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# DEVELOPMENT OF ADVANCED COMPOSTING TECHNOLOGIES FOR MUNICIPAL ORGANIC WASTE TREATMENT IN SMALL COMMUNITIES IN NEWFOUNDLAND AND LABRADOR

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# Harris Centre Applied Research Fund

# FINAL REPORT

# Development of Advanced Composting Technologies for Municipal Organic Waste Treatment in Small Communities in Newfoundland and Labrador

*Submitted to*
**The Harris Centre, Memorial University of Newfoundland**

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# EXECUTIVE SUMMARY

Municipal Solid Waste (MSW) is one of the major fractions of the solid waste in Canada. From 2002 to 2008, Canadian municipal solid waste disposal has increased from 769 kilograms to 777 kilograms per capita. Among the provinces, Newfoundland and Labrador (NL) has one of the highest waste disposal levels per capita in the country. According to the Multi Materials Stewardship Board (MMSB), it is estimated that more than 400,000 tonnes of municipal solid waste (MSW) materials are generated each year in this province and organic waste makes up as much as 30% of all waste generated. To properly manage MSW generated, the Provincial Solid Waste Management Strategy has been identified in 2002, aiming to reduce the amount of waste going into landfills by 50 per cent.

Composting has been regarded as an efficient and effective way to deal with the organic waste and helps work toward achieving the provincial 50 per cent waste reduction goal. It also creates rich organic soil that can enhance lawns and gardens. Therefore, MSW composting has been listed as one of the six new environmental standards applied to new waste management systems in NL. However, NL comprises more than 200 small communities without access to the central composting facility. For those areas, small-scale composting technologies are desired to manage their MSW so as to reduce collection and transport costs and eliminate the other environmental contamination during transportation.

Composting is a biological process that is affected by chemical and physical factors. The lack of understanding of the complexity of biological, chemical, and physical processes can result in malfunction of a composting system. The microbial and physicochemical environment in composting can be affected by the diversity of microbial population, temperature, bulking agent,

aeration, and chemical properties of raw material such as the C/N ratio and moisture content. Interactions among biological, chemical, and physical factors are crucial to the comprehensive understanding of the composting process, and thus viable for process control and system optimization.

This project aims at developing composting technologies applicable to northern communities in NL, and conducting system optimization to increase the composting efficiency and improve compost quality. Six composting reactors (50×20×25 cm) were designed and manufactured. Six mixers were installed in each reactor. An inlet was designed to provide air through a vacuum pump. A perforated plate with holes was installed for air distribution in the system. The exhaust gas was monitored by a gas monitoring system and then discharged into a flask containing $H_2SO_4$ solution (1 M) to absorb the $NH_3$. To prevent heat loss, heat insulating layers were designed and applied to cover the reactor thoroughly. Reactors were filled with food waste as raw material. Factorial design was applied, with sixteen runs conducted, to optimize the operational factors including moisture content, aeration, bulking agent, and C/N ratio. Each composting run lasts 30 days. The effect of main factors and their interactions on composting process was investigated by measuring temporal variations of enzyme activities (dehydrogenase, β-glucosidase, and Phosphomonoesterase), germination index (GI), pH, electrical conductivity (EC), temperature, moisture, ash content, oxygen uptake rate (OUR), and C/N ratio during composting.

Experimental results showed that the breakdown of organic matter by microbial activities led to increase in the temperature of the composting material. As composting progresses, the amount of degradable matter decreased and the temperature declined. When most of the organic matter was consumed, the temperature in the reactor dropped to the ambient temperature. The OUR can

express biological activities during composting and biological stability at the end of composting. The OUR values showed strong correlation with temperature. The maximum OUR was observed concurrently with the maximum temperature. The pH value was low at the first stage due to the accumulation of organic acids, and increased gradually while organic acids were consumed by microorganisms. The EC values increased in all runs as a result of cation concentration increment. Moisture content showed descending trends in all runs due to the evaporation under high temperature. As a result of decomposition of organic matter by composting, the organic matter decreased and ash content increased in all runs. Although the GI data showed notable fluctuation during composting, it started to increase at the end of the composting process. In most of the runs, the peaks of dehydrogenase activity as an indicator of biological activity were observed with the maximum temperature and OUR value simultaneously. The β-glucosidase activity showed with high values at the themophilic phase and after the temperature drop. In addition, high activity of phosphomonoesterase accrued during the thermophilic phase.

Results of the factorial design indicated that aeration rate, moisture content, and bulking agents affect the maximum temperature significantly. Aeration rate has significant influence on the maximum OUR. The C/N ratio and the interaction between aeration rate and bulking agent have major impact on GI. Moisture content is an important factor affecting the cumulative dehydrogenase and the β-glucosidase activity. The C/N ratio influences the β-glucosidase activity as well. The output of this research can help to design the small-scale composting system for MSW management in small communities in NL, and provide a solid base of technical and scientific knowledge for system operation.

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# 1 Introduction

## 1.1 Background

Population growth, aggregation of human settlements, higher living standards, and increased development and consumption of less biodegradable products have increased solid waste generation. The North American urban population produces 0.75 tonnes of garbage per capita per year (Adhikari et al., 2008; Asase et al., 2009). The large amount of municipal, industrial, and agricultural wastes has led increasing environmental, social and economic problems. Stringent environmental regulations for waste disposal and landfills make finding new sites for waste disposal and management a growing challenge. Additionally, landfills use arable lands and soils which can be used for agriculture. The two primarily environmental concerns related to landfills are leachate generation and gas emission. The leachate produced from landfills may contain a variety of toxic and polluting components. If managed improperly, leachate can contaminate groundwater and surface water. Landfill gas emissions are a mixture of carbon dioxide and methane, small amounts of nitrogen and oxygen, and trace amounts of various other gases such as benzene, toluene, and vinyl chloride. Some components of landfill gas may be toxic or explosive, other components can include ammonia, hydrogen sulphide and other organo-sulphur compounds, which produce the characteristic unpleasant odour. The generation of these landfills by-products depends on the constitution of the disposed material. The more organic wastes are present, the more gas is produced by bacterial decomposition; the moisture content is increased, and thus the more leachate is produced (Statistics Canada, 2005). Moreover, disposal sites produce noise, dust and odour which make the surrounding area undesirable for habitation.

Solid waste management requires the application of effective strategies for proper wastes disposal and treatment. Successful waste policy requires a five-step waste management hierarchy. As demonstrated in Figure 1.1, the hierarchy consists of waste prevention, reuse, recycle, recovery, and disposal (Ponsá, 2010). Recycling involves conserving resources and preventing material from entering the waste stream. Biological treatment technologies (e.g., composting and anaerobic digestion) permanently remove the organic material from the waste stream (Sakai et al., 1996).

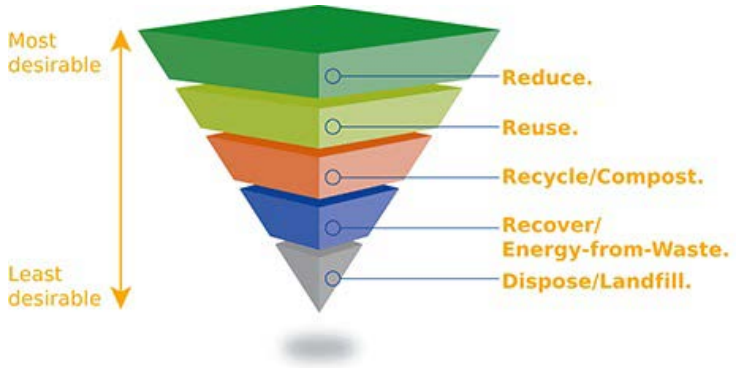


Figure 1.1. Waste management hierarchy

Municipal Solid Waste (MSW) management has become one of the largest environmental concerns in recent decades (Iqbal et al., 2010). Due to the high moisture content (60-70%) and organic fraction (70-80%), MSW receives more attention than other solid wastes because it shows more negative environmental impacts if it is not treated properly. Luckily, the high organic fraction in MSW makes it easy to be converted to the energy sources through composting (Jolanun and Towprayoon, 2010; Ponsá, 2010). Therefore, composting has become an increasingly important strategy for the treatment of MSW. Centralized composting facilities have become more common since the early 1990s. These are used by municipal cities for

households and commercial establishments alike. As well, some businesses and other organizations in the industrial, commercial and institutional sectors use on-site composting facilities (Statistics Canada, 2005).

### 1.1.1 MSW generation and treatment in Canada

Although there is available space for landfills, the waste management situation for major municipalities in Canada does not differ from that in other industrialised nations (Sawell et al., 1996). In 2008, Canadians produced over 1,031 kg of waste per capita. Of this total, 777 kg went to landfills or was incinerated while 254 kg was diverted. Approximately 21 million tonnes of generated waste came from non-residential sources and 13 million tonnes was from residential sources. On a per capita basis, there were 256 kg of residential waste and 520 kg of non-residential waste (Statistics Canada, 2008), Figure 1.2 displays the generated, disposed and diverted waste for Canadian provinces in 2008 (Cant, 2008).

