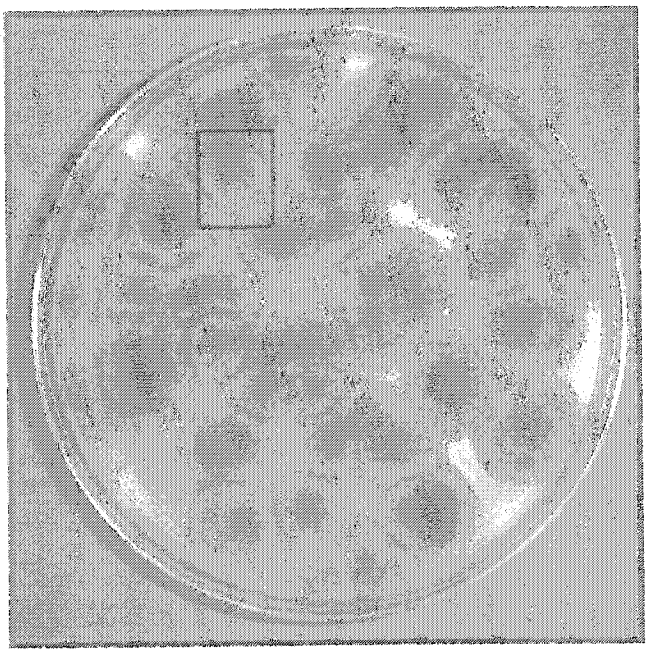
Plating of initial mixture (1/10000) after 48 hours at 16 °C showed an intensive growth of a mixture of psychrophilic fungi and bacteria in addition to *Botrytis cinerea* (Figure 10.17).

The plates of the retrieved samples were examined carefully for the existence of *Botrytis cinerea*. Some growth of *Botrytis cinerea* was noticed in samples treated for 24 h at thermophilic temperature (63.9 ± 1.8 °C). The grape-like clusters of spores were observed under the microscope (Figure 10.18). However, complete disappearance of *Botrytis cinerea* was noticed in the samples treated for 48 and 72 h at thermophilic temperatures (63.5 °C±1.1 and 62.6 °C±1.5 %, respectively). Bacteria dominated this period as clearly shown Figure 10.18b, 10.19b and 10.20b. Some fungi colonies appeared until the second thermophilic day treatment. Composting microorganisms were limited to bacteria after the second day as shown in Figure 10.20.

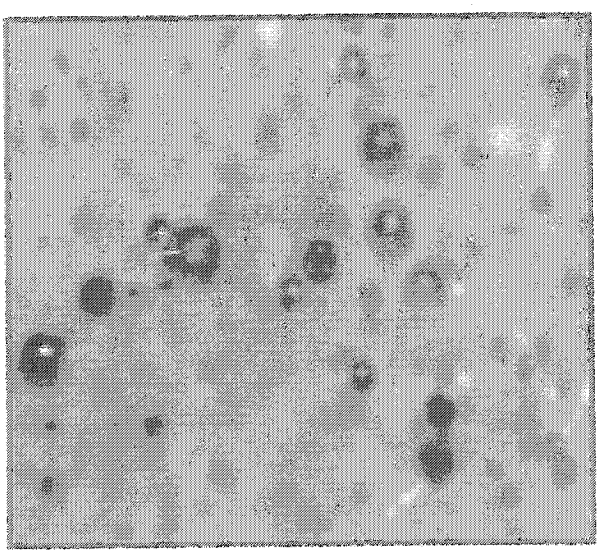
## 10.9 Degradation of Pirimiphos-methyl Study

### 10.9.1 Temperature

The average temperatures profiles of the three pesticide experiments are presented in Figure 10.21. The average temperature increased gradually reaching its peak after 30 hours of operation. Thermophilic temperatures of 63.10 ± 1.44 °C , 63.30 ± 1.61°C and 64.29 ± 1.59 °C were maintained for 24, 48 and 72 hours in the first, second and third bioreactors, respectively. When the addition of used cooking oil ceased, the temperature started to decline reaching mesophilic range (< 40 °C) within a day and continued to declined reaching room temperature after a week. The pesticide contaminated composted materials were kept at room temperature (25 °C) for another additional week.

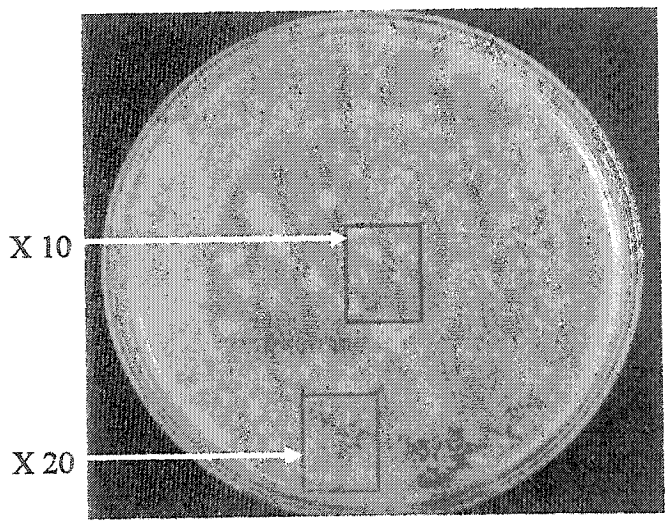


(a) Colonies after 48 h at 16 °C.

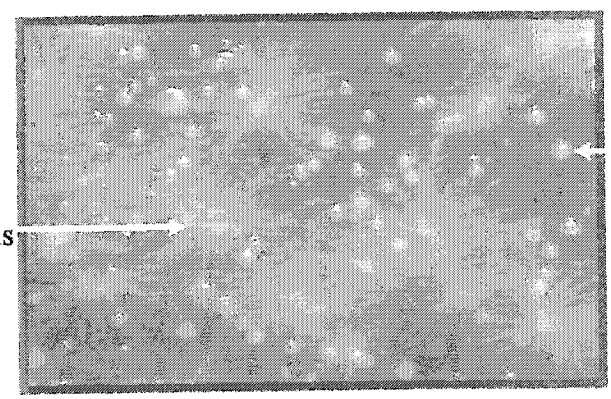


(b) Grape-like clusters of spores (x40).

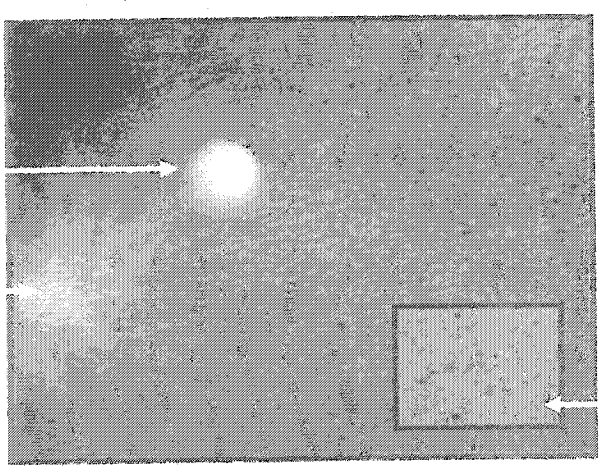
Figure 10.16. Pure culture of *Botrytis cinerea* before composting.




(a) Mixture of fungi and bacteria colonies after 48 h at 16 °C.

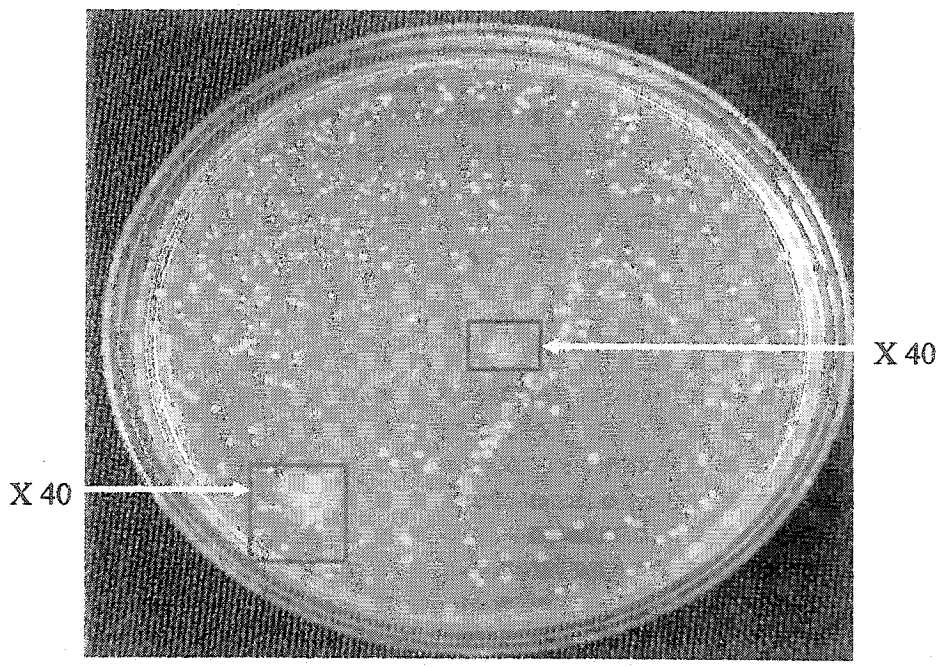



(b) Bacteria and fungi (10x)

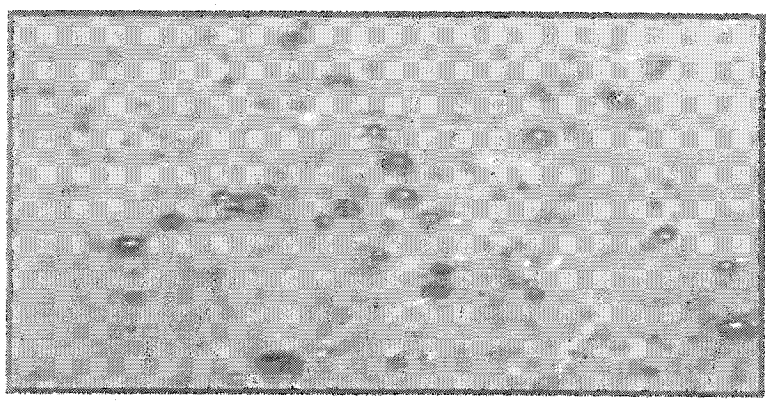



( c) Bacteria and fungi (x20)

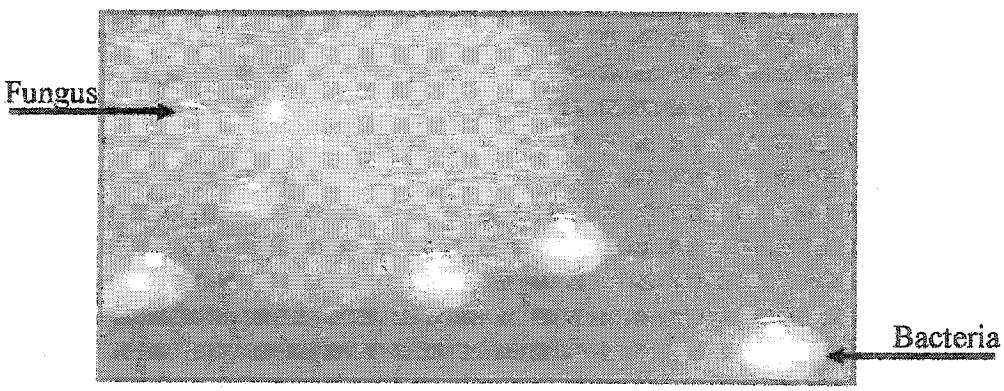
Figure 10.17. Microbial population found in the initial mixture used in the mold study.




(a) Colonies after 48 h at 16 °C.

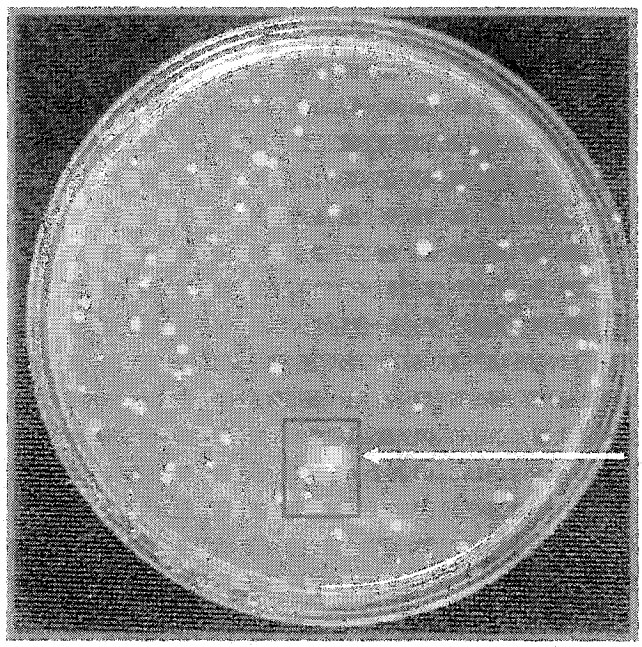


(b) Grape-like clusters of *Botrytis cinerea* (x40).

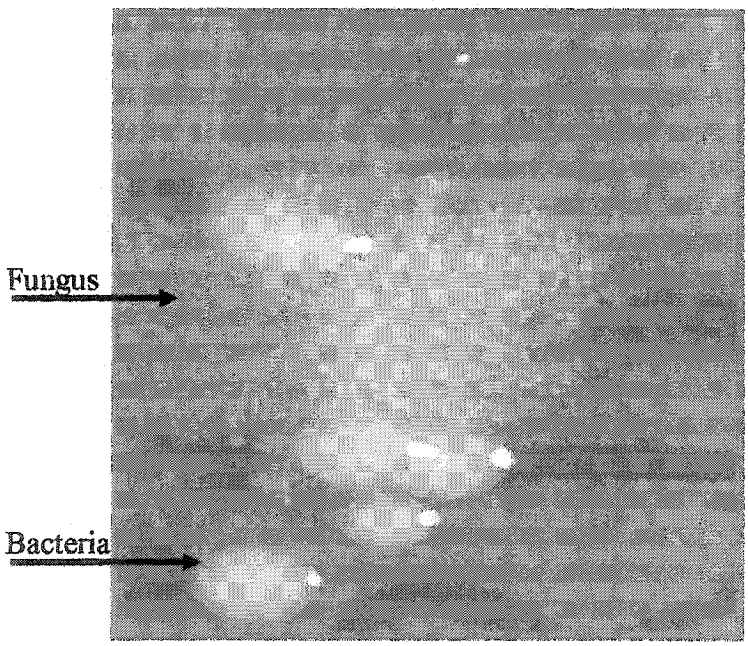



(c ) Bacteria and fungus (x40).

Figure 10.18. *Botrytis cinerea* after composting for one day at thermophilic temperature.

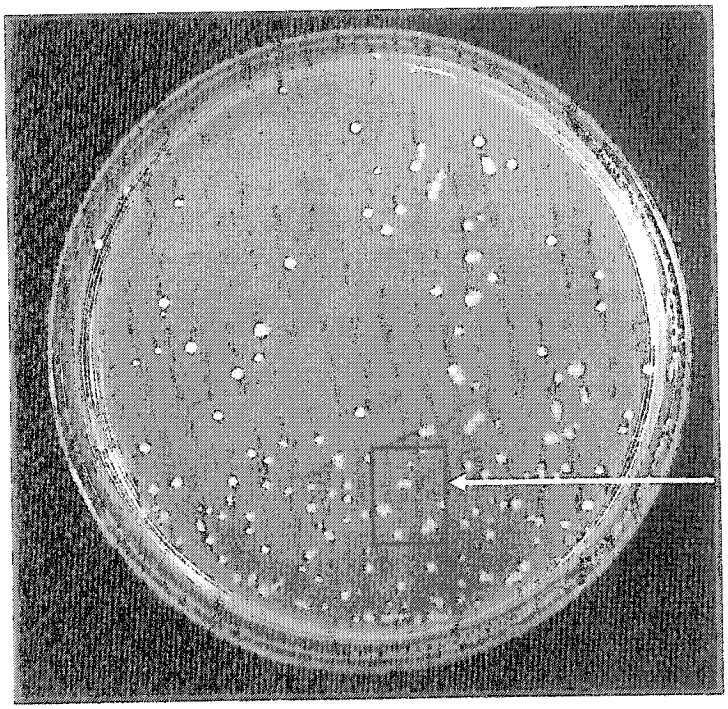



(a) Colonies after 48 h at 16 °C.

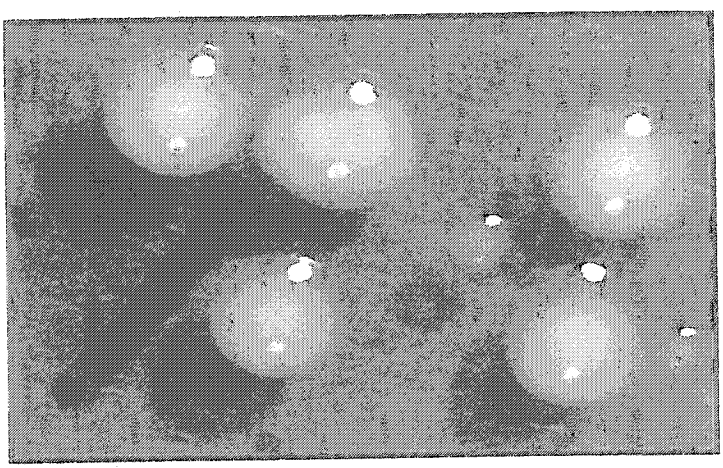



(b) Bacteria and fungus (40x).

Figure 10.19. Disappearance of *Botrytis cinerea* after two days of composting at thermophilic temperature.




(a) Colonies after 48 h at 16 °C.



(b) Bacteria colonies after 48 h at 16 °C.

Figure 10.20. Disappearance of *Botrytis cinerea* after three days of composting at thermophilic temperature.

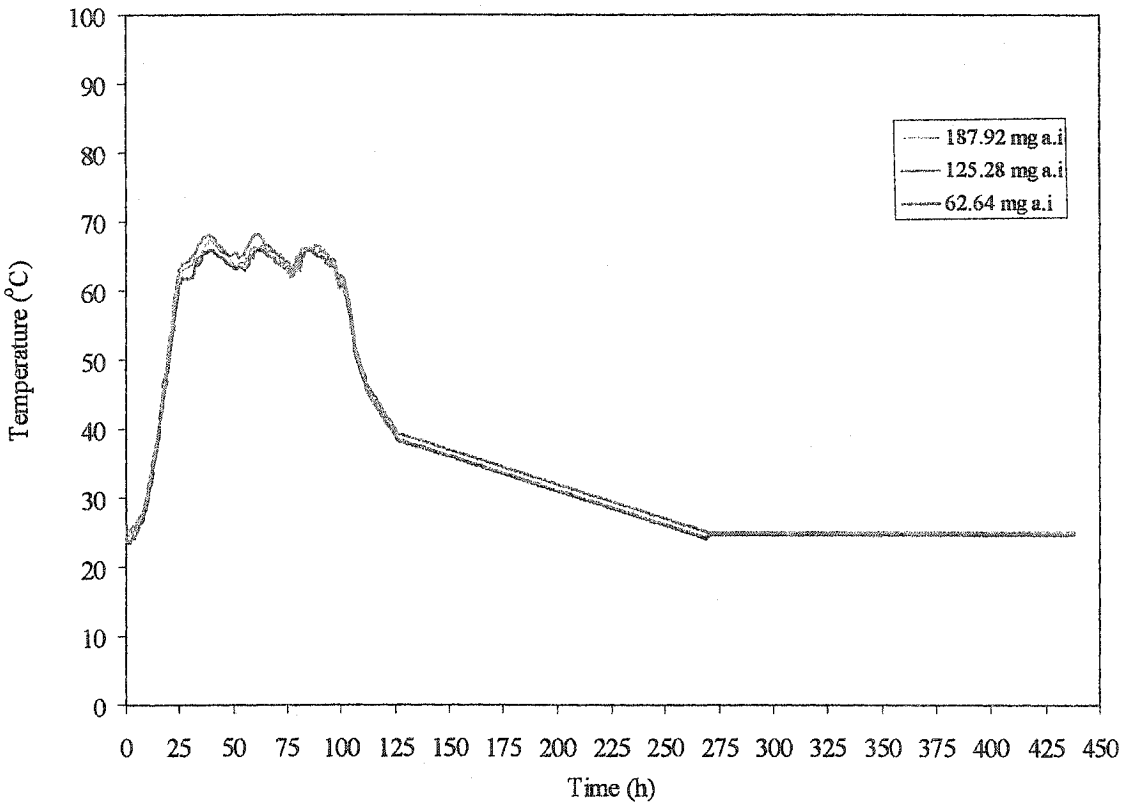



Figure 10.21. Temperatures profiles of pirimiphos-methyl experiments.

## 10.9.2 Pirimiphos-methyl Concentration

Figure 10.22 and Table 10.27 show the concentrations of pirimiphos-methyl during the composting process. The majority of pirimiphos methyl was lost (88.6, 90.0 and 91.6 % for mixtures containing single, double and triple concentrations, respectively) in the first 102 h (starting period of 30 h + thermophilic period of 72 h). Slower reductions were noticed during the mesophilic (<40 C) and psychrophilic (room temperature) periods. Original and double the original concentrations reached non-detectable concentration after 18 days, while triple the original concentration was reduced to 0.37 mg/kg (99.2% removal).

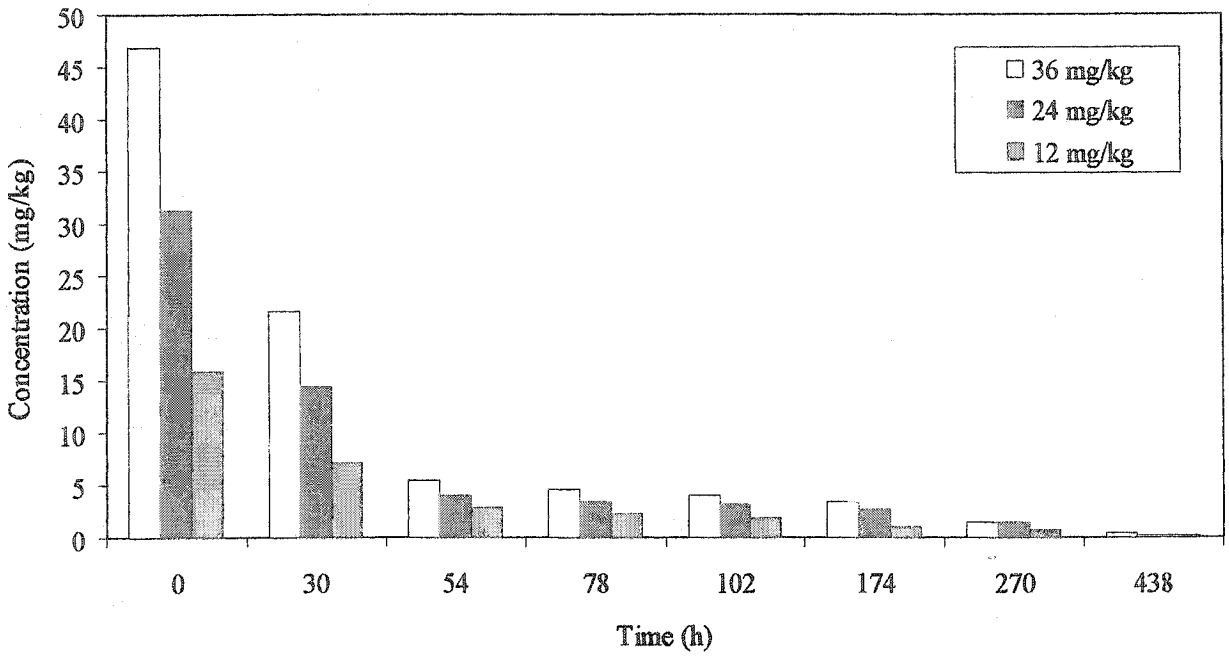



Figure 10.22. Pirimiphos-methyl insecticide concentrations during composting experiments.