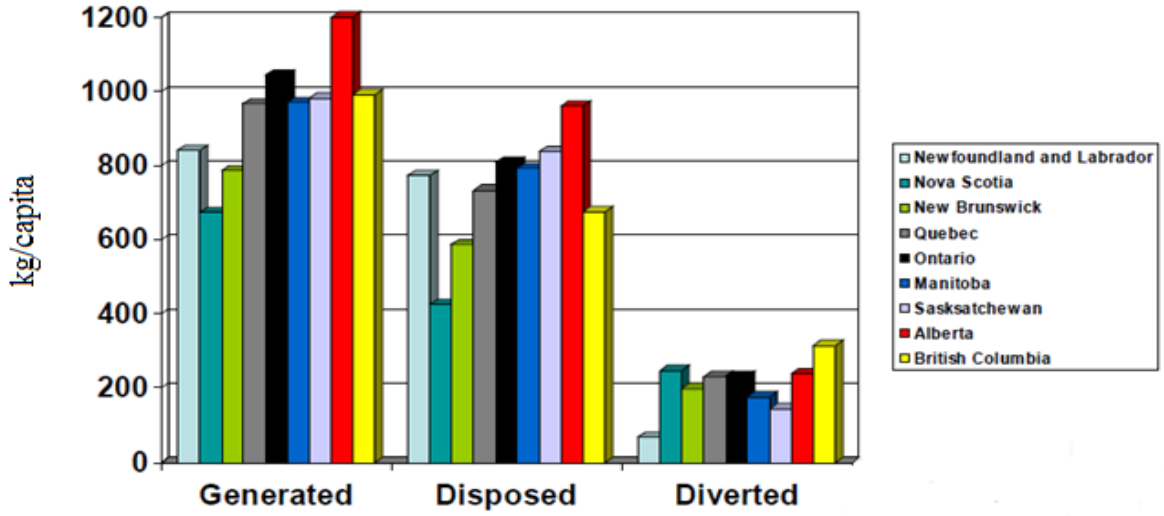


Figure 1.2. Canadian generated, disposed and diverted waste

Figure 1.3 demonstrates the typical content of residential waste in Canada. Organic waste makes up to 40% of the residential waste. As a result of issues related to landfills sites such as leachate and gas generation, most Canadian cities are focusing on building their recycling infrastructure (Adhikari et al., 2008).

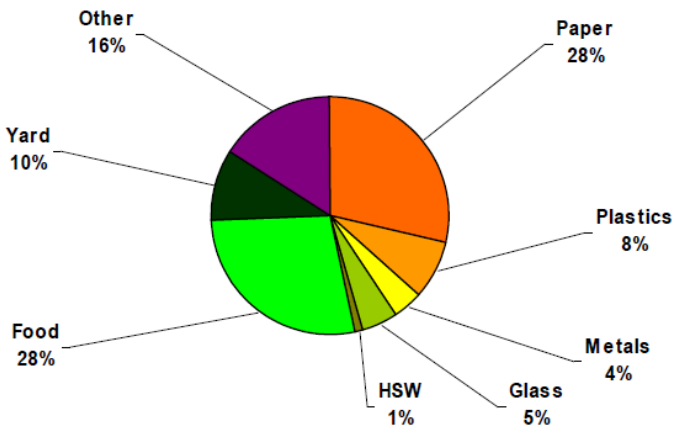


Figure 1.3. Typical composition of residential waste

In Canada, almost 8.5 million tonnes of waste diverted from landfills in 2008, which is 254 kg per person. Among all Canadian provinces, Nova Scotia diverted the most municipal solid waste from landfills. This province banned organic waste from landfill sites and organized separate curbside collection and recycled 310 kg per capita, which contributed to 45% of its total wastes. Other cities in Canada were attempting to follow this lead, with varying degrees of success (Statistics Canada, 2008). The number of composting programs, total population, and population served in Canadian provinces are presented in Table 1.1 (Cant, 2008).

Table 1.1. Composting program in Canada in 2008

| Province | Composting Program | Population Served | Total Population |
|---|---|---|---|
| **British Columbia** | 28 | 2,471,982 | 3,907,738 |
| **Alberta** | 9 | 1,005,619 | 2,974,807 |
| **Saskatchewan** | 2 | 18,400 | 978,807 |

| | | | |
|---|---|---|---|
| **Manitoba** | 3 | 82,400 | 1,119,583 |
| **Ontario** | 57 | 10,003,304 | 11,410,046 |
| **Quebec** | 12 | 2,561,630 | 7,237,479 |
| **New Brunswick** | 2 | 138,180 | 729,498 |
| **Nova Scotia** | 20 | 750,534 | 908,007 |
| **Prince Edward Island** | 1 | 135,294 | 135,294 |
| **Newfoundland** | 0 | 0 | 512,930 |
| **Total** | 134 | 17,167,343 | 29,914,315 |

### 1.1.2 MSW generation and treatment in Newfoundland and Labrador

Newfoundland and Labrador (NL) is located on the eastern edge of North America. The province covers a total area of 405,212 square kilometres (156,453 square miles), with a relatively small population of 514,536 (NL Tourism, 2013). After Alberta, NL has the highest quantity of waste disposal per person, and the lowest proportion of waste (47%) from non-residential sources, i.e., 429 kg of residential waste per capita and 382 kg of non-residential waste per capita. Based on the waste management survey by Government of Canada, NL spent $15 per capita on collection and transportation of solid waste, $14 per person on operation of disposal facilities, and there has been no allocation of funds to operate an organics processing facilities (Statistics Canada, 2008). The Provincial Solid Waste Management Strategy (2010) was based on five primary stages (Government of Newfoundland and Labrador, 2002):

1) Increasing waste diversion, divert 50% of materials going to disposal by 2015;

2) Establishing waste management regions;

3) Developing modern standards and technologies;

4) Maximizing economic and employment opportunities associated with waste management; and

5) Public education

In order to achieve a wastes diversion of 50%, composting can be a simple and inexpensive alternative, and has more public acceptability than the dumping of organic wastes in the ocean, fresh water reservoirs, or landfills (Martin et al., 1993). A central composting facility was expected to be operational in the Robin Hood Bay Regional Integrated Waste Management Plant by 2011, which is intended for the organic material, such as vegetable and fruit peels, tea bags, coffee grinds, meat and fish bones, grains such as bread and rice, left-over food scraps including sauces and oils, and yard wastes such as leaves and grass clippings. This facility was planned to serve the City of St. John's and surrounding areas. Meanwhile, the community composting program has been raised to meet the requirement of organic MSW treatment in areas far from the central composting facility. The Town of Grand Falls-Windsor was the first to introduce community composting in NL more than five years ago. The Multi Materials Stewardship Board (MMSB) has worked with the town to develop a community composting pilot program for the entire province. The Town of Holyrood is the first community to participate in this community scale composting pilot program. The Government of NL, Burin Peninsula Waste Management Corporation (BPWMC), in partnership with MMSB, started another curbside composting pilot program in Grand Bank, which served 450 households to assess the feasibility of composting organics and paper fibre on the Burin Peninsula. This small scale composting system can divert 67% of household wastes from the landfill (MMSB, 2013). Also, the first industrial-scale composter in NL has been installed at Memorial University's Grenfell campus in Corner Brook, which manages up to 100 metric tonnes of organic wastes annually and diverts 20% of Memorial

University's Grenfell campus and College of the North Atlantic’s total wastes from landfills (MMSB, 2013).

## 1.2 Statement of problem

### 1.2.1 Necessity of composting in small communities

Statics Canada showed that NL is comprised of 370 subdivisions, which are city, town and organized and unorganized subdivisions. The population of 200 of the subdivisions are between 100 and 600, which can be considered as small communities. Seventeen of the small communities are located in Labrador while the remainder are in Newfoundland. Table 1.2 lists small communities and their population (Statistics Canada, 2011).

Most of these small communities are located in remote and isolated areas and cannot access large solid waste disposal sites or central organic processing facilities. Transportation of solid wastes to the central organic processing facility, beside the high cost, it may cause more traffic, more air emissions of dust, nitrous oxides and sulphur dioxides, and soil and water contamination from accidental leaks or spills (Statistics Canada, 2005). Therefore, on-site composting facilities have been considered as a viable means to deal with organic wastes in the small communities. On-site composting facilities allow composting of the generated solid wastes in the surrounding area, and then use the output compost within the specific area (Martin et al., 1993). Also, the environmental regulation for on-site composting is not as stringent as that for large-scale facilities because pollution problems are few in small scale. Problems rose in small-scale systems such as smell, noise, temperature drop, and moisture can be easily and quickly handled as well.

Additionally, the operation and maintenance of the small-scale systems are easy with low cost (Martin et al., 1993). In addition, northern regions, which possess a limited amount of arable soil, can benefit from the production of the nutrient-rich compost for soil enhancement. Although a lack of extensive agricultural production in those regions could limit the selection of bulking agents to be employed for composting. Northern regions generally possess peat resources. In many cases, a forestry industry that produces wastes organic materials in the form of sawdust, bark and wood chips to be used as a bulking agent in MSW composting (Martin et al., 1993).

Table 1.2. List of Communities with population under 600 in Newfoundland and Labrador

| # | Geographic name | Geographic type* | Population, 2011 | Population, 2006 |
|---|---|---|---|---|
| **1** | Division No. 5, Subd. C | SNO | 101 | 74 |
| **2** | Division No. 7, Subd. I | SNO | 102 | 121 |
| **3** | Division No. 3, Subd. I | SNO | 103 | 151 |
| **4** | Pinware | T | 107 | 114 |
| **5** | Little Bay | T | 108 | 116 |
| **6** | Colinet | T | 110 | 165 |
| **7** | King's Cove | T | 111 | 121 |
| **8** | Division No. 3, Subd. E | SNO | 114 | 134 |
| **9** | Division No. 1, Subd. D | SNO | 115 | 130 |
| **10** | St. Joseph's | T | 115 | 144 |
| **11** | Morrisville | T | 117 | 128 |
| **12** | Division No. 9, Subd. A | SNO | 117 | 215 |
| **13** | Rose Blanche-Harbour le Cou | T | 118 | 547 |
| **14** | Point Lance | T | 120 | 119 |
| **15** | West St. Modeste | T | 120 | 140 |
| **16** | Nippers Harbour | T | 128 | 151 |
| **17** | Division No. 2, Subd. F | SNO | 130 | 132 |
| **18** | Little Bay East | T | 130 | 140 |
| **19** | Division No. 1, Subd. C | SNO | 131 | 185 |
| **20** | Sandy Cove, Bonavista Bay | T | 132 | 133 |
| **21** | Salvage | T | 136 | 174 |
| **22** | Division No. 2, Subd. I | SNO | 136 | 201 |
| **23** | BaineHarbour | T | 137 | 134 |
| **24** | Miles Cove | T | 137 | 140 |
| **25** | Trinity (Trinity Bay) | T | 137 | 191 |
| **26** | Division No. 2, Subd. H | SNO | 139 | 223 |

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|---|---|---|---|---|
| **27** | Rencontre East | T | 141 | 165 |
| **28** | Division No. 7, Subd. A | SNO | 144 | 172 |
| **29** | English Harbour East | T | 147 | 169 |
| **30** | St. Brendan's | T | 147 | 203 |
| **31** | Beachside | T | 150 | 183 |
| **32** | Admirals Beach | T | 153 | 185 |
| **33** | Point of Bay | T | 159 | 163 |
| **34** | Portugal Cove South | T | 160 | 222 |
| **35** | Port Anson | T | 165 | 155 |
| **36** | Division No. 8, Subd. M | SNO | 165 | 201 |
| **37** | Brighton | T | 171 | 203 |
| **38** | Frenchman's Cove | T | 172 | 166 |
| **39** | Indian Bay | T | 174 | 196 |
| **40** | Lord's Cove | T | 175 | 207 |
| **41** | Gaultois | T | 179 | 265 |
| **42** | Brent's Cove | T | 181 | 204 |
| **43** | Conche | T | 181 | 225 |
| **44** | Bird Cove | T | 182 | 137 |
| **45** | Pool's Cove | T | 182 | 189 |
| **46** | Pacquet | T | 184 | 210 |
| **47** | Division No. 5, Subd. E | SNO | 187 | 186 |
| **48** | Woodstock | T | 190 | 199 |
| **49** | Red Harbour | T | 191 | 210 |
| **50** | L'Anse-au-Clair | T | 192 | 226 |
| **51** | Red Bay | T | 194 | 227 |
| **52** | Raleigh | T | 201 | 248 |
| **53** | Crow Head | T | 203 | 205 |
| **54** | Tilting | T | 204 | 248 |
| **55** | Postville | T | 206 | 219 |
| **56** | St. Lewis | T | 207 | 252 |
| **57** | New Perlican | T | 210 | 188 |
| **58** | Division No. 8, Subd. I | SNO | 211 | 210 |
| **59** | Goose Cove East | T | 211 | 234 |
| **60** | Riverhead | T | 212 | 220 |
| **61** | Division No. 6, Subd. E | SNO | 216 | 326 |
| **62** | Happy Adventure | T | 219 | 227 |
| **63** | Westport | T | 220 | 246 |
| **64** | Lushes Bight-Beaumont-Beaumont North | T | 220 | 275 |
| **65** | Howley | T | 221 | 241 |
| **66** | Heart's Desire | T | 223 | 226 |
| **67** | River of Ponds | T | 228 | 251 |

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|---|---|---|---|---|
| **68** | Hughes Brook | T | 231 | 197 |
| **69** | Division No. 5, Subd. A | SNO | 232 | 223 |
| **70** | Division No. 7, Subd. D | SNO | 232 | 397 |
| **71** | Point May | T | 233 | 260 |
| **72** | Gaskiers-Point La Haye | T | 233 | 302 |
| **73** | Come By Chance | T | 247 | 260 |
| **74** | Branch | T | 247 | 309 |
| **75** | Change Islands | T | 257 | 300 |
| **76** | Glenburnie-Birchy Head-Shoal Brook | T | 258 | 275 |
| **77** | St. Pauls | T | 258 | 309 |
| **78** | Grand le Pierre | T | 260 | 264 |
| **79** | Division No. 2, Subd. D | SNO | 260 | 277 |
| **80** | Seal Cove (Fortune Bay) | T | 263 | 315 |
| **81** | Baytona | T | 264 | 276 |
| **82** | Daniel's Harbour | T | 265 | 288 |
| **83** | Main Brook | T | 265 | 293 |
| **84** | Fleur de Lys | T | 265 | 320 |
| **85** | Division No. 3, Subd. D | SNO | 265 | 379 |
| **86** | Division No. 2, Subd. E | SNO | 269 | 285 |
| **87** | Fox Harbour | T | 270 | 314 |
| **88** | Division No. 1, Subd. I | SNO | 271 | 213 |
| **89** | Cottlesville | T | 272 | 279 |
| **90** | Sandringham | T | 274 | 255 |
| **91** | Bishop's Cove | T | 275 | 329 |
| **92** | Ramea | T | 280 | 618 |
| **93** | Woody Point, Bonne Bay | T | 281 | 355 |
| **94** | Chance Cove | T | 282 | 310 |
| **95** | Traytown | T | 283 | 302 |
| **96** | Bay L'Argent | T | 285 | 287 |
| **97** | Lamaline | T | 286 | 315 |
| **98** | Rushoon | T | 288 | 319 |
| **99** | Whiteway | T | 293 | 220 |
| **100** | Little Burnt Bay | T | 294 | 325 |
| **101** | Division No. 6, Subd. D | SNO | 295 | 287 |
| **102** | Long Harbour-Mount Arlington Heights | T | 298 | 211 |
| **103** | Parkers Cove | T | 301 | 308 |
| **104** | Pilley's Island | T | 301 | 317 |
| **105** | Seal Cove (White Bay) | T | 304 | 331 |
| **106** | Greenspond | T | 305 | 365 |
| **107** | Rigolet | T | 306 | 269 |
| **108** | Flower's Cove | T | 308 | 270 |
| **109** | Charlottetown (Labrador) | T | 308 | 366 |
| **110** | St. Bride's | T | 308 | 386 |

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|---|---|---|---|---|
| **111** | Renews-Cappahayden | T | 310 | 421 |
| **112** | Division No. 1, Subd. N | SNO | 317 | 370 |
| **113** | Fermeuse | T | 323 | 284 |
| **114** | Jackson's Arm | T | 323 | 374 |
| **115** | Anchor Point | T | 326 | 309 |
| **116** | Division No. 8, Subd. O | SNO | 330 | 353 |
| **117** | Ming's Bight | T | 333 | 347 |
| **118** | Fox Cove-Mortier | T | 333 | 351 |
| **119** | Elliston | T | 337 | 306 |
| **120** | Leading Tickles | T | 337 | 407 |
| **121** | Port Rexton | T | 338 | 351 |
| **122** | Hawke's Bay | T | 338 | 391 |
| **123** | St. Vincent's-St. Stephen's-Peter's River | T | 340 | 363 |
| **124** | Division No. 8, Subd. P | SNO | 340 | 380 |
| **125** | Division No. 1, Subd. R | SNO | 344 | 366 |
| **126** | Division No. 1, Subd. B | SNO | 344 | 478 |
| **127** | Hant'sHarbour | T | 346 | 401 |
| **128** | York Harbour | T | 347 | 346 |
| **129** | Burlington | T | 349 | 376 |
| **130** | Division No. 10, Subd. B | SNO | 349 | 475 |
| **131** | Division No. 8, Subd. A | SNO | 352 | 540 |
| **132** | Mount Carmel-Mitchells Brook-St. Catherine's | T | 358 | 438 |
| **133** | Makkovik | T | 361 | 362 |
| **134** | Winterland | T | 363 | 337 |
| **135** | Heart's Content | T | 375 | 418 |
| **136** | Mary's Harbour | T | 383 | 417 |
| **137** | Division No. 3, Subd. F | SNO | 385 | 163 |
| **138** | Division No. 3, Subd. J | SNO | 388 | 71 |
| **139** | Small Point-Adam's Cove-Blackhead-Broad Cove | T | 389 | 438 |
| **140** | Bryant's Cove | T | 396 | 417 |
| **141** | Bauline | T | 397 | 379 |
| **142** | Northern Arm | T | 397 | 385 |
| **143** | Division No. 7, Subd. G | SNO | 398 | 436 |
| **144** | Bay de Verde | T | 398 | 470 |
| **145** | Gillams | T | 407 | 402 |
| **146** | Division No. 1, Subd. H | SNO | 408 | 423 |
| **147** | Steady Brook | T | 408 | 435 |
| **148** | Belleoram | T | 409 | 421 |
| **149** | Fogo Island Region (Part) | RG | 421 | 488 |
| **150** | Seldom-Little Seldom | T | 427 | 444 |
| **151** | Forteau | T | 429 | 448 |
| **152** | St. Mary's | T | 439 | 482 |