Table 10.27. Pirimiphos-methyl insecticide concentrations during composting experiments.

| Time | Initial Concentration (mg/kg) | | |
|---|---|---|---|
| | 12 | 24 | 36 |
| 0 | 15.8 | 31.6 | 47.4 |
| 30 | 7.2 | 14.4 | 21.6 |
| 54 | 2.9 | 4.0 | 5.5 |
| 78 | 2.3 | 3.5 | 4.5 |
| 102 | 1.8 | 3.2 | 4.0 |
| 174 | 0.7 | 2.7 | 3.4 |
| 270 | 0.6 | 1.5 | 1.5 |
| 438 | ND | ND | 0.4 |

ND not detected (detection limit = 0.1 mg/kg).

# 11. DISCUSSION

## 11.1 The Inoculum Size Study

### 11.1.1 Moisture

The initial moisture content of the compost mixtures was 61.07 ± 0.36%. Even through continuous aeration was supplied, little changes were observed in the MC of the material due to the equilibrium between the water produced by microbial respiration and the water lost with the exhaust gas. Water is necessary for microorganisms to utilize dissolved nutrients including oxygen. Oxygen concentration within the pores of the composting mixture is very critical. Therefore, the ideal moisture content would be 100% if sufficient oxygen can be provided (Golueke, 1991). However, moisture content higher than 60 % will limit oxygen diffusion within the composting medium because the voids will be filled with water (Hamoda et al., 1998). Oxygen constraints reduce the rate of decomposition (Richard et al., 1999) and increase the odor emission from anaerobic decomposition (Epstein, 1997; and Haug, 1993). On the other hand, moisture content below 30% will limit microbial activity since there will not be enough water for nutrient solubilization and transport (Haug, 1993). This will arrest the biological process, thus giving physically stable but biologically unstable compost (De Bertoldi et al., 1983). According to Diaz et al. (1993), microbial activity ceases as moisture content of the composted material reaches 8 to 12 %, Miller (1984) reported that lack of water can also restrict the movement of microorganisms.

Tiquia et al. (1998) and McKinley et al. (1985) emphasized the importance of moisture content, and stated that 50 to 60 % moisture content is suitable for efficient composting. Richard et al. (2002) stated that the optimum moisture content of the composting mixtures varies from near 50 to over 70 %, on a wet basis, depending on the type of the composted material. Hamoda et al. (1998) found that during the composting of municipal solid waste, the largest decrease in total organic carbon (TOC) occurred at 60 % moisture content, and less reductions of TOC were observed

at 45 and 75 % moisture contents. Liang et al. (2003) found 50 % moisture content to be the minimum requirement for rapid increase in microbial activity, while 60 to 70 % provided maximum activities during the composting process of biosolids and pine sawmill. In this study, the moisture content was not a limiting factor for microbial growth as it was within the optimum range of 57 to 62 % at all time.

### 11.1.2 Volatile Solids

The volatile solids reductions in the current study were 16.8, 22.2, 25.8, 27.9, 37.2 and 44.7 % for the inoculum size of 0, 10, 20, 30, 40 and 50%, respectively. The results showed that as the inoculum size increased from 0 to 50% (dry weight), the reduction of volatile solids increased from 16.8 to 44.7%. The reductions in volatile solids were within the range reported in the literature for various compost mixtures.

Schwab et al. (1994) simulated municipal solid waste using a mixture of rabbit chow which included alfalfa, shredded newspaper, sand and composted cow manure (3:2:1.5:0.1). The volatile solids reduction reached 34 % by the end of the first 85 days and then remained constant during the rest of the composting period (from day 86 to day 154). Hänninen et al. (1995) reported 21.7 and 77.7 % reductions in the organic matter of source-separated biowaste after 60 and 360 days of composting, respectively. A reduction of 25% of the total solids was observed by Wang et al. (2003) during the composting process of sewage sludge and vegetable food waste for 12 days. Atkinson et al. (1996a) investigated the biodegradability of municipal solid waste (MSW) supplemented with N, P, Vitamins and Trace minerals and unsupplemented (without any addition). They reported volatile solids reductions of 11.6 and 28.5 % after 7 days and 37.5 and 44.0 % after 21 days of composting for the unsupplemented and the supplemented MSW, respectively. In the present study, high reductions in volatile solids were achieved in relatively short composting periods.

### 11.1.3 Total Carbon

The percent reductions of total carbon observed in these experiments were 9.4, 10.0, 12.8, 12.9, 23.0 and 28.4 % for the inoculum size of 0, 10, 20, 30, 40 and 50%, respectively. Sommer and Dahl (1999) studied the fate of carbon during 197 days of composting and observed total carbon reductions of 43, 54 and 52 % for compressed litter, litter mixed after 30 days and untreated litter, respectively. Beck-Friis et al. (2001) achieved total carbon reductions of 65 % after 31 days and 68 % after 22 days of composting using a source separated organic household waste and chopped wheat straw, respectively. Michel et al. (1995) achieved a total carbon reduction of 24 % during composting of a yard trimmings waste consisting of leaves and grass (2:1 dry-weight basis). Wang et al. (2003) observed a reduction of organic carbon of 14 % of total solids during 12 days of composting of sewage sludge and vegetable food waste. These high reductions reported in the literature were due to the relatively longer composting periods. The lower total carbon reductions reported in this study were due to the fact that most of the carbon in wood shavings is nonbioavailable for microbes.

### 11.1.4 Total Kjeldahl and Ammonium Nitrogen

The total kjeldahl nitrogen (TKN) reductions observed in these experiments were 3.4, 3.5, 5.7, 6.6, 20.2 and 25.4 % for the inoculum size of 0, 10, 20, 30, 40 and 50%, respectively. The results of these experiments are in agreement with the TKN reductions of 12 to 27 % reported by Sommer and Dahl (1999). However, Beck-Friis et al. (2001) achieved reductions of 24 and 33 % of the initial nitrogen after 22 and 31 days of composting using a source separated organic household waste and chopped wheat straw.

The initial and final $NH_4$-N concentrations (which is the suitable nitrogen form for microorganisms) were relatively constant (0.6-0.8 g/kgDM) for all mixture as a result of the microbial conversion of organic nitrogen into $NH_4$-N and the conversion of $NH_4$-N back to organic nitrogen (new microbial cells). A part of the

$NH_4$-N can be converted into gas form ($NH_3$-N) which is lost with the exhaust gas. Smell of $NH_3$ was noticed in the exhaust gas. According to Beck-Friis et al. (2001), the initial production of fatty acids, due to the present of anaerobic buckets within the composting material, causes a low initial pH value and thereby causes a low emission of ammonia. Some of the $NH_4$-N could be biologically converted (by nitrification) first into nitrite ($NO_2$-N) and then to nitrate ($NO_3$-N). The nitrification process was not detected in this study. The inhibition of the nitrification process maybe attributed to the excessive amount of $NH_4$ evolution as well as the high temperature of the composting material as stated by Morisaki et al. (1989), Fang et al. (1999) and Tiquia and Tam (2000). Tiquia and Tam (2000) reported very low concentrations of $NO_2$–N and $NO_3$–N for the first 35 days of active composting.

### 11.1.5 C: N Ratio

The change of C: N ratio during composting process is an indicator of the decomposability of the material (Keller, 1962). Livshutz (1962) and Hamoda et al. (1998) recommended an optimum C: N ratio of 30: 1 for the raw waste material at the start of the composting process. The C: N ratio affects the reductions in both carbon and nitrogen contents of the composting material. The reduction in C: N indicates rapid biodegradation of carbon.

Jackson and Line (1997) conducted a large-scale composting experiment based on optimal conditions previously determined through their work with laboratory-scale reactors to investigate the feasibility of pulp and paper mill biosolids in periodically turned windrows. They designed the composting mixture based on a C: N: P: K ratio of 35:1:0.6:0.1. The resulted compost was a well humified and a thermophilic temperature (above 50°C) in the center of the pile was maintained during the duration of the trial. The final C: N ratio was not reported.

Hamoda et al. (1998), while investigating the influence of C: N ratios on the performance of the composting process, reported total organic carbon reduction of 8, 8.7 and 11% at C: N ratios of 15: 1, 20: 1, and 30: 1, respectively. Larsen and

McCartney (2000) investigated the influence of C: N ratio on the performance of a bench-scale bioreactor treating pulp and paper biosolids using four C: N ratios (107: 1, 55: 1, 29:1 and 18: 1) and found the initial C: N ratio of 29: 1 to be the most suitable as judged by the best volatile solid reduction as well as less odor generation.

The final C: N ratio in this study was in the range of 28: 1 to 29: 1. The C: N ratio at the end of the process is an indicator of product stability (Mathur, 1991; Haug, 1993 and Epstein, 1997). McDonnell (1999) reported that the C: N ratio of the final compost should drop over time and eventually become stable as compost becomes more resistant to further degradation. Mathur (1991) reported that mature compost should be similar to soil humus, which has a C: N ratio of 10: 1. In the present study, the reduction in the C: N ratio ranged between 3 to 10%, which is less than value of 60%, reported by Lopez-Real and Baptisa (1996) and Michel et al. (1996) for large-scale composting projects and the value of 33.1% reported by Sadaka and El-Taweel (2003) for laboratory-scale bioreactors. This is possibly due to the short retention time of 5 days and the nonbioavailability of carbon in the mixture which resulted in a shorter thermophilic period. Since the C: N ratios in this study decreased slightly, carbon was a limiting factor during these composting experiments. Therefore, the addition of bioavailable carbon source should be investigated.

### 11.1.6 Nutrients

Beside C and N, other nutrients are important for the growth and maintenance of microorganisms. Macronutrients such as sulfur (S), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe), sodium (Na), and chlorine (Cl) are required primarily for the synthesis of cellular components. Micronutrients including zinc (Zn), manganese (Mn), molybdenum (Mo), selenium (Se), cobalt (Co), copper (Cu), nickel (Ni), and tungsten (W) are required as cofactors in enzymatic reactions (Munnecke, 1984; and Bitton, 1999). Adequate concentrations and proper ratios of macronutrients and micronutrients are needed for optimum growth of microorganisms (Tchobanoglous et al., 1993; and Bitton, 1999). However, the reported values in the literature of microbial requirements of macronutrients and micronutrients

concentrations vary dramatically (Rose, 1965). El-Taweel (1995) reported that microorganisms require macronutrients in a concentration of 0.1 to 1.0 mM, micronutrients in a concentration of 0.1 to 100.0 μM.

Since the composting process involved different kind of microorganisms (bacteria, fungi and actinomycetes), data on nutrients requirements for composting microorganisms are not available in the literature. Most of the work done regarding nutrients concentrations in the compost mixture, especially agricultural based, is concerned with the suitability of utilizing the final product as a plant nutrient (Evans and Tan, 1998; and Manios, 2004).

The nutrients (Ca, Na, Fe, Mg, P, K, Zn, Cl and S) available in different composting mixtures used in this study are presented in Table 12.1. Ca, K, P, Mg and S concentrations of the mixtures decreased as the inoculum size increased while Na, Fe, Zn and Cl concentrations in the mixtures increased as the inoculum size increased. Nonetheless, the final concentrations of these elements in the mixtures used in this study were sufficient for microbial growth and within the range reported in literature for successful composting processes as shown in Table 12.1 (Manios, 2004; and Das et al., 2002).

### 11.1.7 Temperature

The microorganisms utilized the organic materials for energy (respiration) and synthesis (growth) of new microbial cells according to the following equations:

Energy:

$$C_xH_yO_z + O_2 \xrightarrow{\text{Microbes}} CO_2 + H_2O + \text{HEAT} \qquad (11.1)$$

Growth:

$$C_xH_yO_z + NH_4 \xrightarrow{\text{Microbes}} \text{New cells (microbes)} \qquad (11.2)$$

Table 11.1. Macronutrients in the mixtures used in the inoculum study.

| Elemental Composition (mg/g DM) | Mixture: MSW compost | | | | | | Olive and Cucumber biomass[1] | Sludge with green waste [1] | Bedding and Sawdust[2] | Compost Final Product |
|---|---|---|---|---|---|---|---|---|---|---|
| | 100:00 | 90:10 | 80:20 | 70:30 | 60:40 | 50:50 | | | | |
| Ca | 20.88 | 20.79 | 20.70 | 20.62 | 20.53 | 20.44 | 125.9 | 44.8 | 29.8 | -- |
| Na | 0.28 | 0.86 | 1.44 | 2.03 | 2.61 | 3.19 | -- | -- | 4.7 | -- |
| Fe | 0.16 | 0.42 | 0.69 | 0.95 | 1.22 | 1.48 | -- | -- | 2.3 | -- |
| Mg | 1.92 | 1.93 | 1.91 | 1.90 | 1.88 | 1.87 | 18.2 | 6.3 | 1.3 | -- |
| Zn | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | -- | -- | 0.04 | 1.9[3]<br>0.5 [4] |
| K | 23.40 | 21.84 | 20.28 | 18.72 | 17.16 | 15.60 | 25.9 | 4.9 | 4.2 | -- |
| Cl | 0.03 | 0.06 | 0.08 | 0.11 | 0.14 | 0.16 | -- | -- | -- | -- |
| P | 4.20 | 4.05 | 3.90 | 3.75 | 3.60 | 3.45 | 13.9 | 29.6 | 1.8 | -- |
| S | 4.36 | 4.15 | 3.95 | 3.74 | 3.54 | 3.33 | -- | -- | 0.8 | -- |

1- Manios (2004).
2- Das et al. (2002).
3- AAFC (2001).
4- CCC (2004).

The generated heat raised the temperature of the material in the bioreactor and caused the evaporation of moisture (latent heat). Also some heat was lost from the material with the exhaust gas (sensible heat) and through the body and the sidewalls of the bioreactor (conductive heat losses).

The four stages of composting process (lag or inactive phase, exponential or active phase, stationary phase and death phase) were clearly identified in this study (Figure 10.1). Heat is generated as a result of organic matter degradation (Equation 11.1), and temperature rose up through the three thermal phases (psychrophilic, mesophilic and thermophilic) until the readily available substrate was depleted (Doran, 1995). The lag phases of the mesophilic (first lag) and thermophilic (second lag) as well as the rate of temperature increase were determined graphically according to the procedure described by Ghaly et al. (1989) as shown in Figure 11.1. Table 11.2 shows the kinetic parameters (mesophilic and thermophilic lag times and the rate of temperature rise, maximum temperature reached, time of peak and duration) obtained during the inoculum study. The results are also illustrated graphically in Figure 11.2.

The mesophilic lag time and the rate of temperature change for the mixture of tomato remains and wood shavings without the addition of inoculum (MSW) were 5 h and 1.02 °C/h, respectively. Addition of 10 % inoculum to the tomato remains-wood shaving mixture reduced the first lag phase to 1.5 h and increased the rate of mesophilic temperature change to 1.8 °C/h. Further increases in the inoculum size increased the lag time and reduced the rate of temperature increase. The lag time increased to 2.0 h for mixtures receiving 20 and 30 % inoculum, to 2.5 h for the mixtures receiving 40% inoculum, and to 3.0 h for the mixture receiving 50% inoculum. The rate of temperature increase was reduced to 1.27, 1.22, 1.04 and 0.37 °C/h for the mixtures receiving 20, 30, 40 and 50 % inoculum. Furthermore, increasing the inoculum size increased the second lag phase. The mixture that received no inoculum did not reach the thermophilic phase but those which received inoculum had a thermophilic lag (2.2, 3.2, 3.5, 3.8, and 4.2 h

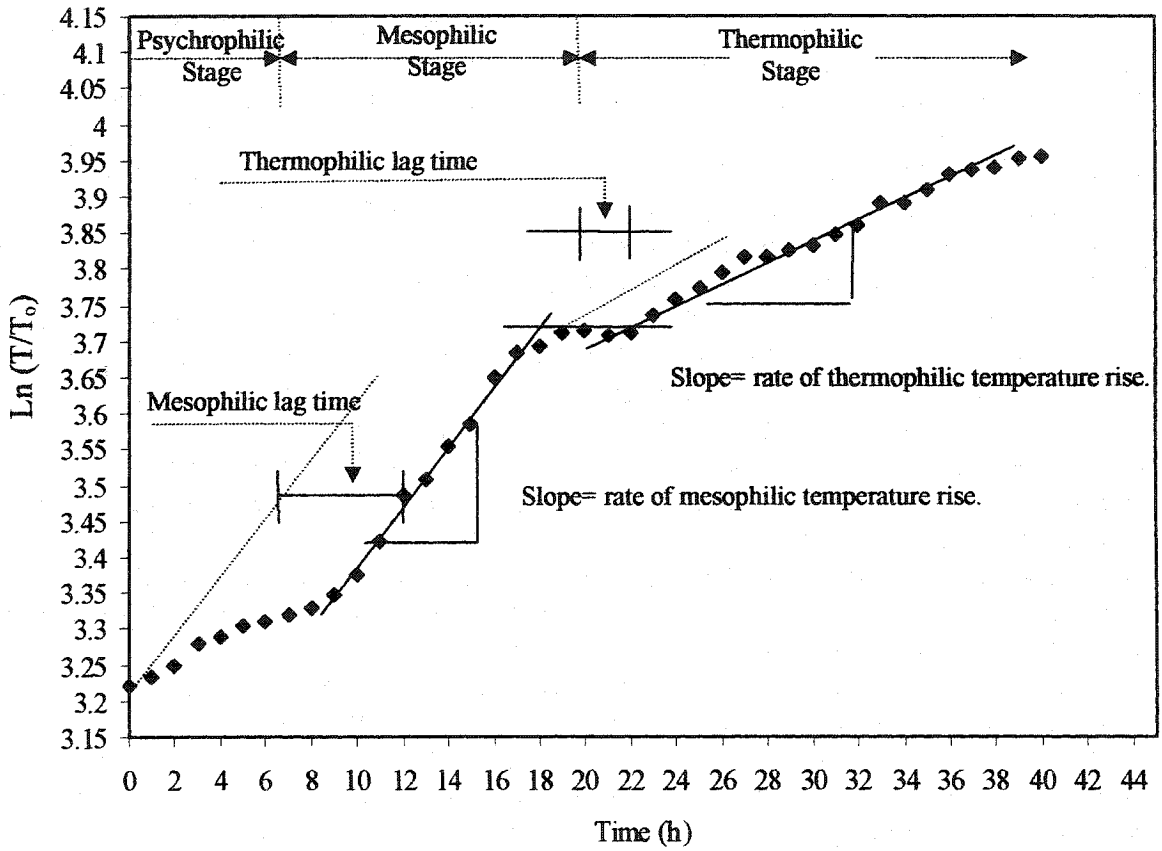


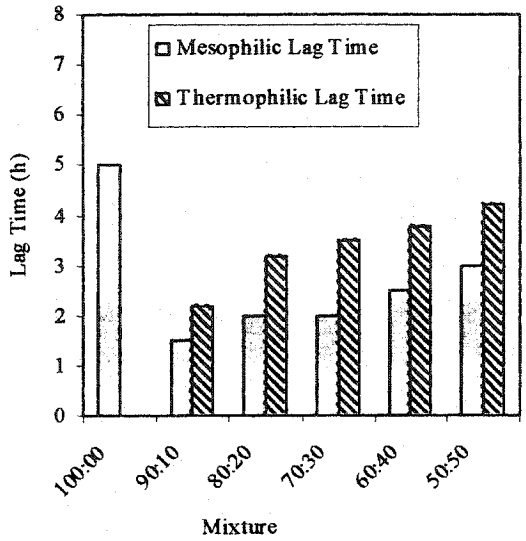

Figure 11.1. Determination of the mesophilic and thermophilic lag periods and the rates of temperature increase during the inoculum study.

Table 11.2. Kinetic parameters of the inoculum study.

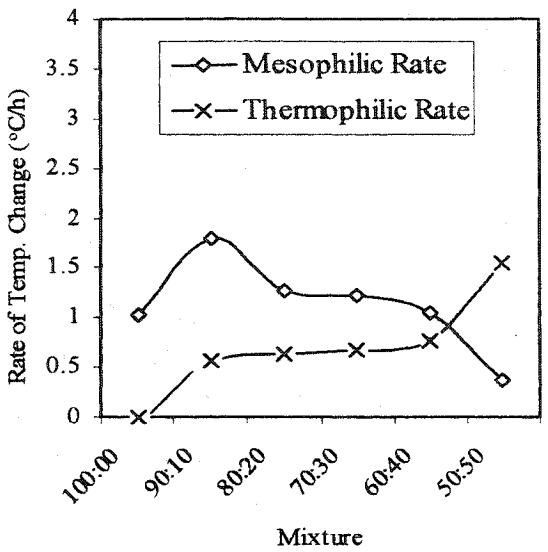
| Mixture[1] : Compost ratio | Mesophilic Range | | Thermophilic Range | | Maximum Temperature | | |
|---|---|---|---|---|---|---|---|
| | Lag Time (h) | Rate (°C/h) | Lag Time (h) | Rate (°C/h) | Temperature (°C) | Time of Peak (h) | Duration (h) |
| 100:00 | 5.0 | 1.02 | - | - | 37.8 | 24.0 | 2.5 |
| 90:10 | 1.5 | 1.80 | 2.2 | 0.57 | 50.8 | 25.0 | 6.0 |
| 80:20 | 2.0 | 1.27 | 3.2 | 0.63 | 51.5 | 38.0 | 6.0 |
| 70:30 | 2.0 | 1.22 | 3.5 | 0.67 | 52.2 | 40.0 | 6.0 |
| 60:40 | 2.5 | 1.04 | 3.8 | 0.76 | 57.1 | 44.5 | 8.7 |
| 50:50 | 3.0 | 0.37 | 4.2 | 1.56 | 61.8 | 46.5 | 13.1 |

1- Mixture consists of tomato remains and wood shavings mixed at a ratio of 1:1.5 by dry weight basis.