| | | | | |
|---|---|---|---|---|
| **153** | Port Hope Simpson | T | 441 | 529 |
| **154** | Port au Port West-Aguathuna-Felix Cove | T | 447 | 386 |
| **155** | Hermitage-Sandyville | T | 450 | 499 |
| **156** | Comfort Cove-Newstead | T | 451 | 451 |
| **157** | Division No. 6, Subd. C | SNO | 452 | 399 |
| **158** | Sunnyside | T | 452 | 470 |
| **159** | Division No. 8, Subd. G | SNO | 452 | 600 |
| **160** | Hampden | T | 457 | 489 |
| **161** | Ferryland | T | 465 | 529 |
| **162** | Chapel Arm | T | 468 | 451 |
| **163** | St. Bernard's-Jacques Fontaine | T | 470 | 525 |
| **164** | Division No. 5, Subd. G | SNO | 470 | 607 |
| **165** | Reidville | T | 474 | 511 |
| **166** | Cow Head | T | 475 | 493 |
| **167** | Middle Arm | T | 476 | 517 |
| **168** | Parson's Pond | T | 478 | 387 |
| **169** | Eastport | T | 482 | 499 |
| **170** | Port Blandford | T | 483 | 521 |
| **171** | Winterton | T | 484 | 518 |
| **172** | South Brook | T | 487 | 531 |
| **173** | Division No. 7, Subd. J | SNO | 498 | 640 |
| **174** | Division No. 1, Subd. X | SNO | 506 | 510 |
| **175** | Cape Broyle | T | 506 | 545 |
| **176** | Lark Harbour | T | 510 | 565 |
| **177** | Division No. 1, Subd. W | SNO | 511 | 561 |
| **178** | Cartwright, Labrador | T | 516 | 552 |
| **179** | Campbellton | T | 520 | 494 |
| **180** | Division No. 8, Subd. C | SNO | 527 | 376 |
| **181** | Terrenceville | T | 530 | 536 |
| **182** | Lourdes | T | 532 | 550 |
| **183** | Southern Harbour | T | 534 | 474 |
| **184** | Division No. 8, Subd. E | SNO | 537 | 698 |
| **185** | Lumsden | T | 545 | 533 |
| **186** | Garnish | T | 545 | 578 |
| **187** | McIvers | T | 546 | 571 |
| **188** | Division No. 1, Subd. F | SNO | 546 | 582 |
| **189** | L'Anse au Loup | T | 550 | 593 |
| **190** | North West River | T | 553 | 492 |
| **191** | Lewin's Cove | T | 555 | 566 |
| **192** | Hopedale | T | 556 | 530 |
| **193** | Musgravetown | T | 556 | 583 |
| **194** | North River | T | 562 | 557 |
| **195** | Birchy Bay | T | 566 | 618 |

| | | | | |
|---|---|---|---|---|
| **196** | Trepassey | T | 570 | 763 |
| **197** | Trout River | T | 576 | 604 |
| **198** | Englee | T | 583 | 618 |
| **199** | Division No. 2, Subd. K | SNO | 595 | 671 |
| **200** | Division No. 2, Subd. C | SNO | 596 | 689 |
| **201** | Port au Port East | T | 598 | 608 |

* SNO: subdivision of unorganized, RG: Region, T: Town

### 1.2.2 Insufficient system optimization, specifically for NL

MSW contains approximately 60% biodegradable matter (Brown et al., 1998). The organic fraction of MSW, with a high moisture content (70-80%) and high concentrations of easily degradable organic substances such as sugars, starches, lipids and proteins, is mostly responsible for the emission of greenhouse gases and the generation of leachate in the landfill (Adhikari et al., 2009). Composting is a useful method to produce a stabilized material from MSW that can be used as a source of nutrients and soil conditioner in fields and can improve the physical and chemical properties of amended soils (Brown et al., 1998, Castaldi et al., 2005). Previously, many studies investigated the physiochemical changes during composting of MSW (Roland Mote and Griffis, 1979; Strom, 1985; Ciavatta et al.1993; Garcia et al., 1993; Canet and Pomares, 1995; Eklind and Kirchmann, 2000; Adhikari et al., 2008; Castaldi et al., 2008; Xiao et al., 2009; Chang and Chen, 2010; Cheung et al., 2010; Iqbal et al., 2010; Jolanun and Towprayoon, 2010; Kayikçioğlu and Okur, 2011). In addition, many studies have been conducted to evaluate the influence of different factors such as temperature (Strom, 1985; Suler and Finstein, 1977) moisture (Suler and Finstein, 1977), aeration rate, and bulking agents (Adhikari et al., 2008; Eklind and Kirchmann, 2000; Chang and Chen, 2010; Jolanun and Towprayoon, 2010) on composting of MSW. However, optimization of the MSW composting to increase the decomposition rate and to produce more stable and mature product is still confronted

with many challenges. Most of the studies just focused on the effect of each factor on the composting process, with no comprehensive consideration of the interaction among the factors during composting.

Furthermore, composting is a promising solution for NL to achieve the goal of solid waste management plan, with diverting 50% of the organic wastes from landfill, specifically for small communities. Full-scale and laboratory scales studies in the province are inadequate to draw a clear picture of the composting process and to build a strong background for initiating and managing a composting system. Therefore, studies are highly desired to monitor and optimize the MSW composting, which can provide a solid base for on-site small-scale composting operation and management in NL.

## 1.3 Objectives

The objective of this study is to fill knowledge and technical gaps of on-site composting in small communities through developing suitable composting technologies for MSW treatment, which can be directly applied to small communities in NL. It entails the following research tasks:

1. Design the composting system for the evaluation of on-site composting processes;

2. Investigate the effect of different factors including moisture content, aeration rate, C/N ratio and bulking agents on food waste composting; and

3. Optimize the operation parameters of the designed system through statistical analysis. Use factorial design to screen the significant parameters and significant interactions for developing a MSW composting model.

# 2 Literature Review

## 2.1 MSW composting

Composting is a biological process in which easily degradable organic matter (OM) is stabilized and converted by the action of microorganisms into a humus-rich product (Eiland et al., 2001). During composting, compounds such as protein, cellulose, and hemicellulose are utilized by microorganisms as carbon and nitrogen sources. The residual plant OM, along with compounds of microbial origin, is transformed by microorganisms to form humic-like substances of increasing complexity (Mondini et al., 2004). Tchobanoglous et al. (1994) suggested the following diagram to describe the composting process:

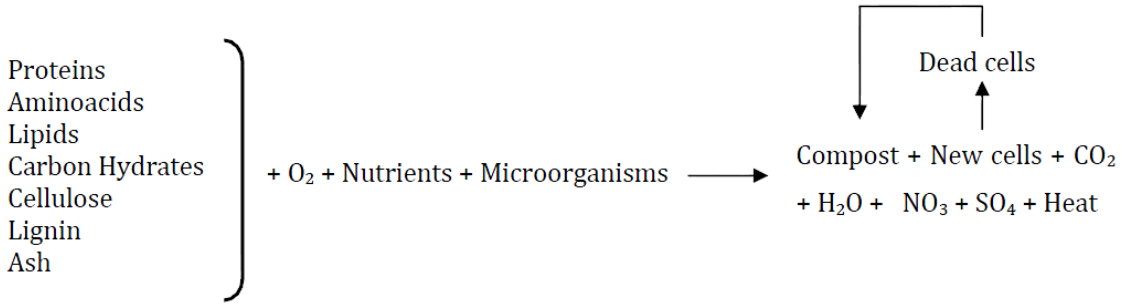



Figure 2.1. Diagram of the composting process

The objectives of composting are (Haug, 1993; Statistics Canada, 2005):

- Diverting organic matter from landfills and reducing the pressure on landfills, leachate content of and odour potential of landfills;

- Converting organic matter to stabilized forms;
- Decreasing the odour potential of the OM;
- Decreasing the moisture content of municipal and industrial sludge;
- Reducing the subsequent cost of transportation; and
- Producing a soil amendment to increase the soil fertility, raise the quality of crops, and improve plant resistance to disease.

Composting can be divided into four stages which include pre-processing, high-rate phase, curing phase, and post processing. Depending on the raw material (feedstock) and the required quality of final products, pre- and post-processing may be required. The pre-processing includes removing unwanted material and reducing size, adjusting moisture content, adding bulking agents, and mixing feed components to provide the optimum composting conditions. In the high-rate phase, microorganisms reduce biodegradable volatile solids and decompose complex organic matter into the simple organic matter. The high-rate phase proceeds in two steps and each step is characterized by a different set of microorganisms. In the first step, mesophilic microorganisms consume carbon sources and temperature rises to 45 °C. The degradation will then increase the system temperature to 70 °C in the second step and the thermophilic microorganisms start to dominate. The high temperature in the thermophilic phase is important to inactivate pathogens and plant seeds. After the high-rate phase, due to the decreasing of microbial activities, the temperature drops under 45°C so that the curing phase starts and stabilization and maturation of organic matter take part. The final products of a composting treatment will be $H_2O$, $CO_2$, and stabilized matter (Figure 2.2) (Haug, 1993).

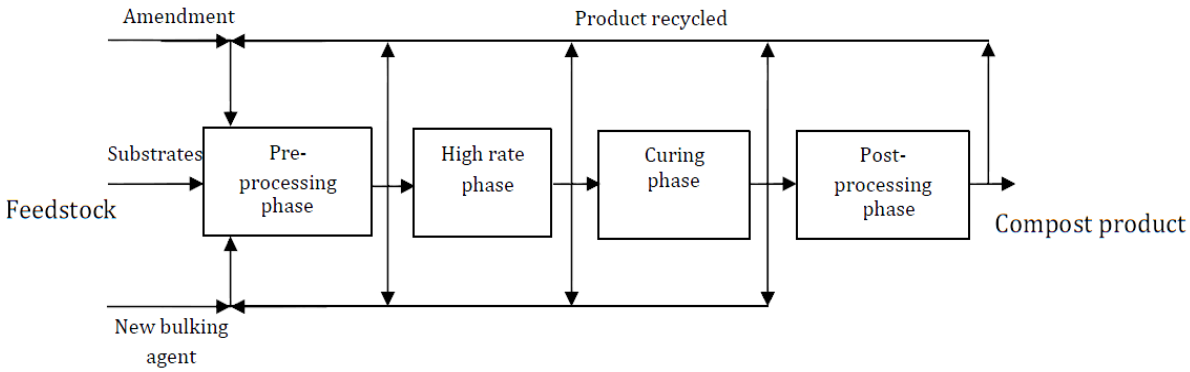



Figure 2.2. Generalized process diagram for composting

Composting first received attention because it is an inexpensive, simple and environmental friendly process (Magalhaes et al., 1993). It reduces the mass, bulk volume, and water content of organic matter (Cronje et al., 2003) and it returns nutrients to the soil (Arslanet al., 2011). In addition, the pathogen becomes inactivated due to the thermophilic stage (Cronje et al., 2003). Physiochemical, microbiological and thermodynamic phenomena and their interaction are involved in the composting process, making the composting very complicated (Petiot and De Guardia, 2004). Decomposition of organic matter produces heat. The energy and mass transfer are indicated by temperature, moisture content, and oxygen concentration. To produce a high quality end product from composting, water content, oxygen, and the composition and quantity of raw material play important roles (Magalhaes et al., 1993). Oxygen deficiency increases odour production because it creates anaerobic situation and reduces the growth of aerobic microorganism; however, excessive aeration can increase costs and slows down the composting process via heat, water, and ammonia losses (Guo et al., 2012). High moisture content enhances the anaerobic condition and produces more leachate. On the other hand, low moisture content decreases the microbial activity (VanderGheynst et al., 1997). Due to these concerns, more

studies are needed to understand the interactions between the process degradation kinetics and the mechanisms of heat and mass transport as well as the process optimization (VanderGheynst et al., 1997; Petiot and De Guardia, 2004). In addition, further studies will allow us to reduce the time, energy and cost of the process, and produce a pathogen free, stable, and mature product (Mason and Milke, 2005).

## 2.2 Parameters effecting performance of composting

There are a wide range of parameters which can be used to monitor physical, chemical, biological, and biochemical variations during composting, such as the aeration rate, temperature, pH, moisture content, carbon/nitrogen (C/N) ratio, respiration, enzyme activity, microbial colony, and bioassay.

### 2.2.1 Temperature

Temperature is an important factor for evacuating composting efficiency (Miyatake and Iwabuchi, 2006). It can affect microbial metabolism, population dynamics (e.g., composition and density) of microbes and diversity of microorganisms (Suler and Finstein, 1977; Arslanet al., 2011), and thus can be considered as a promising index of microbial activities and biooxidative stages (Godden et al., 1983). Godden et al. (1983) suggested three distinct stages during composting, including the (a) mesophilic (below 40°C), (b) thermophilic (above 40°C), and (c) cooling (ambient temperature) stage (Figure 2.3). As composting proceeds, the temperature of the decomposing wastes increases rapidly (Iqbal, 2010). Temperature increase within composting materials is a function of initial temperature, metabolic heat evolution, and heat

conservation (Liang et al., 2003). After the thermophilic stage, the system temperature will decrease gradually and become stable (Iqbal, 2010).

Higher temperature is favorable for the pasteurization of pathogenic microorganisms in the materials, for the increase of water evaporation from the composting solid materials, and for the stimulation of the rate of degradation of organic matter in the composting materials (Nakasaki et al., 1985). On the other hand, temperature in excess of 60°C could reduce the activity of the microbial community as the thermophilic optimum of microorganisms is surpassed. If the temperature reaches 82°C, the microbial community is dramatically restrained (Liang et al., 2003; Miyatake and Iwabuchi, 2005). Besides limitation of microorganism activity which leads to slowing down the decomposition of organic matter, excessive temperature (over 70°C) can increase the ignition risk of composting pile, and enhance the ammonia ($NH_3$) emission (De Bertoldi et. al., 1983; Ponsá, 2010).

Different characterization can be seen in different ranges of temperature. The highest biodiversity of the microbial population, the highest rate of biodegradation, and the highest rate of sanitization of pathogen inactivation have been observed in 25-45°, 45-55°C and above 55°C, respectively (Christensen, 2011). Tang et al. (2007) found that temperatures ranged from 30-45°C and 55- 66°C in mesophilic and thermophilic composting, respectively, and the change in $O_2$ content in the exhaust gas corresponded very well to the change in temperature. Miyatake et al. (2004) demonstrated that enzymatic activity and species diversity of thermophilic bacteria were affected by composting temperatures between 54 and 70 °C. The results showed that the highest activity of thermophilic bacteria was observed at 54 °C. When the temperature increased

to 63 °C, a certain group of bacteria died out, resulting in an overall reduction in bacterial diversity (Tang et al., 2007).

The optimum temperature is considered to be approximately 60°C according to maximizing respiration rates such as oxygen uptake rate and $CO_2$ evolution rate (Miyatake and Iwabuchi, 2006; Tang et al., 2007). However, some research have indicated that lower temperatures might allow higher microbial activity in compost, and the optimum temperature for respiratory activity has not always coincided with 60°C in past composting research (Miyatake and Iwabuchi, 2006). The achievement of minimum temperature levels is essential to an effective composting process and contributes substantially to the high rate of decomposition achieved during processing (Liang et al., 2003). In some studies, composting was also carried out at mesophilic temperatures lower than 45°C. A high decomposition rate was observed for low-temperature composting at about 35°C (Tang et al., 2007).

According to the US environmental protection agency regulation, aerated static piles and in-vessel systems must be maintained at a minimum operating temperature of 55°C for at least 3 days and windrow piles must be maintained at a minimum operating temperature of 55°C for 15 days or longer (De Bertoldi et. al.,1983; Ponsá, 2010).

### 2.2.2 pH

Another important environmental factor is the pH value of composting materials (Nakasaki et al., 1993). The presence of short chain organic acids in raw materials, mainly lactic and acetic acids, leads to low pH of MSW, with the value normally ranging between 4.5 and 6. The degradation of organic waste increases the concentrations of organic acids which are intermediate by-products

of microbial breakdown of easily degraded substrates such as sugars, fats, starch, and greases during the initial phase of composting. Low pH as a result of organic acids most of the time inhibits progress of composting process (Nakasaki et al., 1993; Sundberg et al., 2004). Also, low pH during the process leads to corrosion, odour, and slow decomposition, inefficient use of the facilities, low compost quality and difficulties in attaining high temperatures for proper sanitization. Once optimum conditions for microbial activity are reached, the organic acids will be biodegraded and consumed by microorganisms in the later stages of composting, and pH starts to increase to 8-9 (Cheung et al., 2010). High pH in the presence of high temperature condition could increase the $NH_3$ concentration in compost free air space and may lead to loss of $NH_3$ (Liang et al., 2006). Like temperature, pH follows a typical profile which is shown in Figure 2.3.

Nakasaki et al. (1993) studied the composting of garbage to determine the reaction rate of composting through controlling the pH value. They inhibited pH reduction by adding lime. Their results showed that controlled pH accelerated significantly the rate of reaction at its earlier stage; also it shortened the high-rate composting and avoided the odour problem. Sundberg and Jönsson (2008) shortened the time needed to produce stable compost and improved the efficiency of the composting plants by increasing the aeration rates at the early stage. The operation led to a faster rise in pH and prevented the low pH due to the anaerobic conditions and higher microbial activity.

Said-Pullicino et al. (2008) found that the anaerobic condition due to the storage of the urbane waste material prior to composting in the early stage led to the formation of organic acids which

caused a drop in pH. Providing oxygen through and mixing of the material resulted in an increase in pH as these organic acids were degraded. Release of ammonium or volatile ammonia in result of mineralization of proteins, amino acids, and peptides also contributed to the increase in pH.

### 2.2.3 C/N ratio

The C/N ratio is one of the most important parameters to control the composting process and to determine the feedstock recipe and the degree of maturity of the end product of compost (Iglesias Jiménez and Pérez García, 1992; Doublet et al., 2010; Puyuelo et al., 2011, Guo et al., 2012). Guo et al. (2012) found that the major factors in composting process are aeration rate and C/N ratio. The nutrient that has received the most attention in composting systems is nitrogen since it is the most needed element for plant nutrition. Moreover, it has often been recognised as a limiting factor for microbial growth and activity during the decomposition of plant residues especially in materials with a high C/N ratio. Carbon that provides energy for the degradation process is an element that is also most likely to be lost during the composting process (Eklind and Kirchmann, 2000; Tiquia and Tam, 2000; Dresbøll and Thorup-Kristensen, 2005). Nitrogen content increases through the mineralization of organic matter and consequent loss of $CO_2$, $H_2O$ and decreases through ammonia volatilization. At the later stage, the activity of nitrogen-fixing bacteria compensates the nitrogen loose partially. High temperature can affect adversely the nitrification and nitrogen balance (De Bertoldi et al., 1983). The C/N ratio of the initial composting material has also been reported to affect N loss during composting. A very narrow C/N ratio can lead to loss of N through $NH_3$volatilization, especially if the compost piles are aerated mechanically or turned manually (De Bertoldi et al., 1983; Tiquia and Tam, 2000). When C/N ratio is low, the excess of N can be lost from the composting mass through leaching or

volatilization as ammonia and potential odour problem. Low C/N ratio can be corrected by adding a bulking agent to provide organic carbon. An extremely high C/N ratio makes the composting process very slow as there is an excess of degradable substrate and lack of N for the microorganisms (Gao et al., 2010; Christensen, 2011). If the initial C/N ratio is greater than 35, microorganisms must oxidize the excess carbon, until a more convenient C/N ratio for their metabolism is reached (De Bertoldi et al., 1983).