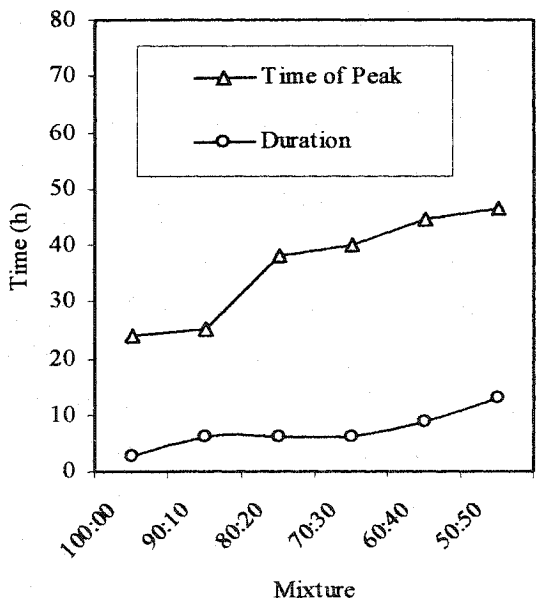
40 °C is the end of mesophilic stage and the beginning of the thermophilic stage.



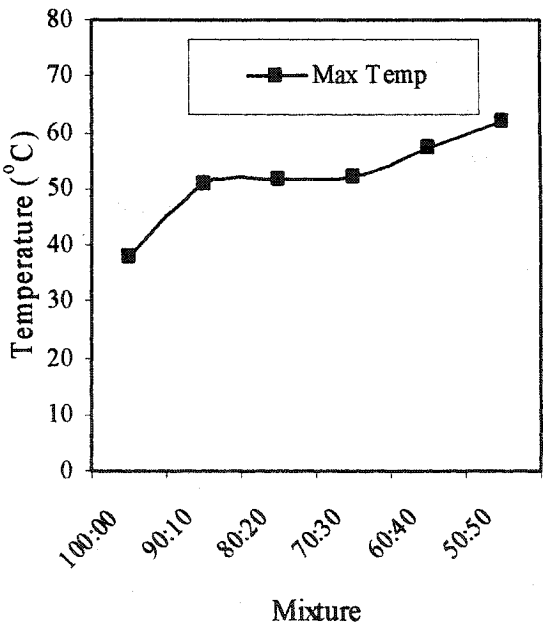

(a) Mesophilic and Thermophilic Lag Time.




(c) Mesophilic and Thermophilic Rate of Temperature Change.




(b) Time of Peak and Duration.




(d) Maximum Temperature Reached.

Figure 11.2. Effect of the inoculum size on the kinetic parameters of inoculum study.

for the 10, 20, 30, 40 and 50% inoculum size, respectively). The thermophilic rates of temperature increase were 0.57, 0.63, 0.67, 0.76 and 1.56 °C/h for the mixtures receiving 10, 20, 30, 40 and 50% inoculum, respectively.

VanderGheynst et al. (1997) reported that a maximum temperature of 60 °C was obtained after 56 h and was maintained for 344 h during the composting of a synthetic food waste and digested biosolids in a pilot-scale (0.77 $m^3$) bioreactor. The reported lag times for the mesophilic (5 h) and thermophilic (12.5 h) stages were longer than the calculated values in the current study, and the rates of temperature increase during the mesophilic (0.05 °C/h) and thermophilic (0.02 °C/h) stages were also very small compared to the current study . This may be due to the use of the mixing system in the present study, which helped to maintain homogenous mixtures during the composting processes. According to Palm and Sanchez (1991) under higher temperatures the breakdown of fats, proteins and complex carbohydrates is accelerated, which means that more carbon will become bioavailable. This could explain the higher temperature reached when the inoculum size was increased.

The times of peak as well as the durations of maximum temperatures were affected by the amount of inoculum added to the mixture. The time and duration of the peak were increased from 24 h and 2.5 h for the mixture that received no inoculum to 46.5 h and 13.1 h for the mixture that received 50% inoculum, respectively. The maximum temperature for the mixture that received no inoculum was 37.8 °C compared to 61.8 °C (63% higher) for the mixture that received 50% inoculum.

The composting process is an exothermic reaction in which the biodegradable portion of volatile solids (available carbon) is utilized by microorganisms for energy. The release of energy results in increased temperature of the compost material. (Haug, 1993; and Liang et al., 2003). The reductions in volatile solids in the current study linearly correlated with the maximum temperature of the compost ($R^2$= 0.84) as shown in Figure 11.3. The relationship can be described by the following equation:

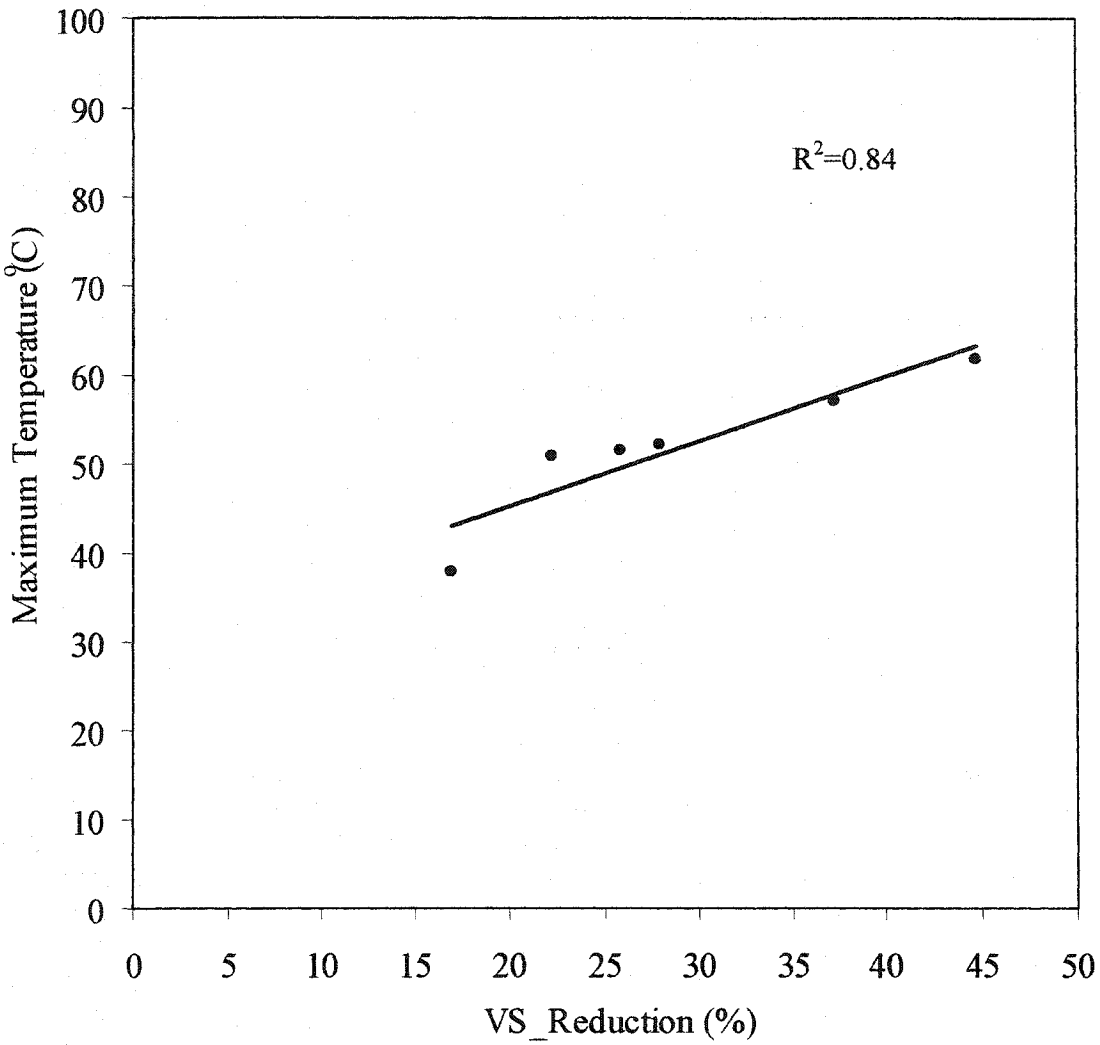



Figure 11.3. Effect of volatile solids reduction on the maximum temperature observed during the inoculum study.

$$T_m = 30.7 + 0.7\,(VS) \qquad (11.3)$$

Where:

$T_m$ = Maximum temperature (°C)

VS = Volatile solids reduction (%)

Namkoong and Hwang (1997) and Papadimitriou and Balis (1996) investigated the effect of composting operational parameters using laboratory scale composting bioreactors. The greatest decrease in volatile solids (and the greatest amount of $CO_2$ evolved) was observed when the temperature of composting process was set below 60 °C.

The reduction in the total carbon in the current study correlated with the maximum temperature of the compost ($R^2$= 0.69) as shown in Figure 11.4. The relationship can be described by the following equation:

$$T_m = 38.1 + 0.9\,(TC) \qquad (11.4)$$

Where:

TC = Total carbon reduction (%)

Conghos et al. (2003) studied the changes of total organic carbon (TOC) during a 45-day incubation of sunflower hulls and mixtures of sunflower hulls and other crop residues (Alfalfa and Vetch) under mesophilic (25 °C) and thermophilic (50 °C) temperatures. The reduction of TOC was only 13-21% under the mesophilic temperature, while it reached 25-41 % under the thermophilic temperature. Hamoda et al (1998) studied TOC degradation during three controlled-temperature composting experiments (20, 40 and 60 °C) and observed that most reduction took place during the mesophilic range (40 °C).

During the composting process, the organic nitrogen is converted to simpler nitrogenous compounds and finally to $NH_4$. The ammonium is required for microbial synthesis. In the present study, nitrogen was not a growth limiting factor

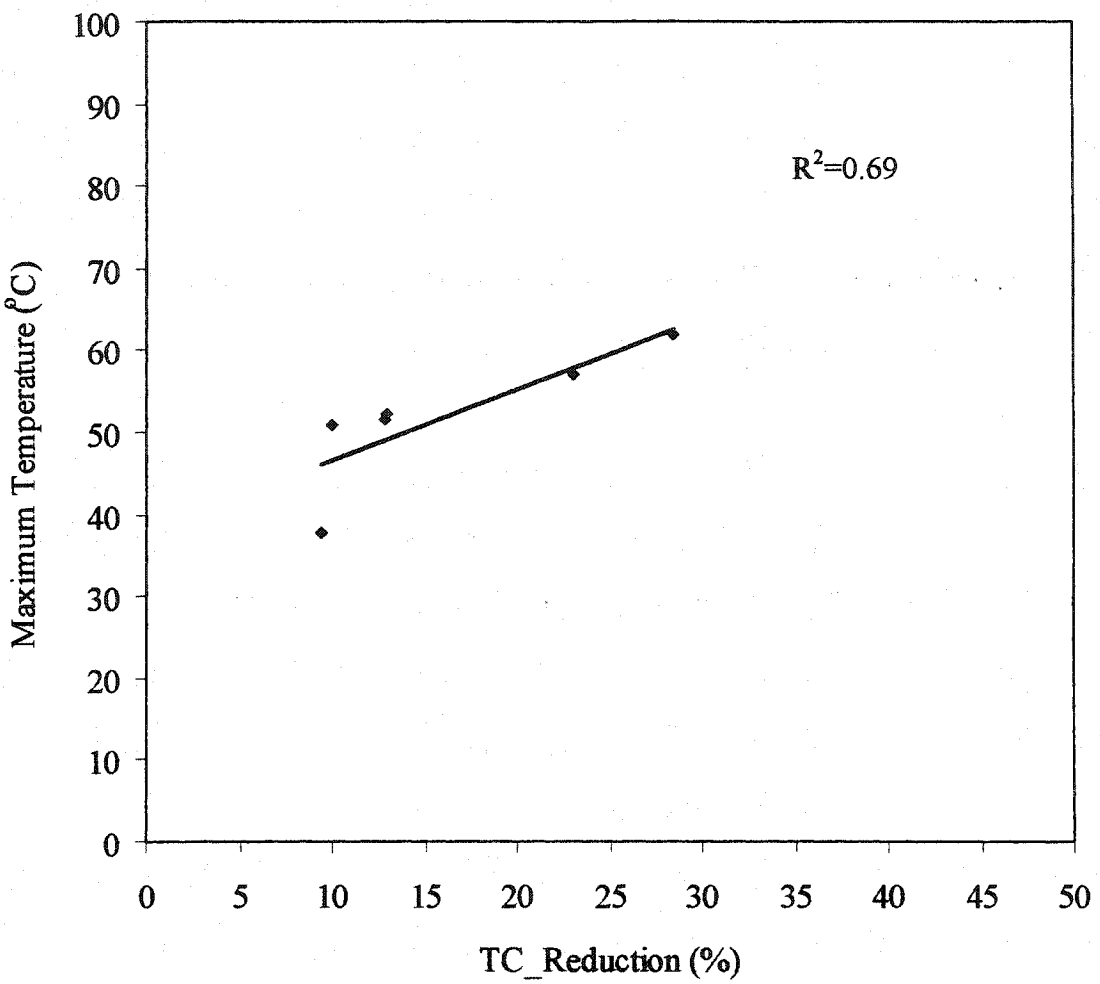



Figure 11.4. Effect of total carbon reduction on the maximum temperature observed during the inoculum study.

as the C: N ratio was adjusted at the start of the experiments (Haug, 1993). The reductions in TKN also correlated with the maximum temperature ($R^2$=0.64) as shown in Figure 11.5. The relationship can be described by the following equation:

$$T_m = 44.6 + 0.7\,(TKN) \qquad (11.5)$$

Where:

TKN = TKN reduction (%)

## 11.2 Addition of Sugar Study

Microorganisms break down simple molecules (sugar) immediately and use them for growth and reproduction (Juma and McGill, 1986; and Chen and Inbar, 1993). As carbon compounds decompose under aerobic condition, part of the carbon is converted to microbial cell mass, while the other part is converted to energy with the release of carbon dioxide (Juma and McGill, 1986). As a result of heat being produced (15.711 kcal/g $_{decomposed}$) due to microbial metabolism, the average bioreactor temperature ($T_{ave}$) is gradually increased (Pagan, 1997).

It is clear from the results obtained from the sugar-addition study that the effect of the sugar as a source of readily available carbon on the average temperature in the bioreactor was positive. The maximum temperature in the control bioreactor (without sugar) reached 50.8˚C and lasted a very shot time (5 h) before starting to decline whereas the average temperature in the other bioreactors (having the same material but with sugar applications) continued to rise and high temperatures (≥50 °C) were maintained for longer periods (18, 35 and 47 h in bioreactor with single, double and triple sugar applications, respectively). The bioreactors with double and triple sugar applications maintained temperatures higher than 60 °C for at least 7 and 18 h, respectively. These results indicate that the bioavailable carbon in the compost material is somewhat limited and the addition of readily bioavailable carbon source (such as sugar) increased the microbial activity, and thus raised the temperature. Rahn and Lillywhite (2001) studied

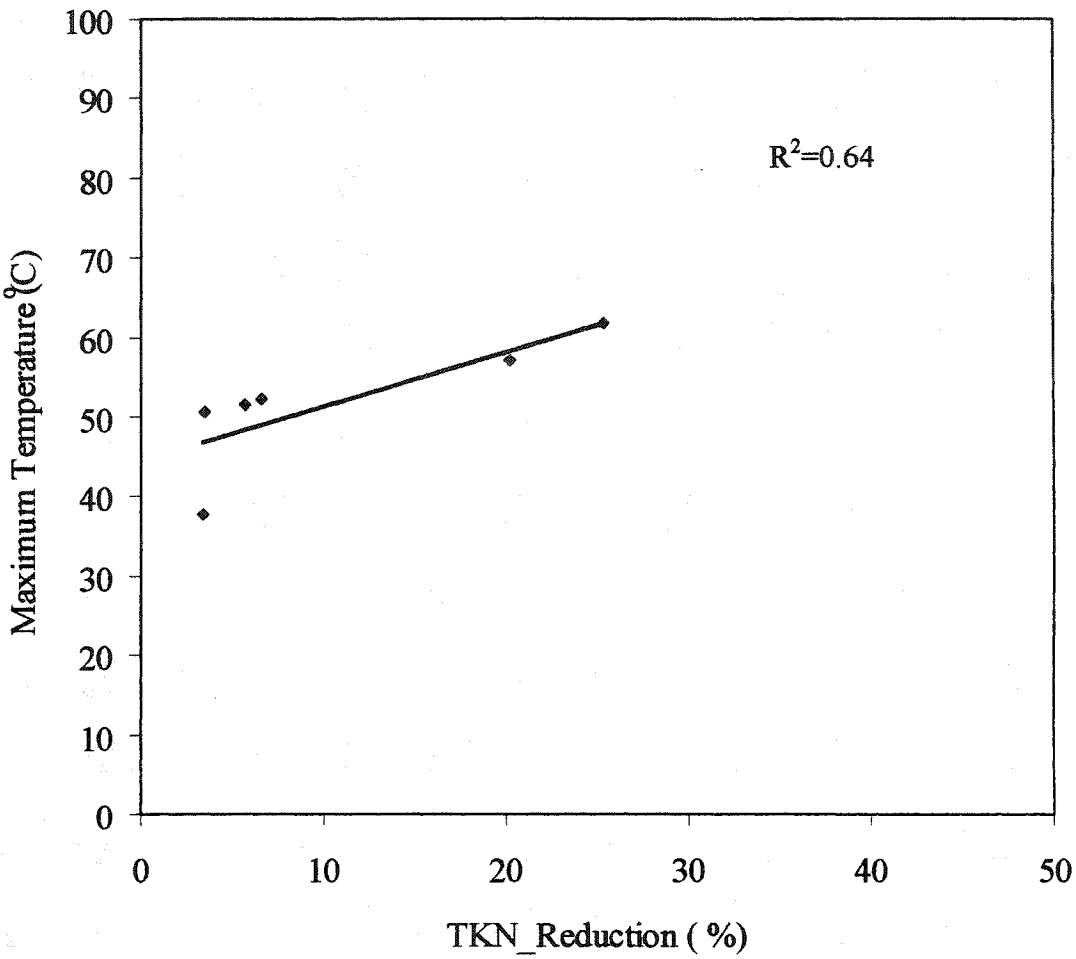



Figure 11.5. Effect of total kjeldahl nitrogen reduction on the maximum temperature observed during the inoculum study.

the influence of the carbon source on the degradation rate of 13 vegetable crop residues. They concluded that the decomposition rate was correlated to the bioavailable carbon and nitrogen contents of the material, and the organic matter remaining after the process correlated with the lignin content of the source material.

## 11.3 Dairy Manure Study

### 11.3.1 Moisture

The initial moisture content (MC) of all mixtures was 60.7 ± 1.27% and the final moisture content was approximately 58.16 ± 3.06 %, which is still within the range of 50 to 70 % required for optimum microbial activity (Liang et al., 2003; and Richard et al., 2002). The reductions of MC during these experiments (0.4 – 3.99 %) are slightly higher than those of the inoculum experiments (0.0 – 3.0 %). This maybe due to the differences in the degradation and respiration rates (Haug, 1993; and Miller, 1993). The dairy manure had slightly lower carbon (43 %) content compared to the compost (44 %). Also, the significant presence of wheat straws in manure (bedding material) lowered the percentage of the bioavailable carbon.

### 11.3.2 Volatile Solids

The initial volatile solids varied from 841 to 872 g /kg DM depending on the amount of manure added to the mixture. The percent reduction of the volatile solids ranged from 16.8 to 32.7 %. The volatile solids reductions in the manure study were 16.8, 20.1, 22.6, 25.2, 28.7 and 32.7 % for the manure ratio of 0, 10, 20, 30, 40 and 50 %, respectively. The results showed that as the amount of manure increased (from 0 to 50 %), the reduction of volatile solids increased (from 16.8 to 32.7 %). The reductions in volatile solids were within the range reported in the literatures for various compost mixtures (Hänninen et al., 1995; Atkinson et al., 1996b; and Wang et al., 2003). Lower volatile solids reductions occurred during the manure study compare to the inoculum study (16.8 to 44.7 %). Although the rates of volatile solids reduction were similar for both the manure and inoculum studies, the bioavailable carbon in municipal compost was

higher than the bioavailable carbon in manure, thus allowing for longer decomposition period (96 h for the inoculum study compare to 68 h for manure study) and as a result higher volatile solids reductions.

### 11.3.3 Total Carbon

The initial total carbon (TC) content varied from 416 to 437 g/kg DM, depending on the amount of manure added to each mixture. The percent reductions of total carbon observed in these experiments were 9.4, 9.6, 10.0, 9.8, 10.1 and 10.8 % for the manure size of 0, 10, 20, 30, 40 and 50%, respectively. These reductions are much lower than the reductions of 43 - 52 % reported by Sommer and Dahl (1999), 65 - 68 % reported by Beck-Friis et al. (2001), and 24 % reported by Michel et al. (1995), but similar to that of 14 % reported by Wang et al. (2003). Although the high reductions reported in the literature were due to the relatively longer composting periods, the TC reductions obtained from the manure study (9.4 – 10.8 %) were also lower than TC reductions achieved during the inoculum study (9.4 - 28.4 %) because the dairy cow manure used consisted of wheat straws (bedding material) that lowered the bioavailable carbon content in the mixture as well as other nutrients. In addition, the current experiment lasted for less than 3 days while the inoculum study lasted for 4 days before the bioreactor temperature reached the ambient temperature, which allowed for more TC reduction. Although the rate of total carbon reduction in the manure study was higher (0.04 - 0.05 kg/day) than that of the inoculum study (0.03 kg/day), the longer composting period observed in the inoculum study resulted in higher TC reductions.

### 11.3.4 Total Kjeldahl and Ammonium Nitrogen

The initial TKN of the mixtures increased as the manure content of the mixture increased. Increasing the manure ratio from 0 to 50 % increased the initial TKN from 14.6 to 15.1 g/kg. The TKN reductions observed in these experiments were 3.4, 4.3, 4.5, 5.4, 6.0 and 6.0 % for the manure ratio of 0, 10, 20, 30, 40 and 50%, respectively, which are lower than the TKN reductions achieved during the inoculum experiments. The TKN reductions in this study were lower than the 12 - 27 % reported by Sommer and Dahl

(1999) and the 24 - 33 % reported by Beck-Friis et al. (2001). The high TKN reductions reported in these studies were due to the higher initial TKN concentration and the longer composting time (22 to 31 days). The initial TKN content of the manure experiment was lower than that in the mixture of the inoculum study. Barrington et al. (2002) and Hamoda et al. (1998) reported that nitrogen evolution during composting process is highly affected by the carbon bioavailability. The lower reductions of TKN in this study can also be due to the lower temperature achieved during the manure study as noticed by Tiquia and Tam (2000) who reported that the loss of nitrogen during composting process is proportional to the maximum temperature reached during the composting process as higher temperature tends to increase nitrogen evolution.

The initial and final $NH_4$-N (which is the suitable nitrogen form for microorganisms) concentrations were relatively constant (1.32 g/kgDM, ±0.29), and were similar to the concentrations of the mixture used in the inoculum study. This was due to the equilibrium between mineralization of organic nitrogen to $NH_4$-N and the conversion of $NH_4$-N to organic nitrogen (microbial protein).

### 11.3.5 C: N Ratio

At the start of all experiments, the C: N ratios were adjusted to the optimum range of 30: 1 as recommended by Livshutz (1962) and Hamoda et al. (1998). It was slightly reduced to 26.2:1 - 28.1: 1 by the end of the experiments. The reduction in C: N ratios (4.4 to 6.2 %) observed in this study are lower than those of 60 % reported by Lopez-Real and Baptisa (1996) and the 33.14 % reported by Michel et al. (1996) for large-scale systems. Since the C: N ratios in the manure study slightly decreased, it can be concluded that nitrogen was not a limiting factor during these composting experiments. However, the reductions in C: N ratios in the manure study were higher by 3 to 7 % than the reductions in the inoculum study. This can be explained by the fact that nitrogen conservation during composting process is highly affected by the carbon bioavailability as explained by Barrington et al. (2002) and Hamoda et al. (1998).

### 11.3.6 Nutrients

The nutrients (Ca, Na, Fe, Mg, P, K, Zn, Cl and S) available in different composting mixtures used in the manure study are presented in Table 11.3. Ca, K, P, Mg and S concentrations of the mixtures decreased as the manure size increased while Na, Fe, Zn and Cl concentrations in the mixtures increased as the manure size increased. However, the final concentrations of these elements in the mixtures used in the manure study were sufficient for microbial growth and within the range reported in literature (Table 11.3) for successful composting processes (Manios, 2004; and Das et al., 2002).

### 11.3.7 Temperature

Although dairy cow manure (10, 20, 30, 40 and 50 %) was added to the mixture of tomato residue-wood shavings to increase the bioavailable carbon portion in the mixture, the heat generated from the decomposition of the mixture did not elevate the temperatures of the composted material to the thermophilic stages. The kinetic parameters for the dairy manure experiments (lag time, rate of temperature rise, maximum temperature reached, time of peak and duration) are shown in Table 11.4 and Figure 11.6.

The average temperature in the bioreactors containing 0, 10, 20, 30, 40 and 50% manure reached 37.8, 39.0, 39.5, 39.0, 39.1 and 41.2 °C after 24, 11, 11, 10, 10 and 10 hours, respectively. Temperatures higher than 35° C were observed in the bioreactors containing 10, 20, 30, 40 and 50% manure, and remained for 19, 19, 19, 20, and 21 hours, respectively. Temperatures higher than 40° C were only observed in the bioreactor containing 50 % manure and were maintained for 7 hours, respectively. Temperatures higher than 45°C were not observed in all bioreactors indicating that a thermophilic stage was not achieved in any of theses bioreactors.

Table 11.3. Nutrients concentration during the manure study.

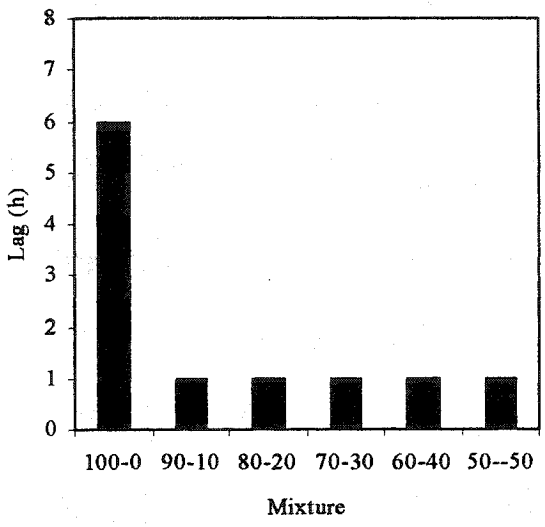
| Elemental Composition (mg/g DM) | Mixture: Manure | | | | | | Olive and Cucumber biomass[1] | Sludge with green waste [1] | Bedding and Sawdust[2] | Compost Final Product |
|---|---|---|---|---|---|---|---|---|---|---|
| | 100:00 | 90:10 | 80:20 | 70:30 | 60:40 | 50:50 | | | | |
| Ca | 20.88 | 19.58 | 18.27 | 16.97 | 15.66 | 14.36 | 125.9 | 44.8 | 29.8 | -- |
| Na | 0.28 | 0.55 | 0.82 | 1.09 | 1.36 | 1.64 | -- | -- | 4.7 | -- |
| Fe | 0.16 | 0.23 | 0.31 | 0.38 | 0.45 | 0.53 | -- | -- | 2.3 | -- |
| Mg | 1.92 | 2.20 | 2.46 | 2.71 | 2.97 | 3.23 | 18.2 | 6.3 | 1.3 | -- |
| Zn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -- | -- | 0.04 | 0.05[3] 1.90[4] |
| K | 23.40 | 24.58 | 25.76 | 26.94 | 28.12 | 29.30 | 25.9 | 4.9 | 4.2 | -- |
| Cl | 0.03 | 0.10 | 0.16 | 0.23 | 0.30 | 0.37 | -- | -- | -- | -- |
| P | 4.20 | 4.25 | 4.29 | 4.34 | 4.38 | 4.43 | 13.9 | 29.6 | 1.8 | -- |
| S | 4.36 | 4.25 | 4.15 | 4.04 | 3.94 | 3.83 | -- | -- | 0.8 | -- |

1. Manios (2004).
2. Das et al. (2002).
3. AAFC (2001).
4. CCC (2004).

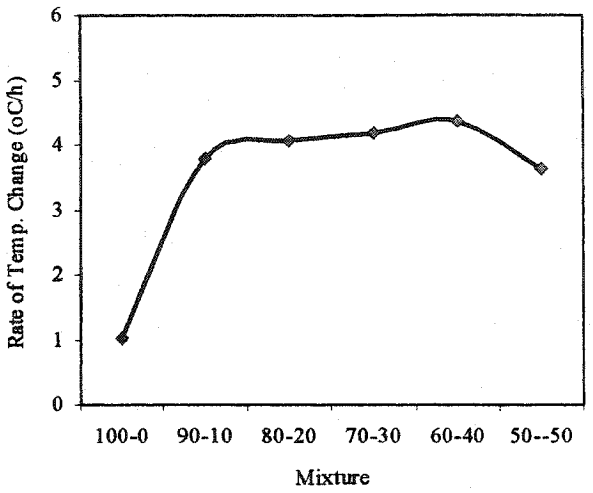
Table 11.4. Kinetic parameters of dairy cow manure study.

| Mixture: Manure Ratio | Mesophilic Range | | Thermophilic Range | | Maximum Temperature | | |
|---|---|---|---|---|---|---|---|
| | Lag Time (h) | Rate (°C/h) | Lag Time (h) | Rate (°C/h) | Temperature (°C) | Time of Peak (h) | Duration (h) |
| 100:00 | 6 | 1.02 | - | - | 37.8 | 24 | 2.5 |
| 90:10 | 1 | 3.79 | - | - | 39.0 | 11 | 5.0 |
| 80:20 | 1 | 4.06 | - | - | 39.5 | 11 | 5.0 |
| 70:30 | 1 | 4.18 | - | - | 39.0 | 10 | 5.0 |
| 60:40 | 1 | 4.37 | - | - | 39.1 | 10 | 6.0 |
| 50:50 | 1 | 3.63 | - | - | 41.2 | 10 | 7.0 |

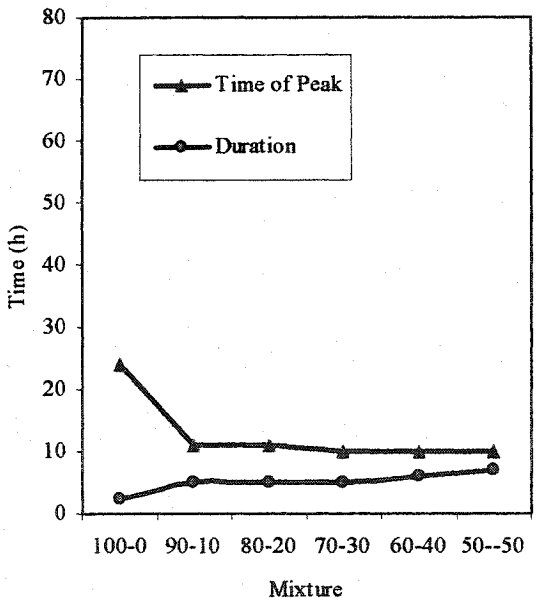
1- Mixture consists of tomato remains and wood shavings mixed at a ratio of 1:1.5 by dry weight basis.



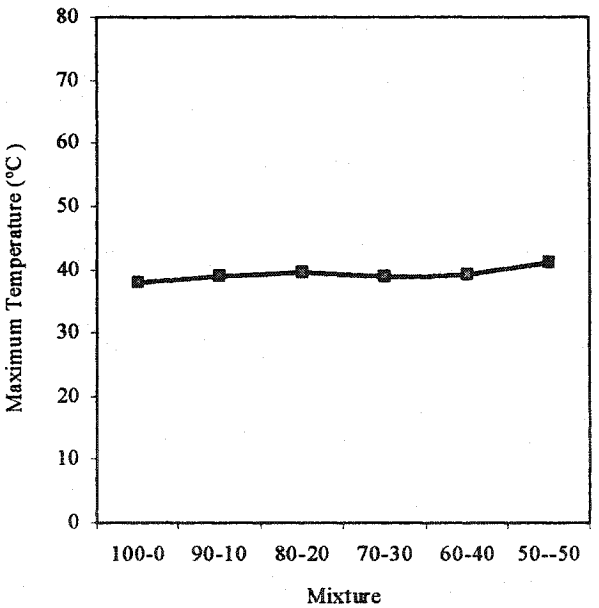

(a) Lag time




(c ) Rate of temperature change.




(b) Time of peak and duration.




(d) Maximum temperature reached.

Figure 11.6. Kinetic parameters of the manure study.

The mesophilic lag time was 6 h for the mixture of tomato remains-wood shavings without the addition of dairy manure. Addition of dairy manure to the tomato remains-wood shaving mixture reduced the lag phase to about 1 hour (for all dairy manure mixtures:10, 20, 30, 40 and 50 %). This is much shorter than the lag time of 30 h reported by Hall (1998) for a similar type of material. The shorter lag time observed in the manure study could be due to the high microbial population present initially in dairy manure and the continuous mixing used in this study, which established a uniform distribution of moisture, oxygen and bioavailable nutrients thus leading to faster microbial growth and metabolism. However, the bioavailable carbon in the manure was not sufficient to rise the temperature to the thermophilic zone.

The maximum temperature for the mixture that did not receive manure was 37.8 °C compared to 41.2 °C for the mixture that received 50 % manure. Although the increase in maximum temperature was very small (9 %), time of peak as well as the duration of maximum temperature were significantly affected by the amount of manure added to the mixture. The time of peak was decreased from 24 h for the mixture that received no dairy manure to 10-11 h for the mixtures that received manure. The duration of the maximum temperature increased from 2.5 h to about 5-7 h due to the addition of manure. The rate of temperature change for the mixtures that received dairy manure was also significantly higher than the rate of temperature change for the mixtures that received no dairy manure. Hall (1998), using similar system and substrate, reported a maximum temperature of 55 °C for 6 h duration. The higher temperature reported in his study could be the result of using higher mass (~4.5kg) compared to only 3.0 kg in the current study. Continuous mixing in the current study also could have resulted in more heat losses with the exhaust gas.

Flynn and Wood (1996) and Lemus and Lau (2002) stated that the temperature profile of the composting process of any organic material is uniquely affected by the carbon source, with small differences between nitrogen sources over time. Flynn and Wood (1996) compared four different bulking agents (peanut hulls, wheat straw, pine bark and paper mill sludge) mixed with chicken litter. The highest reported temperatures were from peanut hulls process (68 °C), followed by pine bark (65 °C) and the lowest

recorded temperatures (< 35 °C) were obtained during the composting process of wheat straw mixture. They attributed the low temperature from the wheat straw mixture to the small weight per unit volume of compost, which most likely prevented heat retention within the small pile they constructed.

The energy released during composting depends on the type of the composted material. Wiley (1955) measured heat out puts of 22.1 to 28.5 kJ/g of decomposed municipal solid waste with significant grease fraction (14.7%). An average value of 18.7 kJ/g of decomposed material was measured by Harper et al. (1992) for chicken litter mixed with straw. A lower value of 15.5 kJ/g of decomposed material was reported by Hogan et al. (1989) for rice hulls and flour. The higher heating value is directly related to the elemental composition of the organic material. Perry and Chilton (1973) define the higher heating value as a fraction of the carbon, hydrogen, oxygen, and sulfur contents. The energy released is due to the oxidation of the organic matter; in which carbon generally dominates (Susott et al. 1975). Susott et al. (1975) and Tillman (1978) found a linear relationship between the higher heating value and the carbon content. In this study, a linear relationship ($R^2$=0.84) between total carbon reduction and the maximum temperature of the composting material was observed (Figure 11.7) and can be described by the following equation:

$$Tm = 11.9 + 2.8\,(TC) \qquad (11.6)$$

Where:

Tm = Maximum temperature achieved (°C)

TC = Total carbon reduction (%)

Reactions in biological systems occur as a result of cell metabolism and enzyme activity. During biological reactions, energy either released (exothermic reaction) or absorbed (endothermic reaction) as a result of internal energy change due to the rearrangement of bonds between atoms. Heat of reaction is equal to the difference in enthalpy of reactants and products (Doran, 1995). Heat of combustion of the organic materials has been considered as an indicator of the total heat produced by the

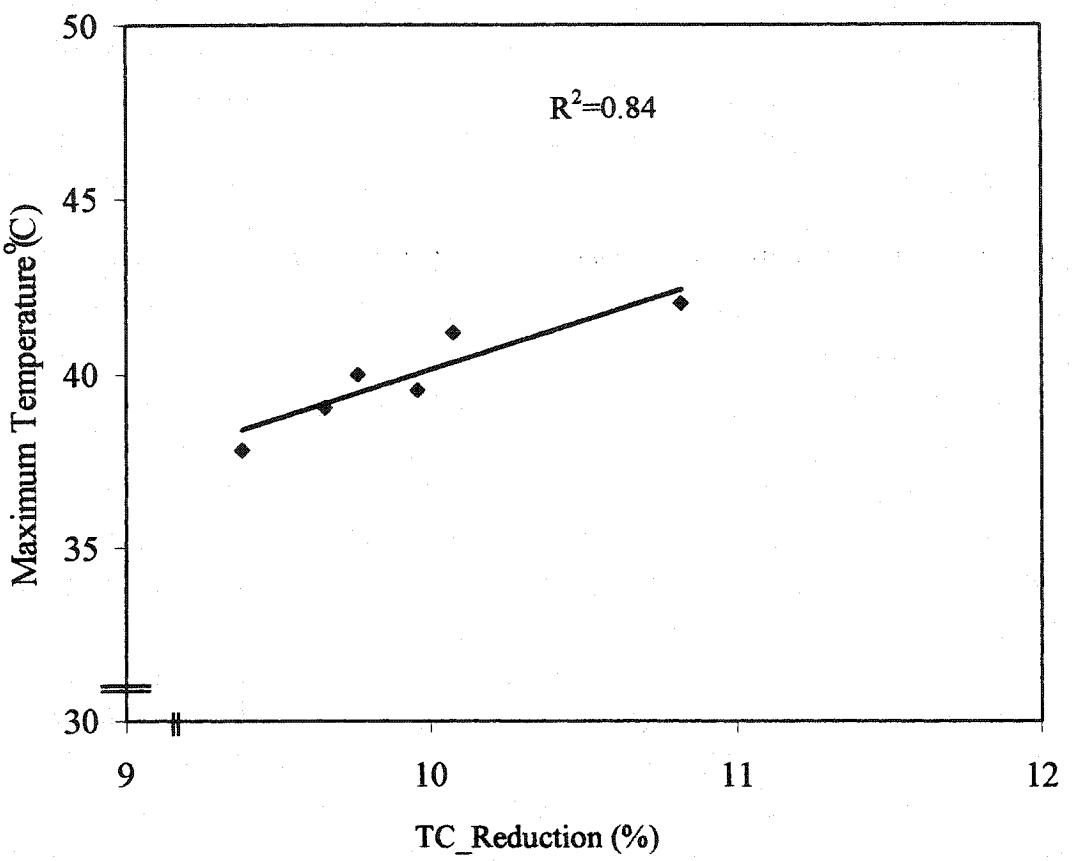



Figure 11.7. Effect of total carbon reduction on the maximum temperature observed during the manure study.

degradation reactions during the composting process (Keener, 1993; and Haug, 1993). However, the real metabolic energy must be calculated based on the bioavailability of nutrients (Miller, 1984; Pagan, 1997; Hogan et al., 1989 and Harper et al., 1992). Thus, heat of chemical combustion is a poor representative of metabolic energy production (biological combustion).

The composting process is an exothermic reaction in which the biodegradable portion of volatile solids (available carbon) is utilized by microorganisms for energy. The release of energy results in an increased temperature of the compost material. (Haug, 1993; and Liang et al., 2003). The reductions in VS and TKN in the current study correlated with the maximum temperature ($T_m$) of the compost ($R^2$= 0.99 and 0.93, respectively) as shown in Figures 11.8 and 11.9. The relationships can be described by the following equations:

$$Tm = -126.4 + 3.8\,(VS) \qquad (11.7)$$

$$Tm = -21.2 + 0.7\,(TKN) \qquad (11.8)$$

Where:

VS = Volatile solids reduction (%)

TKN = Total kjeldahl nitrogen reduction (%)

In animal feed science, corn (mostly starch) and oat straw (lignocellulosic) have identical heat of combustion values (18.6 kJ/g $_{decomposed}$), yet corn has higher biodegradability, and therefore, higher digestive energy. Pure substrates such as glucose, starch, fat and protein contain 15.7, 17.7, 38.6 and 21.6 kJ/g $_{decomposed,}$ respectively (Pagan, 1997). The main substrates that contribute to the energy production are divided into three classes of nutrients: protein, fat and carbohydrates. Carbon content of protein is 53 % with an energy content of 23.7 kJ/g $_{decomposed}$ (Gnaiger and Bitterlich, 1984), while carbon contents of fats and carbohydrates are 74 and 40 %, with energy contents of 39.4 and 17.4 kJ/g $_{decomposed,}$ respectively (Talaro and Talaro, 1999). This explains the

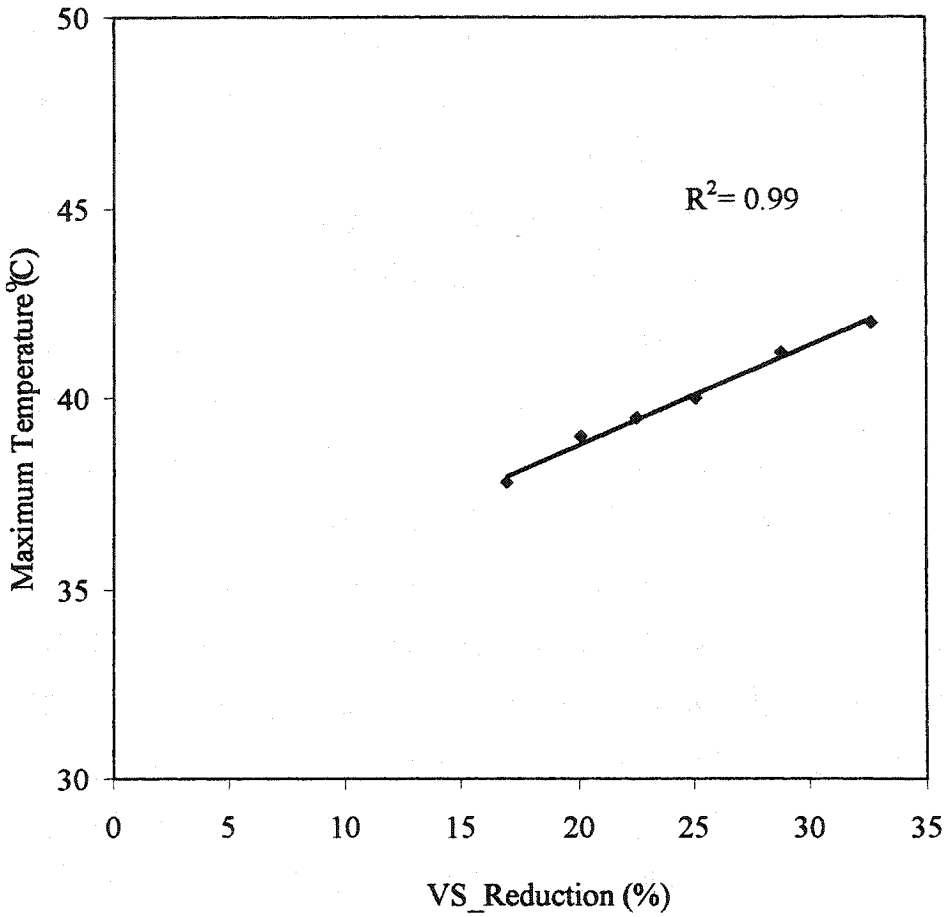



Figure 11.8. Effect of volatile solids reduction on the maximum temperature observed during the manure study.

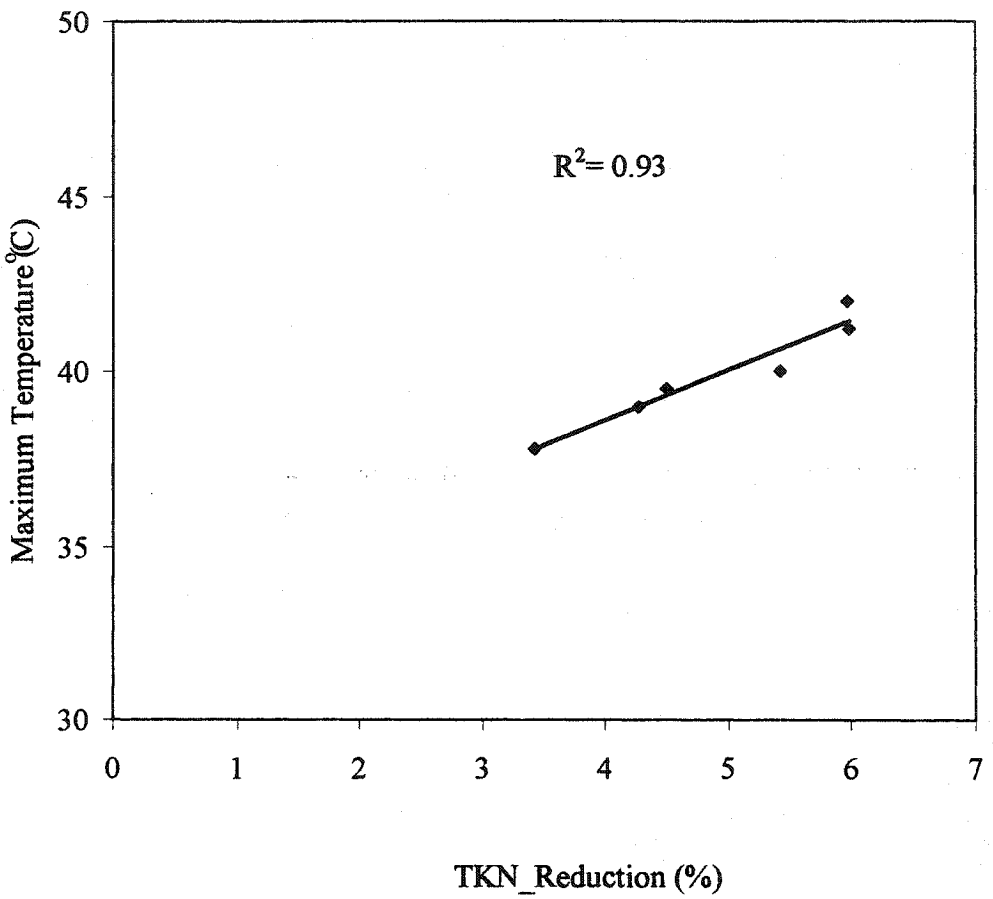



Figure 11.9. Effect of total kjeldahl_nitrogen reduction on the maximum temperature observed during the manure study.

difference of energy gain, in animal feed, between corn (18.6 kJ/g $_{decomposed}$) and soybeans (23.1 kJ/g $_{decomposed}$), as there are more protein and fat in soybeans than corn (Pagan, 1997).