Haug, (1993) proposes an optimum C/N ratio value as 15- 30. The other studies suggested that the suitable C/N ratio of the initial material should be 26-35 to ensure a good composting rate. A C/N ratio below 20 is the indicative of an acceptable maturity in the final product, and a ratio of 15 or even less is preferable (Iglesias Jiménez and Pérez García, 1992; Raut et al., 2008). In general, initial C/N ratios of 25–30 are considered ideal for composting. However, recently some composting studies have successfully been carried out with lower initial C/N ratios (Guo et al., 2012). For example, Gao et al. (2010) concluded that the composting mixture with an initial C/N ratio of 28 maintained the temperature exceeding 55 ºC for more than 3 days and the final $NH_4$-N content of the composting did not exceed the limit value of 400 mg $kg^{-1}$, so that the product could be considered stable compost.

### 2.2.4 Moisture content

Microbial activity and the physical structure in the composting process can be affected by moisture content; also it has a central influence on the biodegradation of organic materials (Ahn et al., 2008; Guo et al., 2012). Moisture content is one of the critical design and operating parameters used in compost engineering systems (McCartney and Tingley, 1998). It is important to transport dissolved nutrients required for the physiological and metabolic activities of

microorganisms (Guo et al., 2012). Moisture works as a medium to transfer dissolved gas and nutrients absorbed through the cell membrane of microorganisms (Haug, 1993; Christensen, 2011). The water during composting is produced as a by-product of microbial activities; also the generated heat through degradation will dry up part of the moisture. The moisture content can be adjusted by blending of components or by adding water (Tchobanoglous et al., 1994).

The moisture content during the active phase of composting is a function of temperature and rate of aeration. Positive aeration, temperature elevation and turning can reduce the moisture content in composting matrix (Said-Pullicino et al., 2008). By filling voids between waste particles and increasing the potential of compaction, the high moisture content reduces the free air space and lessens the oxygen accessible to microorganism leading to anaerobic conditions (Liang et al., 2003; Sundberg and Jönsson, 2008). Liang et al. (2003) found a direct relationship between microbial activities and the moisture content. Even at low temperature, higher moisture content indicated a higher microbial activity. Also high moisture content will lead to the generation of a large amount of leachate which needs to be managed (Iqbal et al., 2010). On the other hand, the microbial activity will be slowed down at low moisture content, leading to the production of biologically unstable composts (Liang et al., 2003). Haug (1993) found that most of the bacteria halted their activity at very low moisture content. The optimal moisture content in composting varies and essentially depends on the physical state and size of the particles (De Bertoldi et al., 1983). The optimum moisture content is 40-60% for municipal solid waste. For biosolid compost, a moisture contentabove 60% was considered as the optimal value (Tchobanoglous et al., 1994; Liang et al., 2003).

### 2.2.5 Aeration rate

The aeration rate is the one of most important parameters for the composting process (Puyuelo and Sánchez, 2010; Arslanet al., 2011). The main purposes of air supply to composting is to provide oxygen for biological degradation, dry up the wet materials and remove excess moisture, and to carry off exhaust gas and generated heat (Haug, 1993). Air flow influences spatial distribution of gases, moisture, temperature, and the decomposition rate of the organic matter (Cronje et al., 2003). The aeration provides oxygen to inhibit anaerobic condition and support the aerobic microbial activity. In addition, it removes the waste gaseous products (Leton and Stentiford, 1990; Puyuelo and Sánchez, 2010). Physical turning (mechanical and non-mechanical) of the mass, natural convection, and forced aeration (positive and negative modes) are well-known ways to control effective aerobic composting (Rasapoor et al., 2009; Jolanun and Towprayoon, 2010). Lack of aeration can lead to anaerobic conditions and excess aeration will increase the cost the heat, as well as the loss of moisture and ammonia (Guo et al., 2012). Shen et al. (2011) found that composting never reached the thermophilic phase at low rate aeration. Also at the low aeration rate, the production of organic acids due to anaerobic conditions led to the relatively low pH, large $CH_4$ production, high $N_2O$ emissions, higher loss of Total Nitrogen (TN), low Total Organic Carbon (TOC) reduction and low Germination Index (GI) (Shen et al., 2011). Rasapoo et al. (2009) stated that a lower aeration rate had a significant effect on the ammonium and nitrate formation. Aeration rates did not have a significant impact on the final concentration of phosphorus (P) and potassium (K).

Haug (1993) recommended the aeration rate with a value ranging from 1.2 to 2.0 g $O_2$/g BVS for most composting substrates and a higher value such as 4.0 g $O_2$/G BVS for saturated substrates. Kim et al., 2009 recommended an aeration rate of 0.5 liters min $kg^{-1}$ of waste for MSW composting. It has been suggested that aeration rate of 0.20 and 1.33 liters min $kg^{-1}$ volatile

matter (VM) are suitable for composting mixtures of municipal sewage sludges and garbages (Lau et al., 1992). Above all, oxygen content in the circulating air should not fall below about 18% (De Bertoldi et al., 1983).

Oxygen consumption can be used for indicating microbial activities. During the first stage of composting, there is a peak in oxygen consumption, simultaneous with the increase of temperature and microbial activity, which lasts for several days. After decomposition of the degradable material when the temperature drops, the oxygen consumption declines to a very low rate (Christensen, 2011).

Respiration ($CO_2$ evolution rate and/or $O_2$ uptake rate) has been used to determine the biological stability and microbial activity (Xiao et al., 2009). High values for oxygen uptake rate (OUR) indicate the degradation of organic compounds through microbial respiration which is mostly observed in the early stages of decomposition (Said-Pullicino et al., 2008). Respirometric methods based on OUT can be dynamic or static; dynamic methods use continuous air supply to limit $O_2$ diffusion whereas static methods do not use continuous air supply during assay (Xiao et al., 2009). Adani et al. (2006) found that dynamic respiration index (DRI) is a reliable indication of the biological stability. DRI values of 1000 and 500 mg $O_2$ $kg^{-1}$ volatile solids (VS) $h^{-1}$ indicate medium (e.g., fresh compost) and high (e.g., mature compost) biological stabilities, respectively. Said-Pullicino et al. (2008) observed the minimum specific oxygen uptake rate (SOUR) was during active phase in which most of the organic matter was degraded. It can thus be concluded that $SOUR_{max}$ is related to the concentration of immediate carbon sources (i.e., sugars, amino sugars, amino acids, simple organic acids). The measurement of oxygen demand shows a steady decrease with compositing time.

## 2.3 Composting Systems

In order to study the composting of organic wastes, different systems and sizes of reactors have been reported in the literature. Some studies were conducted in the full-scale reactors at the composting plant, and others used laboratory scale (pilot scale or bench scale) reactors. Full-scale composting reactors normally exceed 5000 L in volume, and have a relatively low surface area to volume ratio (SA:V) ratio which is estimated at 0.4:1 and 3.8:1 $m^2/m^3$. Bench-scale composting reactors generally have a volume less than 100 L and a SA:V ratio higher than 10:1, while pilot- scale reactors are those with a volume of 100-2000 L and a SA:V ratio in the range of 4-10 (Petiot and De Guardia, 2004).

### 2.3.1 Commercial composting systems

According to composting council of Canada, major groups of organic composting systems are windrow and in-vessel systems. Windrow systems are classified in open turned pile, static aerated pile, and enclosed aerated pile. In-vessel systems include Modular In-Vessel Containers (Static), Modular In-Vessel Tunnels (Static), In-Vessel Bays (Mechanical Agitation), In-Vessel Vertical Silos, and Rotary Drums (HMJ, 2008).

(1) Windrow systems

To use the heterogeneous materials in a windrow, in the pre-processing phase, materials will be grounded or shredded to reduce particle sizes and increase the surface area, be mixed to balance the C/N ratio. Solid wastes after shredding will be placed in elongated piles on the ground or concrete. The windrow can be aerated just by turning periodically with mechanical equipment or by forced or induced aeration through pipes. Also, they could be either covered or open. The advantages of the windrow system include a fairly low cost and simple equipment, and its

disadvantages are labor intensive, hard to reach stable situation, and odour potential (Haug, 1993; HMJ, 2008; Anderson et al., 2010).

**Open turned piles**

In open turned pile, mixed feedstock turned periodically by mechanical equipment to aerate the system. Natural ventilation provides oxygen for system more by buoyancy of hot gas in windrow and less by gas exchange during turning. Oxygen content, temperature, and moisture content are monitored. The system is watered if the moisture content is low and turning frequency is increased if the oxygen content is low. Turning also promotes a uniform decomposition of material since the outer cool layer is moved to the inner layer. Height, width, and shape of the piles vary depending on the particle size and initial density of feedstock, the ability of the turning equipment, the season, and the place. The recommended height and width for open turned piles are 1.5-1.8 meters and 2.4-36 meters, respectively (Russell, 1985; Haug, 1993; HMJ, 2008; Anderson et al., 2010; Ponsá, 2010). The MaxiPile® technology developed by Biomax Inc. incorporates simple turn-over mechanism for static pile composting of organic wastes. This system requires relatively more space and time, but can be more easily operated (HMJ, 2008).