The decomposition process of organic matter is analogous to the digestive process in animals. Some of the components in organic residues are much more resistant to decay than others. Carbohydrates such as sugars and starches will decompose faster than other carbohydrates such as cellulose and hemicellulose, with wax and lignin being the most resistant to decay of all the organic components. Fats and Proteins vary in decay resistance but are generally more resistant than sugars and starches (Hartlieb et al., 2003). During the composting process, microorganisms degrade the raw organic material to synthesize new cellular material and to obtain the energy for these catabolic processes. Several chemical transformations take place as complex compounds are broken down into simpler ones and then synthesized into new complex compounds (NEH, 2000). Carbohydrates are composed of carbon, hydrogen and oxygen. The biochemical degradation of these species under aerobic condition (well aerated composting system) can be described as follows (Polprasert, 1989):

$$\text{Carbohydrates} \longrightarrow \underset{\text{Sugars}}{\text{Simple}} \longrightarrow \underset{\text{Acids}}{\text{Organic}} \longrightarrow CO_2 + \underset{\text{Protoplasm}}{\text{Bacterial}} \qquad (11.9)$$

Alternatively, carbohydrates degradation can be written chemically under ideal condition in a simple form as follows:

$$C_6H_{12}O_2 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad (11.10)$$

Proteins undergo enzymatic oxidation (digestion) to form complex amino compounds through a process called ammonization, which can be described as follows:

$$\text{Proteins} + O_2 \rightarrow \text{Complex amino compounds} + CO_2 + \text{Energy} \qquad 11.11)$$

The complex amino compounds formed can then be synthesized into the microorganisms or undergo additional decomposition into simpler products. The general

reduction in complexity of the amino compounds proceeds from proteoses to peptones to amino acids and acid amides (Hansen et al., 1990). The products of the digestion of the proteins and complex amino acids can only be used in the synthesis of new cellular material if sufficient carbon is available (NEH, 2000). If not enough carbon or energy to incorporate these amino compounds into the cells is available, unstable nitrogen forms accumulate through the process of ammonification. Because the ammonia group is characteristic of amino acids, ammonia ($NH_3$) or ammonium ions ($NH4^+$) will accumulate.

$$R\text{--}NH_3 + HOH \rightarrow R\text{—}OH + NH_3 + Energy \qquad (11.12)$$

Aerobic microbial digestion of lipidic residues results in the production of carbon dioxide, water and biomass. The biological reaction can be described as follows (Jakobsen 1994):

$$\text{Triglycerides} \xrightarrow{\text{Extracellular-lipolitic-enzyme}} \text{Glycerol} + \text{Fatty acids} \qquad (11.13)$$

Fatty acids are transported into the cells, and finally aerobically broken down into $CO_2$ and $H_2O$ (Nunn, 1986;and Ratledge, 1992). However, lipid biological degradation is largely limited because of their insolubility in water (Talaro and Talaro, 1999). Viel et al. (1987) studied the aerobic composting of agricultural rich waste (fats and slaughterhouse). After 7 to 9 days of composting, fats degradation was 80% and peak temperature was 75°C. The lipid concentration after 120 days was further reduced achieving an overall reduction of 95%.

Since municipal solid waste (MSW) usually contains 6 to 15% fats (Peres et al., 1992 and Wiley, 1955), and since lipids contains at least twice the energy of carbohydrates (Wiley, 1957 and Fernandes et al., 1988), this might explain the higher temperature achieved when MSW is used compared to manure, which contains nonbiodegradable carbon in the form of wheat straw as bedding material. Composting high energy content materials in laboratory scale bioreactor is recommended (Lemus and Lau, 2002), especially when thermophilic temperatures are required to achieve pathogen distraction.

## 11.4 Used Oil and Cheese Whey Study

### 11.4.1 Moisture

The moisture contents in all bioreactors stayed within the range of 59-60 % during the experiments due to the equilibrium between the water produced by microbial respiration and the water lost with the exhaust gas. Although higher temperatures and longer period (114 h) were reached during both the cheese whey and oil experiments compared to those of the inoculum and manure experiments, the moisture content stayed relatively constant. Thus, the moisture contents in the current study was within the optimum range of 50 - 60 % reported by Liang et al. (2003) and Richard et al. (2002) and, therefore, moisture content was not a limiting factor in this study.

Drying potential of the composting material is considered a serious problem challenging researchers (Richard et. al., 2002; Walker et al., 1999; Diaz et al., 1993 and Liang et. al., 2003). Significant MC reduction (45 %) was reported by Walker et al. (1999) only after 13 to 20 days of composting under similar aeration condition. Although high temperature was reached during this study, lower moisture content reduction was achieved due to the short composting time (< 5 days) and the compensation of water by the water produced as a by-product of degradation. This finding is in agreement with these of the inoculum and manure studies.

### 11.4.2 Volatile Solids

The volatile solids reductions in the current study were 18.5, 22.2 and 29.1 % for control, cheese whey and used cooking oil experiments, respectively. The results showed that the addition of cheese whey and used cooking oil has increased the volatile solid reduction over that of the control. Although the three mixtures used in this study had similar initial volatile solids concentration, the rates of volatile solids reductions were 0.12, 0.14 and 0.19 kg VS / day for the control and the mixtures receiving cheese whey and used oil, respectively. This indicated that the presence of higher biodegradable

organic carbon in the used cooking oil compare to cheese whey both had higher biodegradable VS concentration than the control mixture. High temperature (52 - 60 °C) has been reported to be the optimum composting temperature (MacGregor et al., 1981; Bach et al., 1984 and Joshua et al., 1998). Both cheese whey and used cooking oil experiments reached thermophilic stage. However, used cooking oil experiment experienced longer composting period, during both the mesophilic and thermophilic stages, than the cheese whey experiment and as a result higher reduction rate of volatile solids was achieved in the used cooking oil experiment.

### 11.4.3 Total Kjeldahl and Ammonium Nitrogen

The initial TKN of the mixtures was 14.3, 18.7 and 14.5 g/kg DM for the control, cheese whey and used cooking oil experiments, respectively. The final TKN values were in the range of 12.9 - 15.4 %. However, the TKN reductions were 3.50, 17.7 and 11.0 % for control, cheese whey and used cooking oil experiments, respectively. The TKN reduction in the control experiment is similar to that of the 10 % inoculum experiment because both mixtures were identical. However, TKN reductions in cheese whey and used cooking oil experiments were higher. De Bertoldi et al. (1982); Diaz et al. (2002); Hamoda et al. (1998) and Martin and Dewes (1992) reported that nitrogen loss during in-vessel composting process is influenced by many factors including carbon bioavailability. The highest reduction (17.7 %) occurred in the cheese whey experiment due to the high initial concentration of nitrogen (1.87 %) and the high temperature achieved (55 °C) that lasted for 14 hours. A TKN reduction of 11.04 % was also noticed in the used cooking oil experiment due to the high temperature (55 °C) that lasted for 17 hours and the relatively high initial nitrogen concentration of 1.45 %.

The initial and final $NH_4$-N concentrations in the mixtures were in the range of 3.3 – 3.5 g/kg DM. This is the result of the microbial conversion of organic nitrogen into $NH_4$-N and the conversion of $NH_4$-N back to organic nitrogen (new cells). In these experiments, $NH_4$-N could not be biologically converted (nitrification) into nitrite ($NO_2$-N) and nitrate ($NO_3$-N) because of the high temperatures.

### 11.4.4 Total Carbohydrate

Total carbohydrates reductions in this study were 21.5, 24.2 and 31.7% for control, cheese whey and used cooking oil experiments, respectively. Higher reductions in soluble forms of carbohydrates (60-86 %) were reported by Sannchez-Monedero et al. (1999), Hsu and Lo (1999) and Mishra et al. (2004). Wood shavings and tomato remains are mostly lignocellulosic materials that have initial high non-bioavailable carbohydrates. Therefore, the reduction in total carbohydrates was only 21.5 % for the control experiment, while it increased to 31.7 % for the same mixture at higher temperature indicating that at high temperature more non-bioavailable carbon become available. This finding is supported by Palm and Sanchez (1991), who stated that the breakdown of complex carbohydrates is accelerated under the higher temperatures.

### 11.4.5 Crude Protein

Crude proteins reductions in this study were 12.4, 25.3 and 17.8 for control, cheese whey and used cooking oil experiments, respectively. A decrease in protein content was also reported by Hsu and Lo (1999). Proteins undergo enzymatic oxidation to form complex amino compounds, which can then be synthesized into microorganisms or undergo additional decomposition into simpler products (Hansen et al., 1990). The products of the digestion of the proteins and complex amino acids can only be used in the synthesis of new cellular material if sufficient carbon is available (NEH, 2000). Otherwise, unstable nitrogen forms ($NH_3$ and $NH_4^+$) will accumulate and become susceptible to volatilization.

### 11.4.6 Total Fat and Grease

Total fat and grease reductions in this study were 64.6, 76.4 and 88.8 for control, cheese whey and used cooking oil experiments, respectively. The difference in reductions of total fat and grease for different mixtures in this study is an indication of the oil bioavailability to indigenous microbial attack. The result obtained in the current study is in agreement with the 85-95% reduction in lipids reported by Fernandes et al. (1988)

and Viel et al. (1987). Viel et al. (1987) reported that most of the thermal energy released was due to the degradation of fats. Higher fats reduction (97 %) was also reported by Baddi et al. (2004) after composting a mixture of olive-mill wastes and wheat straw for one year. Sasaki et al. (2003) reported a reduction of up to 80 % of used soybean oil and 85 % of expired mayonnaise fat were achieved by the end of the composting experiment.

### 11.4.7 Temperature

The generation of heat (as a result of organic matter degradation) continued to raise the temperature until the readily available substrate was depleted (Doran, 1995). The lag period of the mesophilic (first lag) and thermophilic (second lag) phases as well as the rates of temperature increase in the two stages were determined graphically according to the procedure described by Ghaly et al (1989) as shown in Figure 11.1. Table 11.5 shows the kinetic parameters (mesophilic and thermophilic lag times and the rate of temperature rise, maximum temperature reached, time of peak and duration of peak). The results are also illustrated graphically in Figure 11.10.

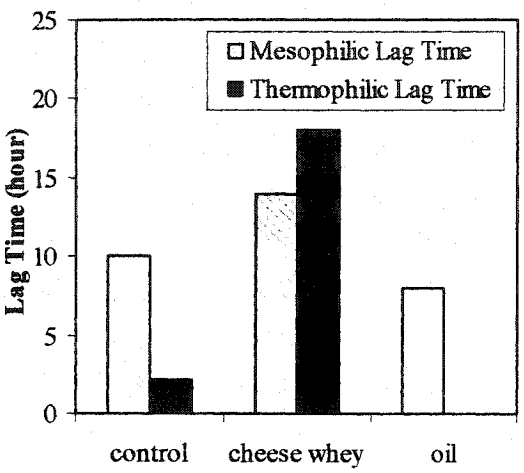
The average temperature in the bioreactors containing cheese whey and oil reached 63.4 and 63.3°C after 60 and 31 hours, respectively. Temperatures higher than 55 °C were observed in the bioreactors containing control, cheese whey and oil and were maintained for 5, 14 and 17 hours, respectively, while temperature higher or equal to 60 °C were recorded in cheese whey and used cooking oil experiments and lasted for 9 hours.

The mesophilic lag time and the rate of temperature change for the control (the mixture of tomato remains: wood shavings: MSW compost without the addition of cheese whey or used cooking oil) were 10 h and 1.84 °C/h, respectively. Addition of cheese whey (1.92 L) to the mixture increased the first (mesophilic) lag phase (14 h), while addition of used cooking oil (64.1 mL) reduced it to 8 h. Composting microorganisms adjusted much faster to the used cooking oil as a nutrient compared to cheese whey. A rate of mesophilic temperature increase of 2.28 °C/h was obtained after the addition of used cooking oil, compare to 1.84 and 1.63 °C/h for control and mixture receiving cheese

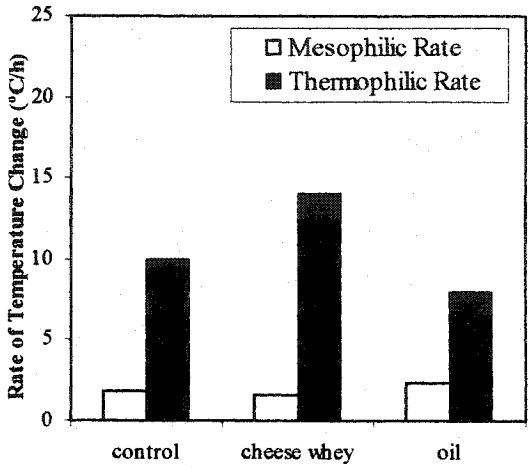
Table 11.5. Kinetic parameters of cheese whey and used cooking oil Study.

| Treatment | Mesophilic Range | | Thermophilic Range | | Maximum Temperature | | |
|---|---|---|---|---|---|---|---|
| | Lag Time (h) | Rate (°C/h) | Lag Time (h) | Rate (°C/h) | Value (°C) | Time of Peak (h) | Duration (T≥ 60°C) (h) |
| Control | 10 | 1.84 | 2.2 | 0.95 | 56.8 | 37 | 0 |
| Cheese Whey | 14 | 1.63 | 18 | 2.24 | 63.4 | 60 | 9 |
| Used Cooking Oil | 8 | 2.28 | 0 | 2.28 | 63.3 | 31 | 9 |

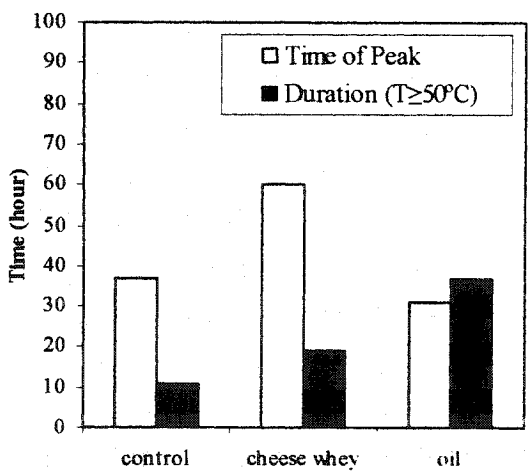
40 °C is the end of mesophilic stage and the beginning of the thermophilic stage.



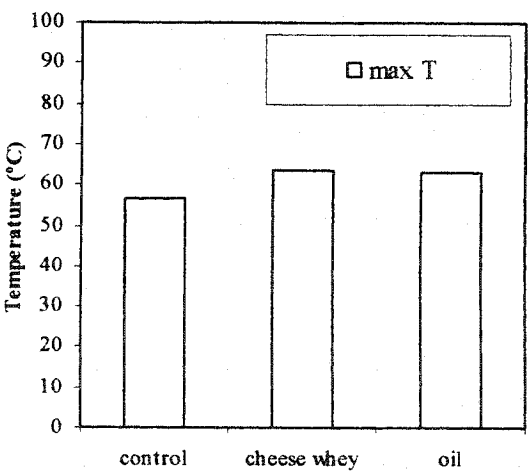

(b) Mesophilic and Thermophilic Lag Time.




(c) Mesophilic and Thermophilic Rate of Temperature Change.




(b) Time of Peak and Duration.




(e) Maximum Temperature Reached.

Figure 11.10. Effects of cheese whey and used cooking oil on the kinetic parameters of the composting process.

whey, respectively. The addition of cheese whey significantly increased the second lag phase from 2.2 (for the control) to 8.0 h. No thermophilic lag time was noticed for mixture receiving used cooking oil as both the mesophilic and thermophilic microorganisms adjusted well to the used cooking oil. The rates of temperature change during the thermophilic stage were 0.95, 2.24 and 2.28 °C/h for the control, cheese whey and used cooking oil experiments, respectively.

VanderGheynst et al. (1997) reported that a maximum temperature of 60 °C was obtained after 56 h and was maintained for 344 h during the composting of a synthetic food waste and digested biosolids in a 0.77 $m^3$ bioreactor with 5 and 12.5 h lag times of mesophilic and thermophilic, respectively. The maximum temperature and mesophilic lag time reported by the authors were in agreement with the calculated value in the current study for the control and the used cooking oil experiments, but the maximum temperature was maintained for a shorter time in this study due to the smaller mass utilized (3.5 kg).

The pH value of the mixture receiving cheese whey was about 5.0 - 5.5. Sundberg et al. (2004) reported very small carbon dioxide production in samples with an initial pH lower than 6.0. Thus, the longer mesophilic lag time occurred in the mixture with cheese whey addition is a result of low pH. Several researchers (Beck-Friis et al., 2001; Weppen, 2001 and Sundberg et al., 2004) reported a decline in microbial activity during the transition from mesophilic to thermophilic stages when composting acidic material (pH ~ 4.5-5.5).

The time of peak was affected by the type of carbon added to the mixture. Maximum temperature was achieved after 31 h during the composting process of the mixture with used cooking oil, while it required double the time (60 h) to peak during the composting process of the mixture with cheese whey. The initial lag period in the cheese whey experiment was very long.

The biodegradable portion of volatile solids (bioavailable carbon in the form of carbohydrates, proteins and fats) is utilized by microorganisms for energy. The release of energy results in increased temperature of the compost material. (Haug, 1993; and Liang et al., 2003). A strong correlation ($R^2$= 0.93) was found between the total fat and grease

reduction and the duration of high temperature (≥55 °C) of the compost as shown in Figures 11.11 and Equation 11.11.

$$D = -33.0 + 0.6\,(TFGr) \qquad (11.11)$$

Where:

D = Duration of temperature ≥55 °C (h)

TFGr = Reduction in fat and grease (%)

However, the initial fat and grease concentration correlated poorly ($R^2$= 0.68) with the duration of high temperature. The relationships can be described by equation (11.12). Similar finding was reported by Fernandes et al. (1988).

$$D = 4.6 + 2.4\,(TFGi) \qquad (11.12)$$

Where:

TFGi = Initial fat and grease (%)

## 11.5 Heat Analysis Study

### 11.5.1 Heat of Mixing Study

The calculated energy required for mixing (2.16 kJ/h) using the heat balance approach was only 83.1 % of the energy measured using multimeter. The 16.9 % difference could be due to the heat losses in the motor itself. Doran (1995) stated that friction in the mixing motor gearbox and seals reduce the transmitted energy. The author indicated that electrical power consumed by mixing motors is always greater than the resultant mixing power and the difference will depend on the efficiency of the drive. Doran (1995) stated that the efficiency of the drive decreases as the motor runs at a lower load due to the unmatched horsepower requirement of the motor to the load requirement.

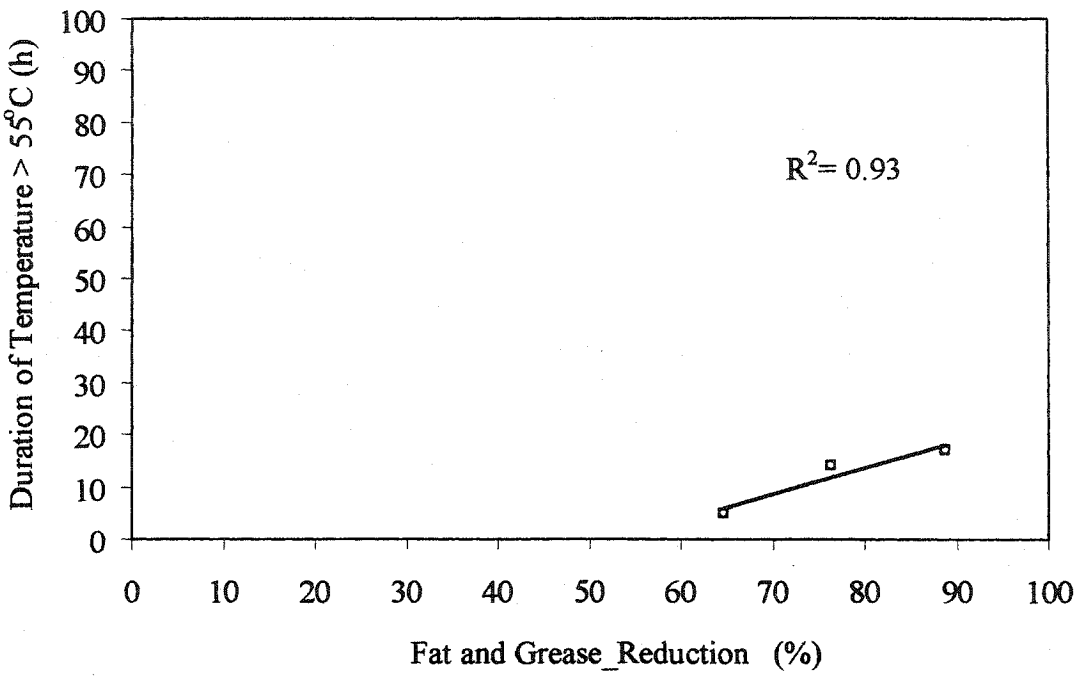



Figure 11.11. Fat and grease reduction during the cheese whey and used oil experiments.

## 11.5.2 Bioreactor Heat Analysis Study

The cumulative heat production is shown in Figure 11.12. Heat evolution during the composting process is due to the microbial degradation of bioavailable substrate (Nell and Wiechers, 1978). The calculated average heat production value in this study was 16.4 kJ/g decomposed material, which is 50 % lower than the value reported by Wiley (1957) when composting municipal solid waste with high lipid content (14.7 %).

Heat production rate during the composting process increased with time reaching its peak value after 30 hour from start of the composting process (Figure 11.13). As the heat was generated, the composted material's temperature increased reaching 63.3 °C at the peak time. The peak of heat production rate was calculated to be 62.5 kJ/h, which is in agreement with the rate reported by Miller (1984) during the composting of sewage sludge and wood chips mixture, and the rate of heat production from dairy manure reported by Iwabuchi et al. (1995). It is also in agreement with the results given by Carlyle and Norman (1941), Mote and Griffis (1979), Harper et al. (1992), Wiley (1955) and Miller (1984) as shown in Table 11.6. The rate of heat production decreased dramatically after the temperature of the material reached 60 °C. This is possibly due to the fact that after this temperature exceeded the optimum condition for the thermophilic microorganisms and, therefore, microbial growth and possibly microbial density declined resulting in decreased bioreactor temperature. Another reason would be the consumption of bioavailable nutrient by the microorganisms.