**Static aerated piles**

The pre-processed waste is located over an aerated floor in static aerated piles. The passive or active aeration provides air for the windrow. The active aeration is more preferred in municipal-scale systems by which air is forced through the composting mass. To prevent the anaerobic situation, the oxygen content generally monitored by the computerized monitoring system controls frequently the amount and duration of oxygen. The windrow is turned time to time to

keep a uniform decomposition condition. The static aerated pile is frequently used for wet substrate like sludge with a bulking agent to keep the air voids. The odours from the exhaust air may be removed using filters and scrubbers. Static aerated piles are 2-2.6 meters in height. This system can compost a large volume of organic materials quickly with less labor, and better control the quality of the end product. Major disadvantage of the static aerated pile system is the comparatively high capital investment for the facility, equipment and training, and for operation and maintenance of specialized and complex equipment. Examples of aerated static pile composting technologies are produced by Engineered Compost Systems Inc. and W.L Gore (Russell, 1985; Haug, 1993; HMJ, 2008; Anderson et al, 2010; Ponsá, 2010).

**Enclosed aerated piles**

In enclosed aerated piles, a fabric system covers the windrow system. This system is a simple way to reduce the odor problem. The cover could be aplastic sheet and aeration can be provided by in floor or above grade pipe, or it could be designed for negative-only aeration and includes single direction air inlets. Suction from the negative-only aeration makes the cover material cling to the piles. The AC composter is a covered aerated static pile system developed by Engineered Compost Systems Inc. It provides a cost effective approach to control odour, volatile organic compounds and $NH_3$ emissions. The Gore Cover System™ manufactured by W.L. Gore and Associates Inc. uses an underlying aeration system that forces air upwards through the window. The proprietary Gore fabric that covers the windrow allows water vapour to escape but does not permit precipitation to enter the windrow or odour to escape (Russell, 1985; Haug, 1993; HMJ, 2008; Anderson et al, 2010; Ponsá, 2010).

(2) In-vessel systems

In-vessel systems are a high rate controlled aeration systems including mechanical mixing of compost, and controlled environmental conditions for a better composting performance. Many of the technologies are modular, which means their capacity can be increased if the volume of the organic material rises. Feedstock is placed in containers, rotating drums, and enclosed buildings (tunnels or channels) where forced aeration is used to feed oxygen to the material. They can be operated regardless of the outside weather conditions. In-vessel systems can be run in continuous-feed as well as in batch modes. The mesophilic and thermophilic phases are short, and due to the highly controlled environment, the efficiency of the process is high. The operation and maintenance of in-vessel systems are costly and need intensive management. They are more preferable than the windrow systems due to the less required space. They provide more control over the composting process, odor emission, and they produce more consistent and high quality composts (HMJ, 2008; Anderson et al, 2010; Composting Council of Canada, 2010).

**Modular in-vessel containers (static)**

In modular in-vessel containers (static), feedstock is placed in the modular systems. There is no agitation equipment in containers and the method is static. Aeration can be active or passive; in either way it provides oxygen and removes heat and moisture. Exhaust gas is mainly treated in a biofilter in a separate container. The containers are different in shape and details in design of the systems including the aeration system, monitoring system and loading and unloading equipment. After filling the container, the material is maintained in the container for ten days to two weeks then is unloaded to transfer to the windrow or static pile for further curing. The number of containers can be reduced since the material needs to be stored in the containers only in the active phase. This type of system has been used for different kind of feedstocks such as sludge,

manure, and MSW. The BioChamber™ is a self-contained, automated, in-vessel thermophilic composting system developed by BioSystem Solutions Inc. to compost food wastes (including meat, dairy and fish waste), animal manure, sewage sludge (biosolids) and other biodegradable organics (Haug, 1993; Anderson et al., 2010; Composting Council of Canada, 2010).

**Modular in-vessel tunnels (static)**

Modular in-vessel system is similar to Modular in-vessel containers. It is in the form of a tunnel running across a building. It contains the forced aeration through a floor and internal air circulation. It is a static, intensive and highly controlled system; temperature and aeration are monitored and the biofilter is used to treat the exhaust gas. It is loaded from one end and operated in a batch mode after the tunnel is fully loaded. The number of tunnels can increase if the volumes of the feedstocks are high. The product of this tunnel is cured in a separate windrow composting facility for 1 to 2 months to yield stable products. On average they are around 4 meters high, 5 to 6 meters wide and around 20 meters long. The SV Composter™ (Stationary Vessel) is a variant of the tunnel technology developed by Engineered Compost Systems. Tunnels are preloaded with organics and the doors are kept sealed. The controlled aeration system then blows the amount of oxygen required into the tunnel (Composting council of Canada; HMJ, 2008).

**In-vessel bays (mechanical agitation)**

Feedstocks are placed in the long channels with walls in in-vessel bays, and an agitation machine travels on the top of the bed to mix the material. Aeration is introduced through the floor. The

aeration method could be either positive or negative. Feedstocks are loaded in the front end and unloaded at the discharge end. Turners move material along the channel. Material slowly progresses from the beginning to the end. The time of the composting is 10 to 28 days and it depends on shifting, distance, turning frequency, and the size of the channel. This system is desirable for dense foodstock because they provide good aeration without adding the bulking agent. Dimensions of individual bays vary from 1 m to 2.4 m deep and 1.9 m to 3.8 m wide and channel lengths typically range from 60 to 90 m. The product of the bay should be cured in a separate structure. The In-Vessel Composter (Figure 2.4) developed by Wright Environmental Management Inc. is a daily-fed plug flow type of composter. Everything in the unit is contained within a box resembling a shipping container. The floor of the container is made up of trays which support the mass of organics above. At the beginning of the operational day, a hydraulic ram pushes the trays horizontally to advance the plug within the container. This causes one of the trays in the system to be forced out of the other end (HMJ, 2008; Anderson et al, 2010; Composting Council of Canada, 2010).

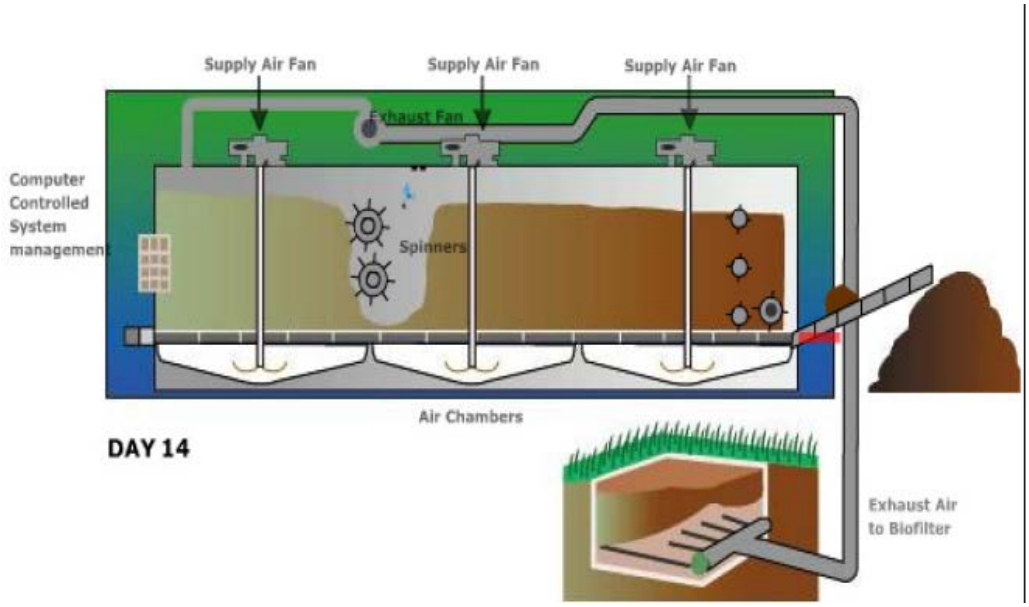



Figure 2.3. Process description of Wright Environmental Management Inc. In-vessel bays

**Rotary drums**

In rotary drums, a cylindrical drum slowly rotates continuously. The rotary drum systems generally are used with other in-vessel systems. Rotary drums are used for mixing and tumbling the materials, reducing their size without shredding, and screening them in a short retention time. Aeration can be provided through natural ventilation by creating small holes on the wall of the drum or can be provided through pressurized air. Although they provide a high rate of decomposing the organic matter in short residence time, they are not so convenient to be used due to the high capital cost when comparing to the other in-vessel systems. Bedminster Bioconversion Corp., Texas, has long been a leader in developing drum composting systems. They have unveiled plans for marketing a version of their high-tech drum system used for municipal composting on a scale suitable for institutional use (The Clean Washington Center, 1997; Anderson et al., 2010; Composting council of Canada, 2010).

### 2.3.2 Lab scale composting systems

(1) System description

Proper scale-down techniques should be applied in the design of laboratory scale reactors, to be able to use them as representative of the large scale composting reactors. The generation and transfer of heat in the composting system, moisture and water vapour transport, natural ventilation, volatilisation, oxygen status and temperature distribution patterns are important in the scaling-down, due to their effect on biological activities. Non-thermodynamic factors, such as mixture compression and spatial airflow patterns, can also be important due to their effect on both the thermodynamic regime and other state variables including moisture content, $O_2$ and $CO_2$ concentrations, and temperature (Mason and Milke, 2005). Laboratory scale reactors should be able to provide the same "working condition" (e.g., oxygen content, moisture content, and temperature) as the large-scale ones to create the same biochemical transformation for a given substrate. The different working conditions will provide different medium for microorganisms, consequently induce differences between laboratory scale and large scale composting (Petiot and De Guardia, 2004). The variations in aeration methods, the presence or absence of ventilative heat management (VHM), mixing and in-process moisture addition need to be incorporated at the laboratory-level (Mason and Milke, 2005)..