In this experiment, 36.5% of the total heat produced was lost by conduction through the cylindrical body and sidewalls of the bioreactor. According to Clark et al. (1977) and Miller (1993), the conductive heat losses in laboratory-scale bioreactors are expected to be high due to the higher surface area to volume ratio. Bach et al. (1987) reported that the conductive heat losses from a well-insulated composting experimental chamber accounted for as high as 61.6% of the overall heat losses. Therefore, when simulating the actual composting system, it is a usual practice to totally reduce the conductive heat losses in laboratory scale bioreactors by using controlled water bath

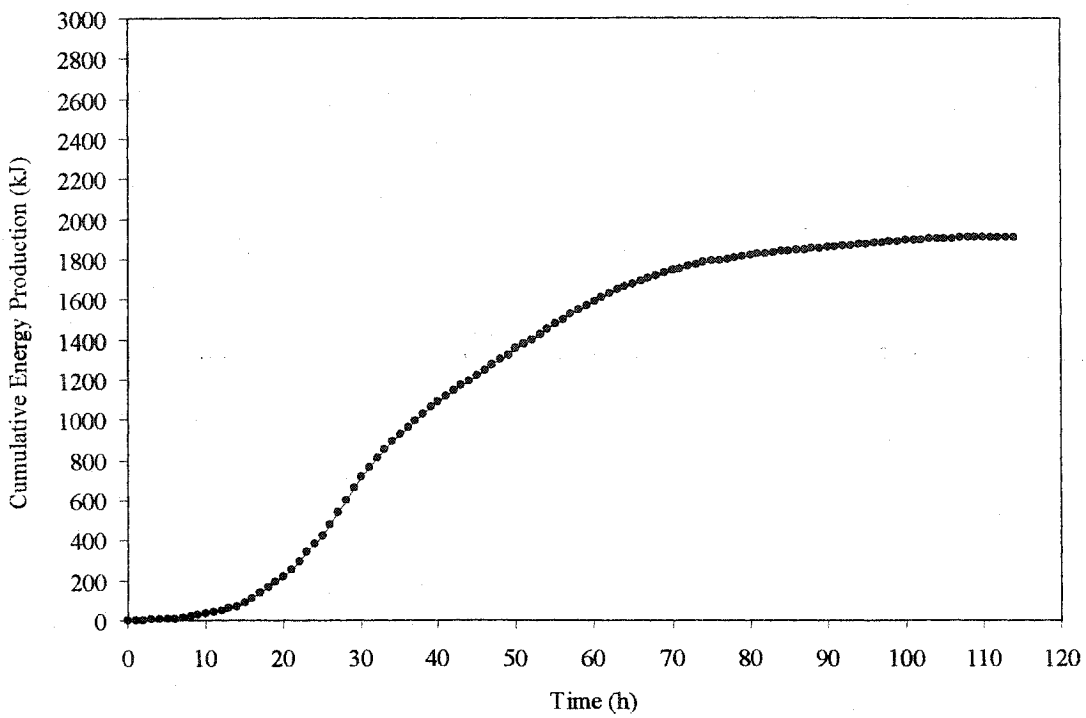



Figure 11.12. Cumulative heat production during the heat analysis study.

Table 11.6. Some of rate of heat production reported in literatures.

| Material | MC | VS | | DM | C/N | Heat Production Rate | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | In | Out | | | kJ/g.DM initial | kJ/g.DM decomposed | Duration (h) | |
| | (%) | (%) | (%) | (g) | | | | | |
| Cotton gin (1 year old) | 57.4 | --- | --- | 350 | 21.5 | 1.2 | NR | 16 | Mote and Griffis(1982) |
| Cotton gin (new) | 57.4 | --- | --- | 350 | 26 | 1.6 | NR | 16 | Mote and Griffis(1982) |
| Dairy manure and Rice hulls | 65.5 | --- | --- | 500 | 30 | 2.3 | NR | 24 | Mote and Griffis(1982) |
| Municipal waste (14.7% fat) | 65.7 | 93.1 | 92.2 | 6636.4 | 34 | 2.6 | 22.1-28.5 | 144 | Wiley (1955) |
| Primary sludge + wood chips | | | | | | | 15.2-21.8 | | Miller (1984) |
| Mixture of Rice hulls and | 54 | 81 | 77.9 | 2965 | NR[a] | 2.4 | 14.2 | 240 | Hogan et al. (1989) |
| flour,(50:34:16) | 54 | 81 | 77.9 | 2895 | NR[a] | 2.6 | 16.8 | 240 | Hogan et al. (1989) |
| Chicken litter with wheat straw | 75.7 | 87 | 80.1 | 8583000 | 23.5 | 6.2 | 15.4-22.0 | 190 | Harper et al. (1992) |
| Mixture of tomato and wood shavings | 60 | 87.2 | 61.8 | 1400 | 30 | 1.4 | 16.4 | 114 | Present study |

[a] C/N was not reported, however, nutrients were added to eliminate any nutrient limitation.

NR Value not reported.

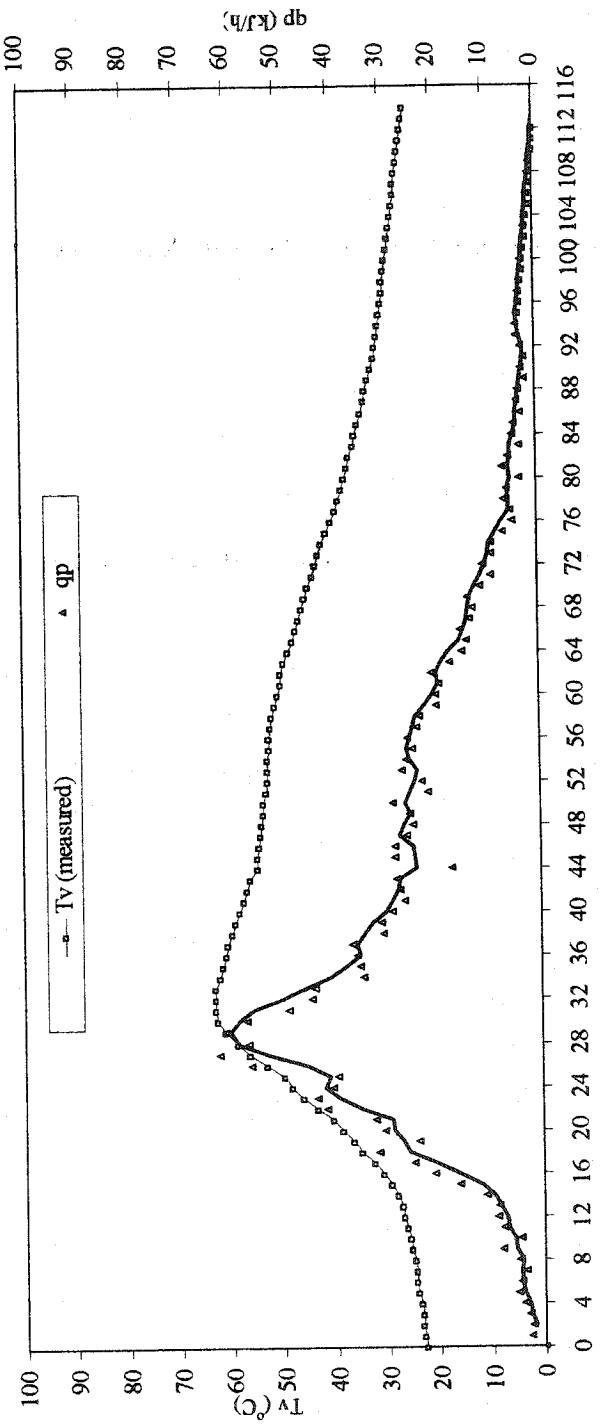



Figure 11.13. Rates of heat production and average bioreactor temperatures during the heat analysis study.

with an average temperature as close as possible to the one inside the bioreactor (Sikora et. al., 1983; Hogan et al., 1989; Iwabuchi et al., 1995; and Huang et al., 2000), controlled air bath as an insulative medium (Strom, 1985; Atkinson et al., 1996a; and Larsen and McCartney, 2000), or electrical coil around the system (Huang et al., 2000). Due to the good insulation of the bioreactor used in this study, the total conductive heat losses were less than those of 90 % reported by Hogan et al. (1989) in laboratory scale bioreactors with minimum insulation. Heat loss due to aeration (as sensible and latent heat) in this study accounted for 62.6 % of the total heat produced. According to MacGregor et al. (1981), the latent portion can be as high as 90% of the total heat losses due to aeration.

## 11.6 Continuous Addition of Used Cooking Oil study

### 11.6.1 Moisture

The moisture contents in first bioreactors receiving 9 mL of used cooking oil was reduced by only 2.6 % after 5 days of composting, while the reduction in moisture content was higher (5.2 and 14.5 %) for the mixtures receiving 18 and 36 mL of oil, respectively. The reduction in moisture content correlated ($R^2$= 0.99) with the bioreactor maximum temperature as shown in Figure 11.14. The relationship can be described by the following linear equation:

$$MC_Reduction = -221.2 + 3.6\,(T_m) \qquad (11.13)$$

Where:

MC_Reduction = Moisture reduction (%)

As the temperature increased, more water was evaporated from the material. However, the moisture contents of these mixtures (52-60 %) were still within the optimum moisture content range of 50-60 %. Therefore, moisture content was not a limiting factor during this study.

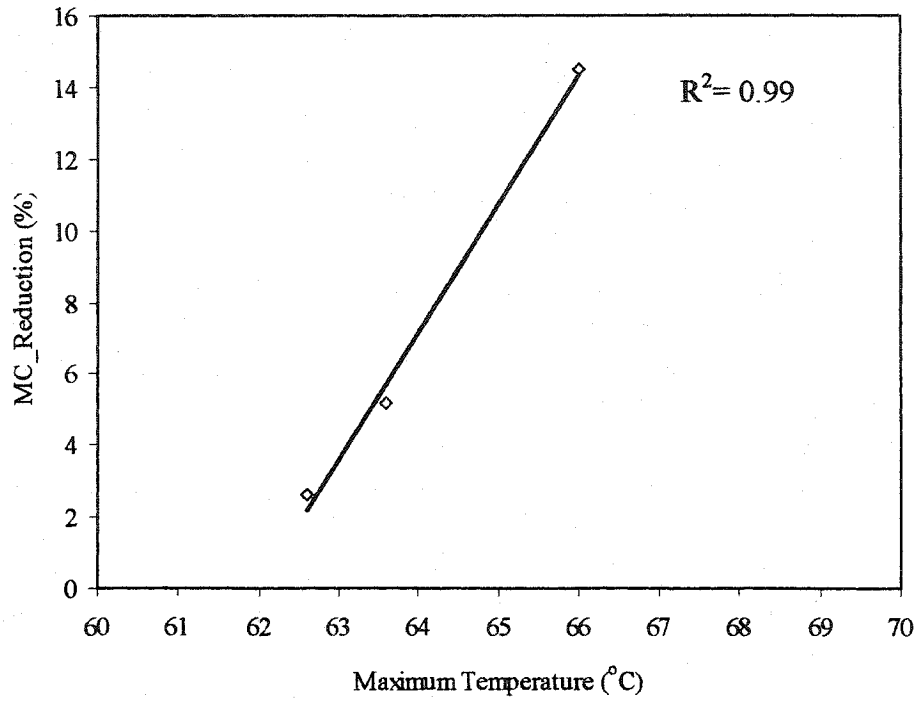



Figure 11.14. Effect of maximum temperature on the moisture content reduction during the continuous addition of used cooking oil study.

### 11.6.2 Volatile Solids

The volatile solids reductions were 2.8, 2.6 and 2.1 % for mixtures receiving 9, 18 and 36 mL of used cooking oil, respectively. The results showed that the addition of used cooking oil at 18 mL every 12 h has decreased the volatile solid reduction by 7 % over that of 9 mL every 12 h, while the addition of 36 mL every 12h had the lowest reduction of volatile solid (2.1 %). Lemus and Lau (2002) reported that most of the thermal energy released was due to the degradation of fats. Therefore, continuous addition of used cooking oil at a higher rate provided bioavailable source of carbon that was preferred by microorganisms over the carbon in the initial volatile solids.

### 11.6.3 Total Kjeldahl and Ammonium Nitrogen

The initial TKN of the mixtures used in the study were approximately 14.8 g/kg DM. The final TKN values were 6.5, 7.3 and 5.9 g/kg DM for the mixtures receiving 9, 18 and 36 mL of used cooking oil, respectively. The reductions in TKN were in the range of 39.5 – 57.1 %, which are higher than 12-27 % reported by Sommer and Dahl (1999). However, they are in agreement with the reduction of 37 - 60 % reported by Tiquia et al. (1998) during the composting process of manure and corn stalks mixture in a static windrow and the reduction of 20 - 77 % reported by Martins and Dewes (1992). The highest reductions were in the bioreactors receiving 9 mL and 18 mL of used cooking oil, and the lowest reduction was in the bioreactor receiving 36 mL of used cooking oil. The TKN reductions in all bioreactors were higher than reductions previously reported in the inoculum and manure studies because of the continuous addition of the carbon source, which resulted in more nitrogen being utilized. However, the differences in reduction among the three used cooking oil treatments can be explained by the fact that nitrogen losses are mainly by volatilization in the form of $NH_3$, and possibly $N_2$ and $NO_x$ as reported by Martins and Dewes (1992). Nitrogen volatilization depends on the nitrogen balance with the available carbon (Rynk et al., 1992). Therefore, the least nitrogen reduction was in the bioreactor receiving 36 mL of used cooking oil.

The initial and final $NH_4$-N concentrations were relatively constant (3.2 g/kg DM) for all mixture as a result of the microbial conversion of organic nitrogen into $NH_4$-N and the conversion of $NH_4$-N back to microbial cells. The nitrification process was inhibited by the high temperature as reported by Morisaki et al. (1989) and Fang et al. (1999).

### 11.6.4 Total Fat and Grease

Total fat and grease reductions in this study were 73.6, 88.5 and 81.8 for mixtures receiving 9, 18 and 36 mL of used cooking oil, respectively. The result of the current study is in agreement with the 85-95% reduction in lipids reported by Fernandes et al. (1988), Lemus and Lau (2002) and Baddi et al. (2004). Increasing the dose of the used cooking oil from 9 to 18 mL every 12h increased the reduction of the total fat and grease at the end of the experiment (5 days) by more than 20 %. Although, higher dose of oil (36 mL/12h) did not show higher reduction, the average temperature in the bioreactor receiving 36 mL of used cooking oil every 12 h was still high (~50 °C).

Repeated batch composting processes were implemented by Sasaki et al. (2003), who studied the bioavailability of used soybean oil during the composting process as an environmental friendly way of disposal. The reduction of oil content reached 80 % by the third application and continued at a constant rate during the fourth and fifth applications. However, a slight decrease was notice thereafter (61 % by the seventh application). Almost 3 % of the oil remained at the end of each application, which they explained was due to the fact that some oil permeated deeply into the saw dust and was not bioavailable for microbes.

### 11.6.5 Temperature

The heat generated as a result of organic matter degradation continued to raise the temperature until the readily available substrate was depleted. The lag period of the mesophilic (first lag) and thermophilic (second lag) stages as well as the rates of temperature increase in the two stages were determined graphically according to the procedure described by Ghaly et al (1989) as shown in Figure 11.1. Table 11.7 shows the

Table 11. 7 . Kinetic parameters during the continuous addition of used cooking oil study.

| Mixture | Mesophilic Range | | Thermophilic Range | | Maximum Temperature | | |
|---|---|---|---|---|---|---|---|
| | Lag Time | Rate | Lag Time | Rate | Value | Time of Peak | Duration (T≥ 55°C) |
| | (h) | (°C/h) | (h) | (°C/h) | (°C) | (h) | (h) |
| Addition of 9mL | 8 | 2.2 | 0 | 2.2 | 62.9 | 31 | 37 |
| Addition of 18mL | 8 | 2.2 | 0 | 2.2 | 63.4 | 30 | 40 |
| Addition of 36mL | 8 | 2.2 | 0 | 2.2 | 63.3 | 31 | 94 |

40 °C is the end of mesophilic stage and the beginning of the thermophilic stage.

kinetic parameters (mesophilic and thermophilic lag times and the rate of temperature rise, maximum temperature reached, time of peak and duration of peak).

The average temperature in the bioreactors receiving 9, 18 and 36 mL of used cooking oil reached 62.9, 63.4 and 63.3.0°C after 31, 30 and 31 hours from the start of the composting process, respectively. Temperatures higher than 55°C were observed in all bioreactors and were maintained for 37, 40 and 94 hours, while temperature higher or equal to 60°C lasted 8, 27 and 52 hours for the reactors receiving 9, 18 and 36 mL used cooking oil, respectively.

The mesophilic lag time and the rate of temperature change for the mixtures were 8 h and 2.2 °C/h, respectively. Thermophilic lag time was not observed during these experiments, and the thermophilic rate of temperature increase was similar (2.2 °C/h) to that of the mesophilic rate. That is because all these mixtures were identical and reached thermophilic stage before the addition of used cooking oil. The differences among these experiments were the duration of high temperature. Temperatures higher than or equal to 60 °C were recorded (8, 27 and 52 h for mixtures receiving 9, 18 and 36 mL of used cooking oil, respectively). This can be explained due to the fact that more bioavailable carbon was added. All three bioreactors reached average temperature of approximately 62-63 °C at almost the same time ~30-31 h. However, temperature continued to increase in the bioreactor receiving 36 mL of used cooking oil reaching 66.0 °C after 47 h from the start of the composting process.

The total amount of used cooking oil added to the mixtures correlated with the duration of high temperature (≥55 °C) of the compost ($R^2$= 0.92). This is because the used cooking oil added is fat and as a result only fat contributed to the increase of temperature as shown in Figures 11.15. The relationship can be described by the following equation:

$$D = 10.0 + 2.2\ (TFG) \qquad (11.14)$$

Where:

D = Duration of temperature ≥55 °C (h)

TFG = Total amount of oil added (mL)

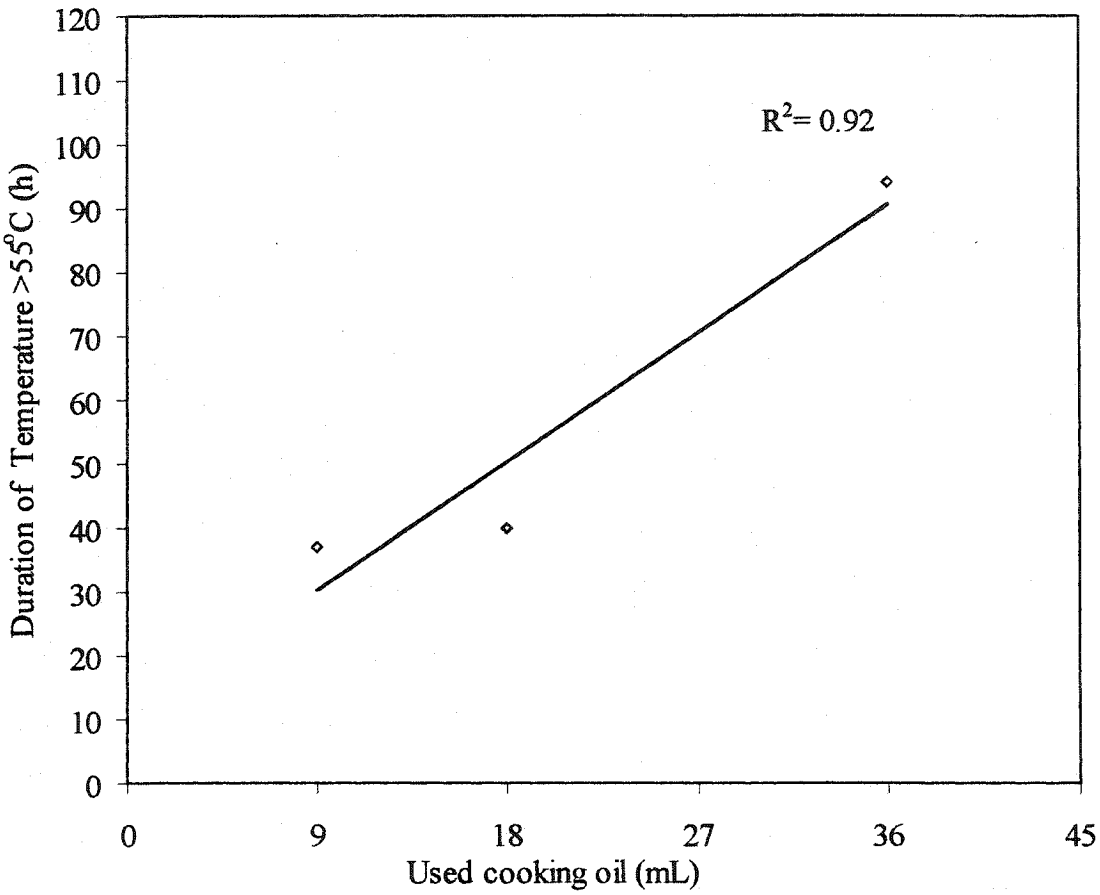



Figure 11.15. Effect of the total amount of used cooking oil on the duration of high temperature during continuous addition of used cooking oil study.

# 11.7 Virus Study

## 11.7.1 First Tomato Batch

The first batch of grown tomato plants (Golden Boy variety) was closely monitored and the leaves were tested for TMV on a regular basis for a month after the first sign of mosaic-like symptom was noticed. However, negative results were always given by ELISA assay. A green house specialist in the Biology Department of Dalhousie University was contacted to help in determining the type of infection. Samples of tomato leaves were checked under a microscope. A large population of two spotted spider mites was observed (Figure 11.16) on the tomato leaves. It was concluded that the mosaic-like symptoms were due to the two spotted spider mites manifestation.

The two spotted mites have been reported to infest over 200 species of plants including ornamentals, fruit crops, vegetable crops such as tomato, bean, pea, squash, eggplant and cucumber and trees. The mite is one of the most destructive groups of pests to agricultural crops worldwide, and is also a serious pest in greenhouses (Fasulo and Denmark, 2004). The life cycle of the two spotted spider mite is composed of five stages: the egg, three immature stages and the adult (Alston and Reding, 2003). Each immature stage goes through three phases including active feeding, a resting period and a molt when the skin is shed. Eggs and immature stages are usually located on the underside of leaves, but can also be found on the upper surfaces when population densities are high. The adult female lives for two to four weeks and is capable of laying several hundred eggs during her lifetime. The length of time from egg to adult varies greatly depending on temperature. Under optimum conditions (~ 26 °C), spider mites complete there development in 5 to 20 days (Fasulo and Denmark, 2004; and Alston and Reding, 2003). Adults and immature stages of the mites primarily feed on plant leaves. The mites have needle-like mouth, which they use to penetrate plant tissues (Fasulo and Denmark, 2004). Symptoms of mite infestations include (a) whitish or yellowish speckled areas on the

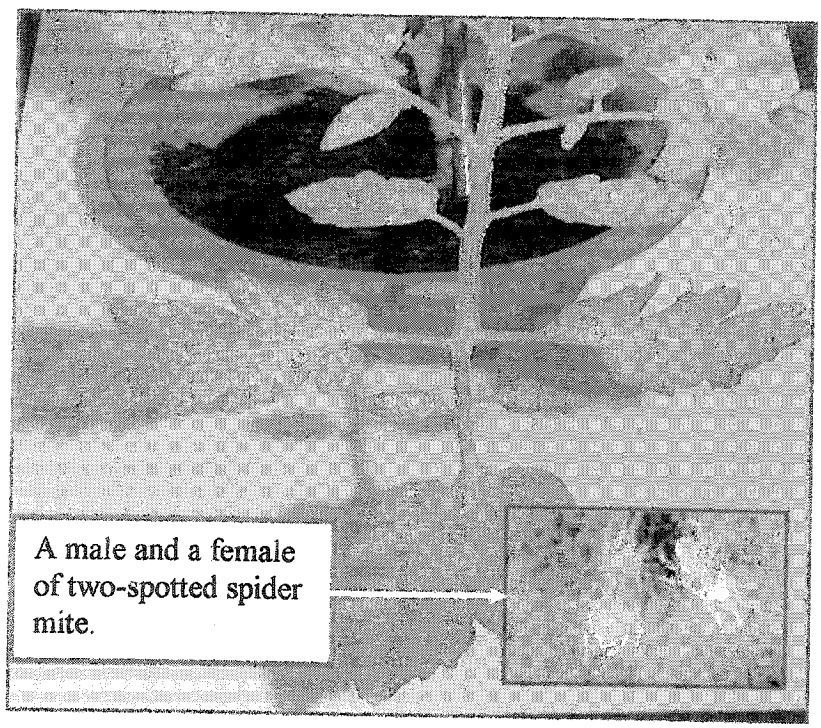



Figure 11.16. Tomato leaf infested by two spotted spider mites.

upper surfaces of leaves caused by damage to chloroplasts/chlorophyll, (b) leaves turning yellow, gray or bronze as the result of continued feeding, (c) a reduction in photosynthetic activity and fruit color, size and production, and (d) complete defoliation, stunting and death may occur if the mites are not controlled (Fasula and Denmark, 2004 and Alston and Reding, 2003) as was the case in this study (Figure 10.10).

The low density of inocula used in the inoculation procedure and spider mites manifestation could be the reason of the inoculation failure. Another possible reason is the mechanical damage technique (filling) used in the first inoculation procedure, which may have resulted in the death of tomato plant cells causing the virus particle to be isolated within a dead lesion thereby preventing the virus from spreading into the vascular plant system (Abbink et al., 1998). An attempt was made to find if the tomato plants used in the study were genetically manipulated to resist TMV infection. The greenhouse from which the tomato plants were purchased could not provide this information.

### 11.7.2 Second Tomato Batch

After spider mites manifestation was confirmed, the first experiment was terminated. All tomato plants were removed (with soil) and the hydroponic system, tools and pots were first washed using 3% trisodium phosphate (TSP) solution which has a high pH and completely inactivates TMV (Zitter and Provvidenti, 1984). A second wash was preformed with diluted bleach solution (4 %). A final rinse was performed using steamed water. Then, the hydroponic system was left to dry before being sprayed with Trounce, a natural fast acting short-lived contact insecticide (Safer Ltd., Scarborough, Ontario), which is most affective against insects including spider mites, aphids and whitefly. The hydroponic system was left for a week before the second TMV inoculation procedure was carried out.

Three different varieties of tomatoes (Roma, Scotia and Red Robin) were grown for the second inoculation in order to increase the chance of infection. Samples of the second inoculated tomato plants were tested for TMV infection along with the infected

tomato and tobacco leaves received from the Potato Research Centre (AAFC, Fredericton, New Brunswick). Positive result of infection was achieved in all collected samples from the second batch (3 varieties) and the leaves received from the center.

### 11.7.3 Local Lesion Bioassay

The average temperatures profiles of TMV experiments increase gradually due to the utilization of bioavailable carbon reaching a peak of 63.3 °C after 31 hours of operation. Thermophilic temperatures of 61.3 ± 0.92°C, 63.2 ± 0.96 ° C, 64.5 ± 2.0 °C, 64.8 ± 1.9 °C , 64.9 ± 1.7 °C and 64.9 ± 1.7 °C were maintained in the first, second, third, fourth, fifth and sixth bioreactors for 24, 48, 72, 96, 120 and 144 hours, respectively. The temperature profile is similar to that recorded during used cooking oil experiment (36 mL).

The retrieved samples were tested for the *tobacco mosaic virus* (TMV) ability to infect a susceptible plant host using local lesions bioassay. The bioassay showed an initial concentration ( in the uncomposted infected material) of 150 local lesions/leaf (LL/L), which was reduced to 35, 12, 2, 0, 0 and 0 LL/L after 24, 48, 72, 96, 120 and 144 hours of the thermophilic composting at temperatures of 61.3, 63.2, 64.5, 64.8, 64.9 and 64.9 °C, respectively.

### 11.7.4 TMV Inactivation

TMV infected composting materials are always considered higher risk because TMV is not completely inactivated in some composting systems and can be directly transmitted to plant roots without a vector (Bollen and Volker, 1996). The authors recommended that compost from plant residues infected by TMV should either be burned or not be used in susceptible crops. In the current study, TMV completely lost its ability to infect the leaves of a susceptible host after less than 4 days of controlled thermophilic composting. Ryckeboer et al. (2002) investigated the fate of *tobacco mosaic virus* (TMV) during two days of thermophilic anaerobic digestion at 52 °C followed by 19 days (at 58 °C) or 12 days (at 68 °C) of thermophilic aerobic composting. TMV was not inactivated

during the anaerobic pretreatment, but it was significantly reduced (by a factor of three) when the anaerobic treatment was followed by a composting process of 19 days at 58 °C and was reduced even further in an aerobic composting treatment of 12 days at 68 °C. It must be noted that the aerobic treatment of their study was simulated using hot air incubator to simulate the composting condition. However, the real composting environment has other advantageous destruction mechanisms beside high temperature such as microbial competition (antagonism) and toxicity of by products (pH, ammonia and organic acids) released as a result of plant residues decomposition (Lopez-Real and Foster, 1984 and Bollen, 1993) that if utilized could inactivate TMV in a shorter time.

The inactivation period of TMV observed in the current study is significantly shorter than the two weeks reported by Marciniszyn and Gottschall (1999), the 21 days at 64-70 °C reported by Noble and Roberts (2004), and the 12 days at 68 °C reported by Ryckeboer et al. (2002). The short time required for complete inactivation of TMV in the current study was achieved as a result of maintaining a constant high temperature in the bioreactor by the continuous addition of bioavailable source of carbon (used cooking oil) and the utilization of a continuous low mixing (5 RPM) that eliminated any temperature gradient in the composting system.

According to Hogland et al. (2003) and Ryckeboer (2002), the high temperature (about 60 °C) that can be reached during the thermophilic stage of composting is the most important factor for inactivation of plant pathogens. Although higher temperature will decrease pathogens dramatically, temperature fluctuations, clumping of solids and improper mixing of raw material and amendment are the most negative characteristics of solid mixtures during composting process (Haug, 1993). Bruns et al. (1993) reported that complete inactivation of plant pathogens depends on the kind of pathogen, the raw composted material type and the composting method (system) utilized.

Bollen et al. (1986) stated that temperature and time relation should be considered as the most reliable parameter for prediction of pathogens inactivation. However, Hay (1996) stated that continuous monitoring of bioreactor temperature-time duration is not always enough, and it should always be supplemented by the monitoring of indicator

pathogens. In this study, the TMV reduction as a function of temperature and time (Figure 11.17) can be described by the following equation ($R^2$=0.996):

$$LL_t = 200.000 - 10.900\,(t) - 2.010\,(T) + 0.148\,(T \times t) + 0.007\,(t)^2 \qquad (11.15)$$

Where:

$LL_t$ = number of local lesions at time t (-)

t = time (h)

T = temperature (°C)

## 11.8 Mold Study

The average temperatures profiles of the three experiments are similar. The average bioreactors temperatures increased gradually reaching the peak of 63.3 °C after 30 -31 hours of operation in all bioreactors. The average thermophilic temperatures of 63.9 ±1.8 °C , 63.5 ± 1.1°C and 62.6 ±1.5 °C were maintained in the first, second and third bioreactors for 24, 48 and 72 hours, respectively.

### 11.8.1 ELISA Assay

The initial quantity of the dried mycelium in the infected uncomposted material was 14.6 µg/g of mixture which was reduced to 12.9, 8.8 and 2.4 µg dried mycelium /g of compost after the 54, 78 and 102 hours of composting (24, 48 and 72 hours of thermophilic composting), respectively. The reductions were 11.6, 39.9 and 83.4 % after 24 hours (at 63.9 ± 1.8 °C) , 48 hours (at 63.5 ± 1.1 °C) and 72 hours (at 62.6 ± 1.5 °C), respectively. According to Bollen et al. (1986), temperature is considered to be the most important factor for the elimination of plant pathogens. The effect of the temperature is mainly attributed to the denaturation of cell proteins. ELISA test was used in the study to measure Botrytis cinerea specific protein. The test, however, can not distinguish between viable and dead cells (Christensen et al., 2001; and Chitarra and Van den Bulk, 2003) and

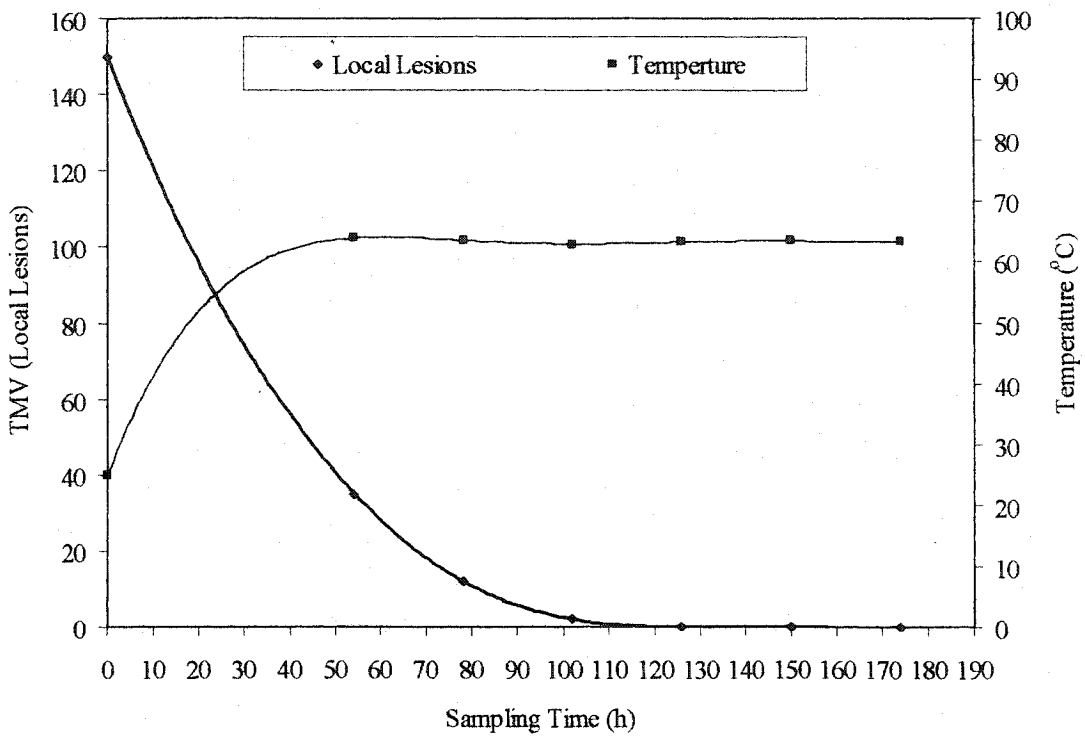



Figure 11.17 TMV local lesions and temperature changes during the TMV study.

as such it was not known if the remaining *Botrytis cinerea* specific protein was for active or dead cells. Christensen et al. (2001) and Suárez-Estrella et al. (2002) suggested using the ELISA test as a secondary confirmation of plant disease in infected horticultural wastes during the composting process, especially in the beginning of the process.

### 11.8.2 Plating Assay

Plating assay was necessary to determine the time at which *Botrytis cinerea* was completely inactivated. The plate with the initial mixture (infected uncomposted sample) showed the pure colonies of *Botrytis cinerea* and intensive growth of a mixture of psychrophilic microorganisms (fungi and bacteria), because of the low incubation temperature (16° C) which retarded the growth of mesophilic and thermophilic composting microorganisms. The colonies of *Botrytis cinerea* were gray in color, circular filamentous in shape with raised elevation. The microscopic observation of the pure culture plate of *Botrytis cinerea* gave a clear understanding of the morphology of the mold at high magnification (x500). *Botrytis cinerea* produced gray mycelia with long-branched condiophore that had rounded apical cells bearing grapelike clusters as described by Agrios (1988) and Willetts (1997).

The plates of the retrieved compost samples (initially infected with *Botrytis cinerea*) were examined carefully for the existence of the target mold. Some growths of *Botrytis cinerea* were noticed in plates treated for 24 hours (at 63.9 ± 1.8 °C). However, complete disappearance of *Botrytis cinerea* was achieved in the plates of the compost samples treated for 48 hours (at 63.5 ± 1.1°C) and 72 hours (at 62.6 ± 1.5 °C), respectively.

### 11.8.3 *Botrytis cinerea* Inactivation

Some fungi appeared during the mesophilic stage and until the second day of thermophilic stage. Most fungi are inactivated during thermophilic stage. Lopez-Real and Foster (1984) obtained complete inactivation of *Plamodiophora brassica* spores in plant tissue after 24 h exposure in compost at 54 °C, but not at 65 °C for 10-min (vitro). Suárez-Estrella et al. (2003) studied the effect of high temperature generated during the

temperature controlled (45, 55 and 65 °C) vitro (laboratory scale) composting process on the fungus *Fusarium oxysporum* f. sp *melonis*. Complete inactivation was achieved in high temperature regimes (55 and 65 °C) after 2 to 3 days. While, 45 °C treatment required longer time (10 days). Hoitink et al. (1976) reported complete destruction of *B. cinerea* in an incubator after 7 and 21 days at temperatures of 50 and 40 °C, respectively. Lopez-Real and Foster (1984) investigated the survival of *Botrytis cinerea* in vitro condition and found that *B. cinerea* was completely inactivated at an average temperature of 54 °C within 72 to 96 h. In this study complete inactivation of *Botrytis cinerea* was achieved in less than 48 h.

Bacteria dominated the thermophilic period. They are considered the most important group of composting microorganisms during the initial and most active period accounting for 80-90 % of the microbial activity (Haug, 1993, Finstein and Morris, 1975 and Palmisano and Barlaz, 1996). Haug (1993) stated that the high surface to volume ratio of bacteria (due to their small sizes of 0.3–0.5 μm diameter) accelerates the exchange of soluble substrate with their environment, which makes them dominate the first stage of composting process.

In this study, composting microorganisms were limited to bacteria after the second day of high thermophilic temperature (> 60° C). Strom (1985) stated that the high bioreactor temperature is very selective for thermophilic bacteria (*Bacillus*), and when temperature is above 65 °C, composting microorganisms are reduced to the pure culture of *Bacillus strearothermophilus*.

The constant maximum temperature (~ 63 °C) achieved in this study, the uniform temperature distribution (due to the use of continuous mixing) and the extension of thermophilic stage (by the continuous addition of used cooking oil as a bioavailable carbon source) contributed to the effectiveness of the composting process in destroying the tomato mold (*Botrytis cinerea*). The density of *Botrytis cinerea* (measured by the mold specific protein using ELISA test) as a function of temperature and time (Figure 11.18) can be described by the following equation ($R^2$=0.99):

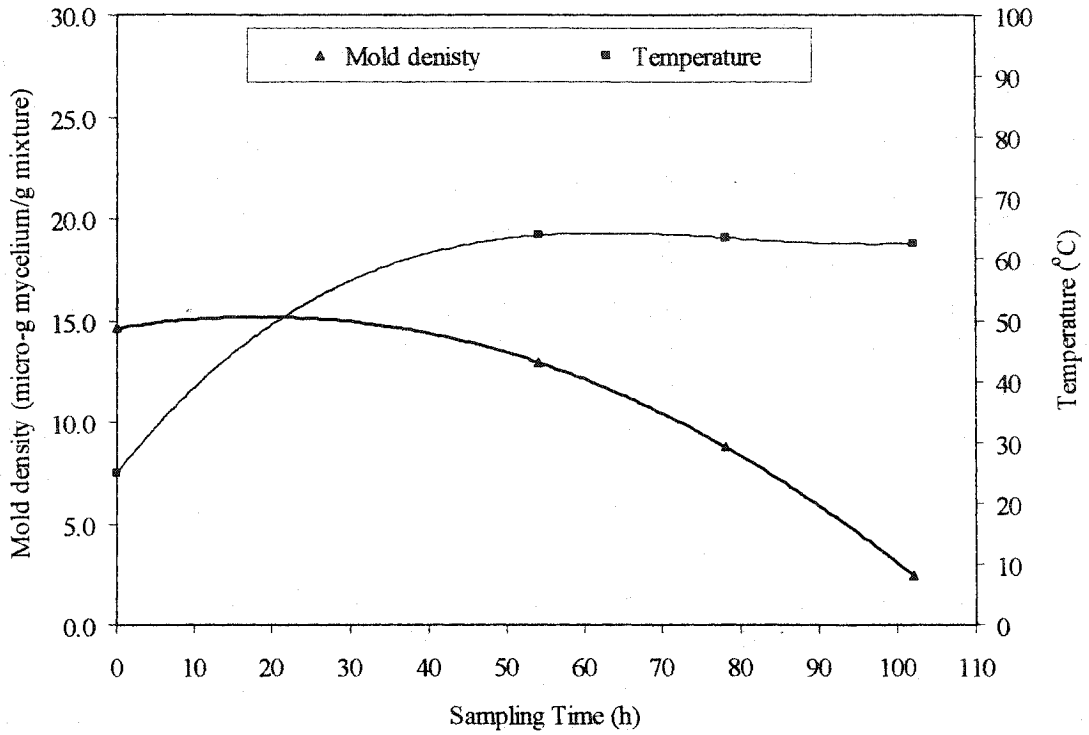



Figure 11.18 *Botrytis cinerea* and temperature changes during the mold study.

$$MD_t = 15.2.000 - 0.023\ (T) + 0.094\ (t) - 0.002\ (t)^2 \qquad (11.16)$$

Where:

$MD_t$ = mold density at time t (μg mycelium/g mixture)

T = temperature (°C)

t = time (h)

## 11.9 Pirimiphos-methyl Study

The average bioreactor temperature increased gradually due to the microbial metabolism of bioavailable carbon (used cooking oil) reaching its peak after 30 hours. Thermophilic temperatures of 63.10 ± 1.44 °C , 63.30 ± 1.61°C and 64.29 ± 1.59 °C were maintained in the first, second and third bioreactors for 24, 48 and 72 hours, respectively. When the addition of used cooking oil ceased, the temperature started to decline reaching mesophilic range (< 40 °C) within a day. The pesticide contaminated composted materials were kept at room temperature (25 °C) for two additional weeks.

The majority of pirimiphos methyl was lost (88.6, 90.0 and 91.6 % for mixture containing single, double and triple concentrations, respectively) in the first 102 h (starting period of 30 h + thermophilic period of 72 h). Slower reductions were noticed during the mesophilic (<40 C) and psychrophilic (room temperature) periods. Original and double the original concentrations reached non-detectable concentrations after 18 days, while triple the original concentration was reduced to 0.37 mg/kg (99.2% removal).

The fate and microbial degradation of pesticides in soils is extensively studied (Fogarty and Tuovinen, 1991, and Racke and Frink, 1989). Bollag and Liu (1990) and Wu and Nofziger (1999) stated that degradation of pesticides in soils is the result of a combination of chemical and biological events. Rocha and Walker (1995), Walker (1974) and Walker and Barnes (1981) indicated that chemical and biological reactions are dependent on soil temperature

In a review of literature, Büyüksonmez et al. (1999) reported number of physical, chemical and biological mechanisms that contribute to the biodegradation of pesticides during composting process. These mechanisms included: mineralization, abiotic transformations, adsorption, leaching, humification and volatilization. Reddy and Michel (1999) reported that thermophilic microbial communities are involved in the mineralization and biotransformation of pesticides during the composting process. Fogarty and Tuovinen, (1991) stated that volatilization has been shown to represent a major route of pesticides removal mechanism in laboratory studies. Valzano (2000) stated that the rate of degradation is significantly faster during composting than that observed in soil, due to increased temperatures, moisture levels and biological activity, which can make pesticides more bioavailable. Fogg et al. (2003) stated that composting process is able to degrade a complex mixture of pesticides better than soil due to higher temperature. Büyüksonmez et al. (1999) reported that biodegradation in compost is accelerated by high temperatures, increased organic matter content, and biological activity. Vandervoort et al. (1997) investigated the fate of several pesticides during the composting process of grass clippings and found that pesticides concentrations were lower in samples taken from the turned pile and from the interior of the pile where higher temperature occurred. They concluded that the destruction process of pesticides is biological in nature and increases in the temperature will speed up the biological process.

In this study, the reduction in pirimiphos-methyl as a function of the initial concentration, time and temperature (Figure 11.19) can be described by the following equation ($R^2$= 0.94):

$$C_t = e^{[3.370+0.031(C_i)-0.015(t)-0.039(T)]} \quad (11.17)$$

Where:

$C_t$ = pesticide concentration at time t (mg/kg)

$C_i$ = initial pesticide concentration (mg/kg)

t = time (h)

T = temperature (°C)

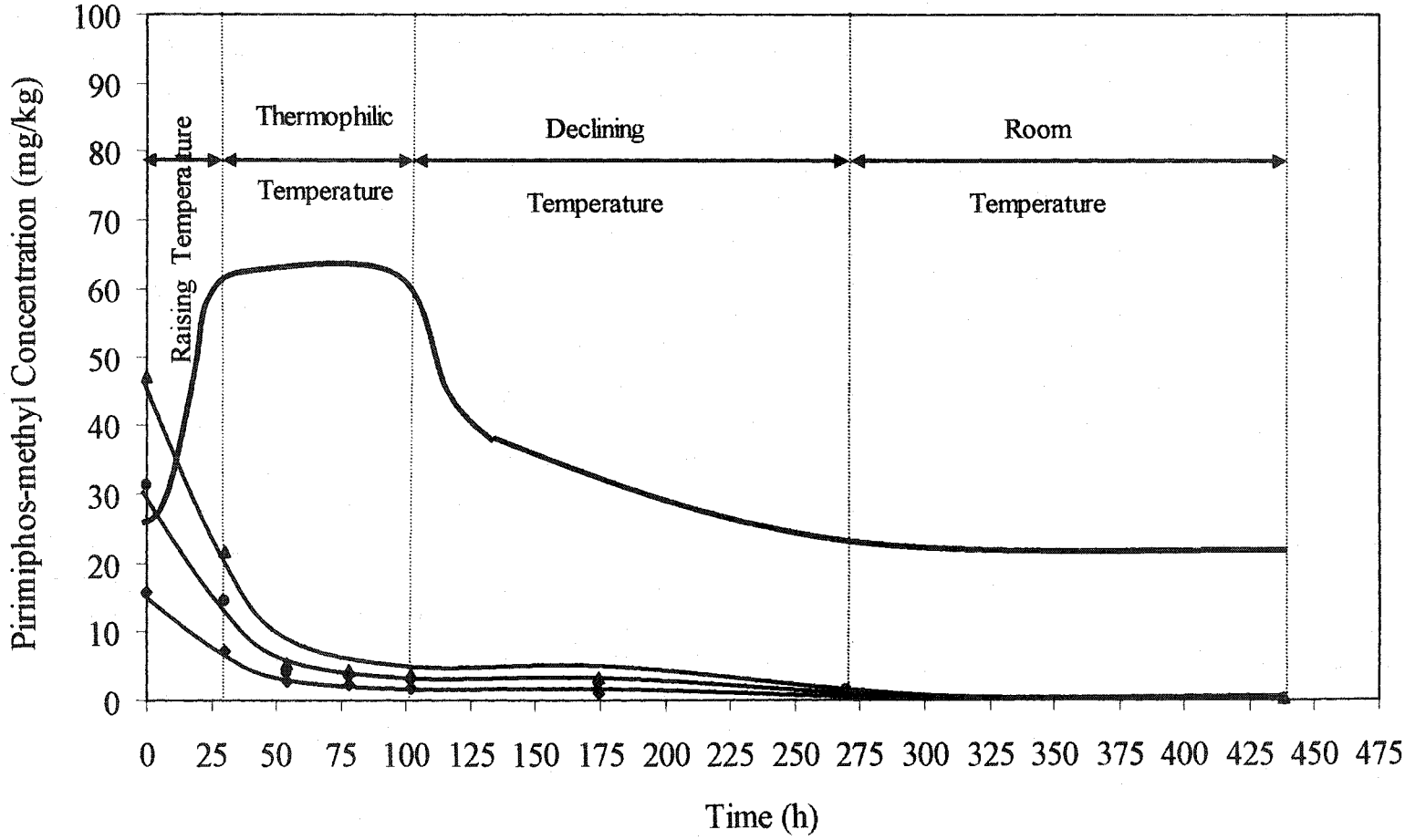



Figure 11.19. Pirimiphos-methyl and temperature changes during the pesticide study.

According to Lyman et al. (1990), Haug (1993), Wang and Hoffman (1991) and Eneji et al. (2002) degradation of organic substrate can be described using the following first order model:

$$C_t = C_0 e^{-kt} \quad (11.18)$$

Where

$C_t$ = concentration of the organic substrate at time t (mg/kg)

$C_0$ = initial concentration of the organic substrate (mg/kg)

k = rate constant ($h^{-1}$)

The authors suggested that a plot of Ln ($C_t$ /$C_0$) versus time yields a straight line with a slope equal to k. However, plotting the data obtained from the present study did not fit straight line for the entire composting period (Figure 11.20) because the rate constant (k) is a function of temperature. The linear relationship between Ln ($C_t$/$C_0$) and time for pirimiphos-methyl is only true for specific temperature zones as shown in Figure 11.21. The results shows in Table 11.8 indicated that a degradation rate constant of 0.026 $h^{-1}$ was observed in the initial stage (Time 0-30 h, Temperature 25-63 °C) regardless of the initial concentration of pirimiphos-methyl. During the thermophilic stage (Time 30-102 h, Temperature 63 °C), the degradation rate constant was lower and was affected by the initial concentration of pirimiphos-methyl, it increased from 0.018 h-1 to 0.022 as the initial concentration of pirimiphos-methyl increased from 15.8 mg/kg to 47.4 mg/kg. The degradation rate constant was not affected by the pirimiphos-methyl initial concentration during the temperature declining and ambient temperature zones.

Eneji et al. (2002) monitored the disappearance of pirimiphos-methyl in two different soils and found the average rate constant (k) to be 0.003 $h^{-1}$. Palmisano and Barlaz (1996) stated that the mesophilic and thermophilic temperatures achieved during composting resultes in much faster biochemical reactions than those achieved under ambient temperature. Michel et al. (1995) and Reddy and Michel (1999) indicated that thermophilic microbial communities are involved in the mineralization and

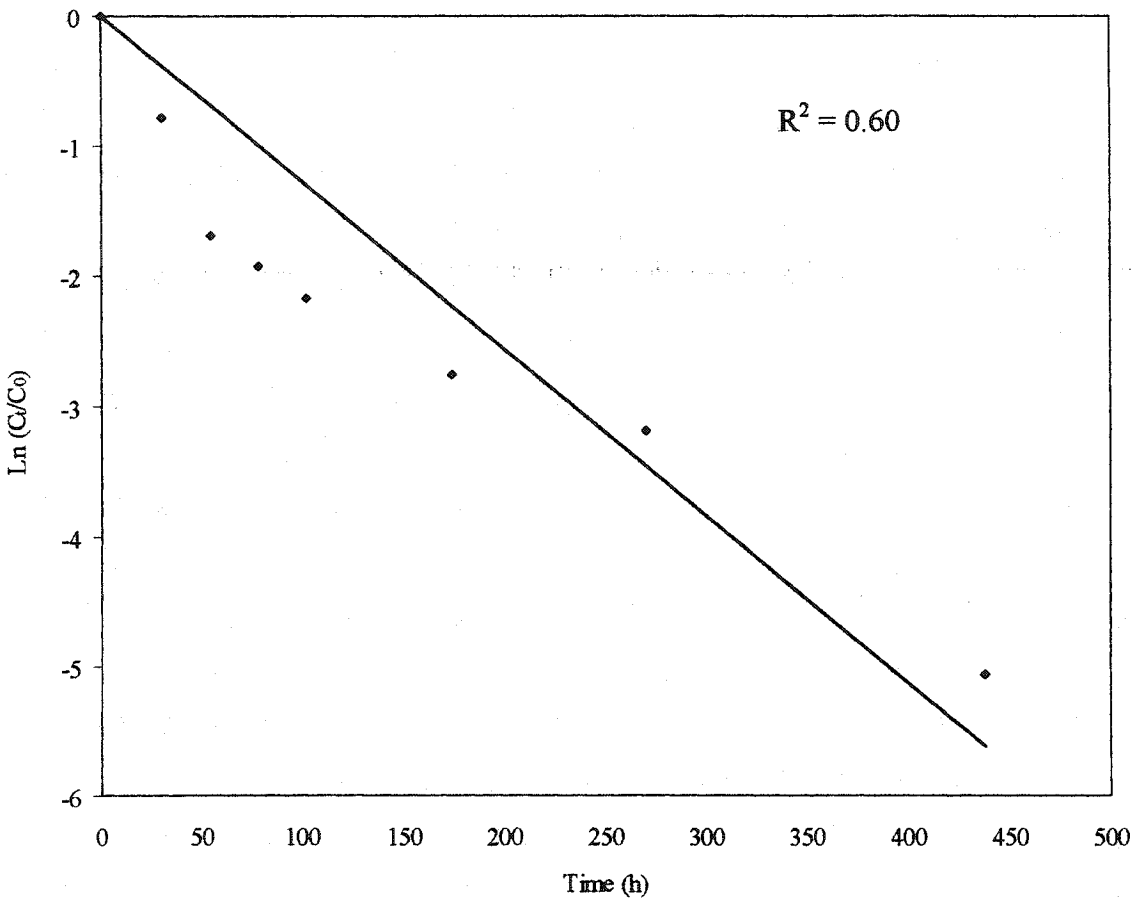



Figure 11.20. Determination of overall rate constant (k) for pirimiphos-methyl degradation according to the procedure described by Lyman et al (1990).

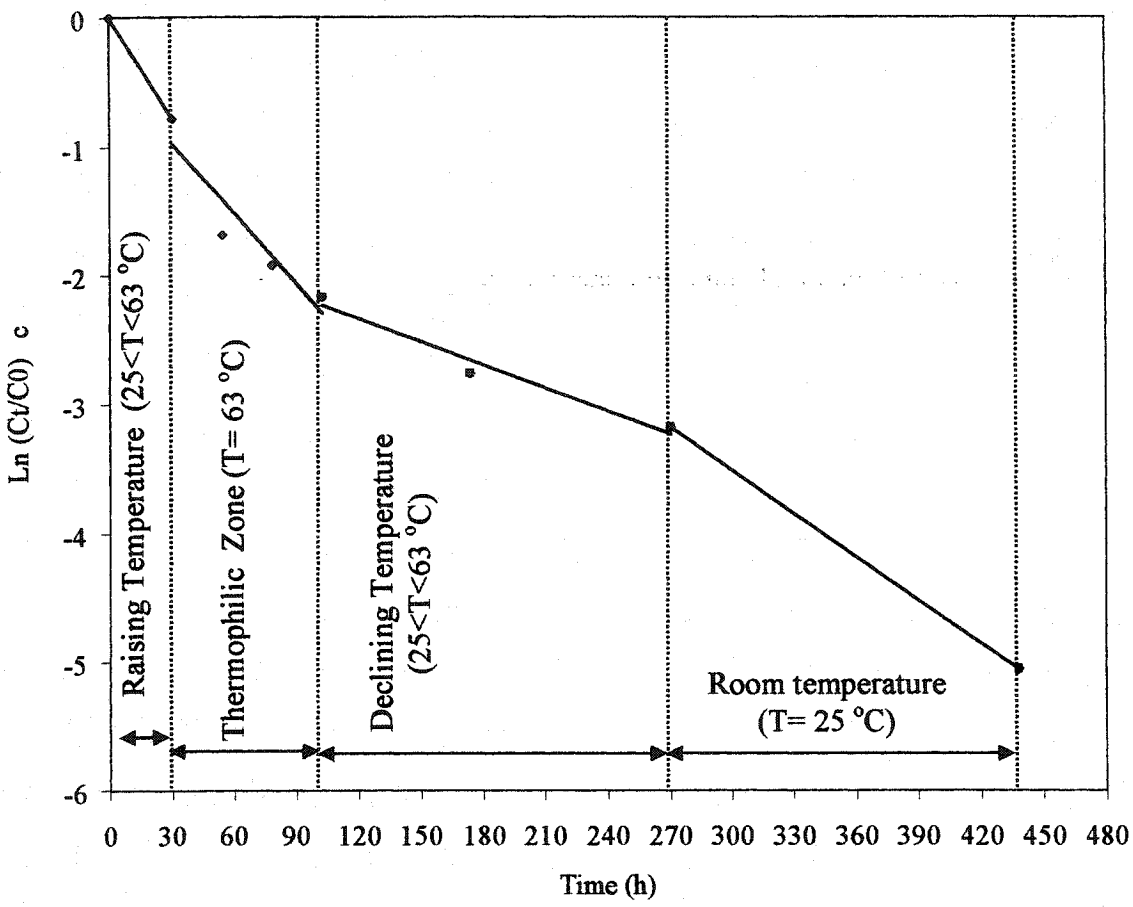



Figure 11.21. Determination of the rate constant (k) for pirimiphos-methyl degradation for different temperature zones.

Table 11.8. Rate constant for pirimiphos-methyl degradation.

| Time | Temperature | k ($h^{-1}$) | | |
|---|---|---|---|---|
| (h) | (°C) | Original | Double | Triple |
| 0 -30 | 25-63 | -0.026 | -0.026 | -0.026 |
| 30 -102 | 63 | -0.018 | -0.020 | -0.022 |
| 102 -270 | 63-25 | -0.006 | -0.005 | -0.006 |
| 270 -438 | 25 | -0.011 | -0.011 | -0.010 |
| Average | | 0.015 | 0.016 | 0.016 |

Original = 15.8 mg/kg
Double = 31.6 mg/kg
Triple = 47.4 mg/kg

biotransformation of pesticides during composting. *Pseudomonas* species were reported to be an active mesophilic group during the composting process (Hayes, 1968; Stanek, 1971; and Fermor et al., 1979). Mandelbaum et al. (1995) reported that the mesophilic bacteria were capable of mineralizing 80 % of 100 ppm atrazine solution in 150 hours. Hegazy et. al. (2000) investigated the fate of pirimiphos-methyl under different temperature regimes (20, 30, 40 and 50 ° C) for 192 h and found that high temperature increases the destruction of pirimiphos-methyl. In this study, the achieved average degradation rate constant (k) was five times higher than that reported in soil and the degradation rate constant for the mesophilic bacteria was higher than that of the thermophilic bacteria.

# 12. CONCLUSIONS

1. The moisture content remained within the optimum range of 50 – 70 % at all times for all experiments due to the equilibrium between the water produced by microbial respiration and water lost with the exhaust gas.

   (a) The moisture content was not a limiting factor in any of the composting experiments.
   (b) The lower moisture content reductions achieved in this study for all experiments were due to the short composting period (< 5 days).
   (c) The reductions in the moisture content during the manure study (0.4 -3.99 %) were slightly higher than those (0.0 - 3.0 %) of the inoculum study due to the differences in the degradation and respiration rates.
   (d) Increasing the amount of bioavailable carbon (used cooking oil) enhanced the biodegradation process which increased the reduction in moisture content (from 2.6 % to 14.5 %).

2. The reductions in the volatile solids were affected by the source and amount of bioavailable carbon and temperature.

   (a) Increasing the inoculum size (from 0 % to 50 %) increased the reduction in volatile solids (from 16.8 % to 44.7 %).
   (b) Increasing the amount of manure added to the mixture (from 0 % to 50 %) increased the reduction in the total volatile solids (from 16.8 % to 32.7 %).
   (c) Lower volatile solids reductions were observed in the manure study compared to the inoculum study because the amount of bioavailable carbon in the municipal compost was higher than that in the manure and the composting process for the inoculum study lasted for 96 h compared to 68 h for the manure.
   (d) The reductions in the volatile solids were affected by the source of bioavailable carbon. Higher reductions were observed with used cooking oil

(29.1 %) compared to cheese whey (22.2 %) and municipal solid compost (18.5 %).

(e) The rate of volatile solid reduction was affected by the source of the bioavailable carbon (0.12, 0.14 and 0.19 kg VS/ day for municipal solid compost, cheese whey and used cooking oil experiments, respectively.

(f) Continuous addition of used cooking oil at higher rates resulted in lower reductions of the volatile solids as the microorganisms preferred the used cooking oil over other sources of carbon in the mixture.

(g) The reductions in volatile solids were affected by the temperature and the duration of higher temperature; the longer the period of higher temperature, the greater the reductions in the total volatile solids.

3. Lower total carbon reductions were observed in the present study due to the fact that most of the carbon in the wood shaving was nonbioavailable for microbes in the short run.

   (a) Increasing the inoculum size (from 0 % to 50 %) increased the reduction in total carbon (from 9.4 % to 28.4 %).

   (b) Increasing the amount of manure added to the mixture (from 0 % to 50 %) slightly increased the reduction in total carbon (from 9.4 % to 10.8 %).

   (c) The reductions in total carbon achieved in the inoculum study (from 9.4 to 28.4 %) were much higher than those achieved in the manure study (from 9.4 % to 10.8 %) because manure consisted of bedding material (wheat straw) that lowered the bioavailable carbon content in the mixture.

4. The ammonium nitrogen content remained relatively constant for all mixtures as a result of microbial conversion of organic nitrogen to ammonium by the mineralization process and the conversion of ammonium back to organic nitrogen (microbial protein) by the assimilation process.

   (a) The nitrification of ammonium into nitrite ($NO_2$) and nitrate ($NO_3$) was inhibited by high temperature.

5. The reduction in the total kjeldahl nitrogen (TKN) was affected by the initial TKN and carbon contents, the balance between bioavailable nitrogen and bioavailable carbon and the temperature.

   (a) Increasing the inoculum size (from 0 % to 50 %) increased the TKN reduction (from 3.4 % to 25.4 %).
   (b) Increasing the amount of manure (from 0 % to 50 %) slightly increased the TKN reduction (from 3.4 % to 6.0 %).
   (c) The TKN reductions achieved in the manure study were significantly lower than those achieved in the inoculum study due to the lower initial TKN content and lower bioavailable carbon in the manure which affected the nitrogen mineralization process.
   (d) Higher TKN reductions were observed in the used cooking oil study (39.5 - 58.7 %) compared to the inoculum study (3.4 - 25.4 %) and manure study (3.4 - 6.0 %).

6. The reduction in C: N ratio was affected by the carbon bioavailability.

   (a) The final C: N ratio for manure study (26.2: 1 - 28.4: 1) was slightly lower than the final C: N ratio of the inoculum study (28.1: 1 - 29: 1).
   (b) The lower reduction in C: N ratio obtained in this investigation (3 to 10 %) indicated that the nitrogen was not a growth limiting factor for the composting microbial population but the bioavailable carbon was the limiting factor.
   (c) The bioavailability of carbon affected the nitrogen mineralization process.

7. The Macronutrients (Ca, Na, Fe, Mg, P, K, Zn, Cl and S) available in the composting mixtures were sufficient for microbial growth and were within the range reported in the literature for successful composting process.

8. The four phases of composting process (initial lag or inactive phase, exponential or active phase, stationary phase and death or maturation phase) were clearly identified in all the experiments.

   (a) The heat generated from the degradation of the organic matter raised the temperature though the three thermal stages of the active phase (psychrophilic, mesophilic and thermophilic).

   (b) The two lag phases (mesophilic and thermophilic) were easily identified and graphically determined.

   (c) The addition of 10 % inoculum (municipal solid compost) reduced the lag phase and increased the rate of temperature increase. However, an inoculum size higher than 10 % increased the lag phase, decreased the rate of temperature increase and increased both the maximum temperature and its duration.

   (d) The higher temperatures achieved with municipal solid compost, compared to those achieved with manure, are due to the fact that municipal solid compost had a higher fat content which contains at least twice the energy of carbohydrates.

   (e) The higher temperature achieved with higher inoculum size accelerated the break down of fats, proteins and complex carbohydrates which made more carbon to be bioavailable to sustain longer periods of high temperature.

   (f) The mixture that received no inoculum and those which received manure never achieved thermophilic stage.

   (g) Increasing the amount of manure added to the mixture significantly decreased the mesophilic lag phase and increased the rate of temperature increase.

   (h) The addition of bioavailable carbon (sugar) increased both the maximum temperature and its duration.

   (i) The maximum temperature positively correlated ($R^2$= 0.82 - 0.99) with the reductions in volatile solids, total carbon and TKN.

(j) The total amount of used cooking oil (bioavailable carbon source) positively correlated with the duration of thermophilic (63 °C) phase.

9. A heat balance was performed on the bioreactor.
   (a) The energy required for mixing (2.16 kJ/h) was only 83.1 % of the energy input into the bioreactor, 16.9 % was due to the heat losses in the motor assembly.
   (b) The peak heat production rate (at 63 °C) was 62.5 kJ/h.
   (c) The rate of heat production decreased dramatically after the temperature had reached 60 °C due to the decline in microbial growth and activity.
   (d) Approximately, 36.5 % of the total heat produced was lost by conduction through the cylindrical body and side walls of the bioreactor whereas the heat losses with the exhaust gas accounted for 63.5 %.

10. The composting process was successful in destroying the *tobacco mosaic virus*. The TMV completely lost its ability to infect the leaves of a susceptible host after less than four days (or 126 h from the start of the composting process) of controlled thermophilic (62-65 °C) composting.

11. The fungus *Botrytis cinerea* was completely destroyed after two days (or 78 h from the start of the composting process) of controlled thermophilic (63°C) composting.

12. The relatively short time required for complete inactivation of TMV and *Botrytis cinerea* in this study were achieved as a result of maintaining a constant high temperature, a uniform distribution of temperature and the extension of the thermophilic stage by the continuous addition of the proper amount of bioavailable carbon (used cooking oil).

13. Fungi and /or bacteria were observed during the three thermal phases of the composting process.
    (a) The Fungi and bacteria were abundantly present in the psychrophilic phase.
    (b) Some fungi appeared during the mesophilic phases and until the second day of the thermophilic phase.
    (c) Bacteria dominated the thermophilic phase.

14. The composting process was capable of destroying pirimiphos-methyl.
    (a) The majority of pirimiphos-methyl (87-92 %) was destroyed within the first 102 h, depending on the initial concentration. Complete destruction of the pesticide requires approximately 438 h.
    (b) The mesophilic degradation rate constant was not affected by the initial concentration of pirimiphos-methyl and was higher than that of the thermophilic phase.
    (c) The thermophilic degradation rate constant was affected by the initial concentration of pirimiphos-methyl.

# 13. RECOMMENDATIONS

## 13.1 For the Operation of Composting System:

1. About 10 % of good quality inoculum should be added to the composting mixture. Addition of inoculum will shorten the lag period and increase the degradation rate, thereby significantly reduce the composting time and improves the economics of the composting process.

2. A fat containing bioavailable carbon source should be used when possible, instead of carbohydrate containing material, if higher temperature with longer duration of thermophilic phase are desirable especially for the destruction of plant pathogens and/or pesticides.

3. An energy balance should be performed on the composting system to determine the amount of bioavailable carbon needed to compensate for the heat losses. Continuous addition of bioavailable carbon can compensate for the heat losses and extend the thermophilic stage to the desirable length required for the destruction of plant pathogens and/or pesticides.

4. It is important to consider the time – temperature relationship when evaluating the destruction process of plant pathogens and pesticides by the composting process.

## 13.2 For Future Research:

1. A better technique for measuring the C: N ratio of the mixture based on the bioavailable carbon and nitrogen should be used. Measuring C: N ratio on the basis of total carbon and total kjeldahl nitrogen does not provide information on the bioavailability of carbon and/ or nitrogen.

2. The distribution of microbial populations in the three thermal stages (psychrophilic, mesophilic and thermophilic) of the active phase and their rules in the degradation process should be investigated and quantified.

3. The metabolic activities of the various microbes found in the three thermal stage (psychrophilic, mesophilic and thermophilic) of the active phase should be evaluated and quantified.

4. The heat lost with the exhaust gas from the laboratory bioreactor accounted for over 64 % of the heat generated in the bioreactor. Ways to minimize these heat losses should be investigated.

5. The insulation of the laboratory bioreactor minimized the heat losses through the bioreactor body (36 % compared to 60-90 % reported in the literatures). A good quality insulation material should be used.

6. In order to reach and sustain a temperature above 55 C for 6 days: a total of 10.3 mL used cooking oil/ 12 h is required for each kg of compost mixture. The availability and economics of this source of bioavailable carbon should be investigated.

7. The need and suitability of bulking agent and particle size reduction in relation to porosity and bulking density should be investigated.

8. A highly idealized laboratory bioreactor was used in this study. A pilot scale system of at least 30 kg capacity should be operated to verify the results obtained in this study for scale up purpose.

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