The laboratory scale reactors have been built in different shape and size. For the practical reason, the cylindrical shape is the most common one for laboratory scale reactors because of the minimal volume to surface area ratio (SA: V ratio) it provides which decreases the heat loss from the surface area (Petiot and De Guardia, 2004). The most widely applied reactor configuration in lab-scale systems consists of a vertical packed bed with the forced aeration (VanderGheynst et

al., 1997). The following table represents the volume and surface area of the reactors used to conduct composting experiments.

Table 2.1. Reactor volume and SA:V ratio

| V(l) | SA:V(M2/M3) | Scale | Reference |
|---|---|---|---|
| **0.4** | 88 | Bench scale | Magalhaes et al., 1993 |
| **7.9** | 28 | Bench scale | Sikora et al., 1983 |
| **770** | 7.4 | Pilot scale | VanderGheynst et al., 1997 |
| **450** | 15.6 | Pilot scale | Hogan, et al., 1989 |

(2) System Control

Although composting accrues spontaneously in nature, the process is long and heterogeneous. This kind of composting is not suitable for commercial applications. Factors such as oxygen, moisture, temperature, and conditions of starting material should be monitored and optimized to decrease the degradation time, provide the optimum medium for microbial activity and produce homogenous end products (De Bertoldi et al., 1983). A variety of methods and systems have been developed for this purpose in the laboratory scale reactors, which have been described in the following section.

**Temperature control**

The increase in the composting medium temperature is the result of energy balance stated as:

In+ Production-Out = Accumulation

Where “In” represents thermal energy brought by air into the composting reactor, “production” heat generated by microbial activity, and “Out” represents heat loss induced by either free or forced convection (conduction, convection, and radiation (CCR) through external surface) (Petiot

and De Guardia, 2004). Heat generation in the reactor is associated with the quantity of biodegradable matter and the volume of the substrate. As well, the heat loss is associated with convection, conduction, and radiation losses from the external surface (Petiot and De Guardia, 2004). Therefore, SA: V ratio should be considered as an important factor to achieve the thermophilic phase in the laboratory scale reactors. As SA: V ratio increases, the potential for heat loss from the reactor wall increases (VanderGheynst et al., 1997). Laboratory scale reactors have relatively large external SA: V ratio consequently they show large heat losses (Cronje et al., 2003). In a full scale system, heat loss is primarily through evaporation of water. In contrast, heat loss in laboratory systems is primarily through conduction (Magalhaes et al., 1993). According to Cronje et al. (2003), a full scale reactor which lost about 76% of heat generated from microbial activity through evaporation, while more than 30% of the microbial generated heat dissipated from the walls of an insulated laboratory reactor. Bach et al. (1987) compared the heat loss between and industrial plant and a laboratory scale reactor during sludge composting. Heat loss due to the conduction was 61% and 11%, 34%, and 76% due to the evaporation in the laboratory scale reactor and industrial plant, respectively.

Thermodynamically, laboratory scale reactors can be classified as self-heating, fixed-temperature, controlled temperature difference (CTD) and controlled heat flux (CHF) (Campbell et al., 1990a; Mason and Milke, 2005).

Self-heating reactors rely on the microorganism's capacity to degrade the substrate and produce heat to achieve the thermophilic phase; they have external insulation in most cases but no other temperature control device. The amount of the generated heat depends on the microbial activity and quantity of substrate used (Campbell et al., 1990b). Self-heating lab-scale reactors have been used to investigate the influence of moisture content, aeration, and temperature on bulk

composting (Campbell et al., 1990a). Ekinci et al. (2004) developed a model for heat release rate due to the biological activity from reactor.

External heating and cooling is applied to achieve the predetermined temperature regime in fixed-temperature reactors (Campbell et al., 1990a; Mason and Milke, 2005). Fix-temperature can be achieved by placing the reactor in the thermostatically-controlled chambers such as the isothermal incubator (Miyatake and Iwabuchi, 2005) or water-baths (Suler and Finstein, 1977; Sikora and Sowers, 1985), or by wrapping the reactor with a heating ribbon. Fixed temperature reactors are very useful to investigate the process under the particular temperature, study the reaction rates, temperature optima microbiological activity, the degradation of specific compounds and exhaust gas composition (Mason and Milke, 2005), and determine optimal temperatures (Campbell, et al., 1990a). For example, Strom (1985) placed the reactor in the incubator to create the fixed-temperature condition to study microbial population and diversity. Strom (1985) and Nakasaki et al. (1985) kept the temperature fixed by controlling the rate of airflow to find the optimum temperature for composting. However, using fix-temperature regime has been criticized to simulate the whole dynamic of the composting process due to creating unrealistic conditions (Campbell et al., 1990b).

In Controlled Temperature Difference (CTD) and Controlled Heat Flux (CHF) regime, the reactor relies solely on microbial heat production to reach and maintain process temperatures, where CCR heat losses are controlled by supplying heat to the outer surface of the vessel in order to maintain a pre-determined temperature or heat flux difference across the composting material and/or the reactor wall(s) (Mason and Milke, 2005).

Hogan et al. (1989) used a 14L prototype laboratory scale reactor to simulate heat loss processes observed in the field. They designed a conductive flux control reactor to remove the appropriate level of heat by ventilation and keep the desire temperature for microbial activity. The mathematical model has been used to calculate the conductive flux through the walls. The conductive heat losses in the reactor were 33.5% with insulation and 2.4% with insulation and incubation (Hogan, et al., 1989). Hogan et al. (1989) found that the reactor with the CHFC (Conductive heat flux control) system showed a similar behaviour in the temperature, oxygen and water content as that in the full-scale system.

Temperature control requires reliable temperature monitoring instruments such as thermocouple, thermistor and probes, which were placed at different points in the reactor. Beside the number of thermometers, the location of the thermometers is very important especially when thermometer feedbacks are used to control the airflow rate. They can be placed vertically at different heights (Gao et al., 2010) radian and axial (Tremier et al., 2008).

**System insulation**

Insulation is essential for preventing the heat loss from surface due to the high SA: V ratio in the reactors. Without a proper insulation, it is hard to achieve temperatures above 50°C (Campbell et al., 1990a). Variety of insulation material with different thickness have been used in the literature including glass wool, rock wool, mineral wool, polystyrene, polyurethane, urethane sheeting, an d fiber glass. Hogan et al. (1989) used 2 layer of Polyurethane (18 and 55 mm). Magalhaes et al. (1993) covered the 400 $cm^3$ reactor with 2.54 cm thick fiber glass and wrapped the lid and bas with 1.27 cm thick foil-faced polyethylene. Cronje et al. (2003) used rock wool. VanderGheynst et al. (1997) applied 12.7 mm foam to the surface of the reactor and 5 cm polyisocyanurate foam

board with reflective for bottom insulation. Campbell et al. (1990a) put 75 mm of expanded polystyrene around their reactor to resist the heat flow.

**Aeration and $O_2$ concentration control**

Aeration can influence microbial activity, substrate degradation and temperature variation during composting, (Puyuelo and Sánchez, 2010) resulting in a high impacts on the quality of the end product and on the environmental consequences of the treatment (gaseous emissions and odours) (Tremier et al., 2008). Raw composting materials can be aerated by one of following methods: physical turning of the mass, natural convection of static pile, and forced aeration (passive or active) (Puyuelo and Sánchez, 2010; Arslanet al., 2011). The majority of laboratory-scale reactors have utilized forced aeration (Mason and Milke, 2005). Forced aeration uses a ventilation unit to force air into a perforated system located underneath the compost pile, induces air convection movement into the materials and deliver oxygen to microorganisms (Arslanet al., 2011). The forced aeration rate can be a fixed rate, variable rate and automated rate of aeration control (Leton and Stentiford, 1990). Fixed aeration rates have been most frequently reported, although dual aeration systems have sometimes been used to facilitate VHM (ventilation heat management) (Mason and Milke, 2005). The fixed aeration can be continues, fixed rate or intermittent in a fixed cycle (e.g., 5 min on and 30 min off) (Puyuelo and Sánchez, 2010). In the variable rate aeration system, the airflow rate is high at the beginning and decreased by time during composting, (Leton and Stentiford, 1990). The rate and duration of aeration is regulated via feedback control of the temperature (Leton and Stentiford, 1990; Ekinci et al., 2004) or oxygen concentration in the exhaust gas (Leton and Stentiford, 1990; Puyuelo and Sánchez, 2010) when the automated aeration rate is applied. Removing of excess heat which is generated

from the microbial metabolism and accumulated in the system from the composting matrix is the basis of the systems which use the temperature feedback control to regulate their air flow. While in the system based on the feedback from the oxygen concentration in the exhaust gas, the oxygen concentration in the exhaust gas can be kept between 5% and 15% through regulating the air flow. Oxygen levels under 5% can cause anaerobic conditions, whereas levels over 15% are the indicative of excessive aeration which tends to cool the material. An oxygen levels between 5 and 20 (%, v/v) has been mentioned as the optimum range (Puyuelo and Sánchez, 2010).

In some experiments to evaluate to compost progress, carbon dioxide content in the exhaust gas was monitored. To facilitate the measurement of carbon dioxide in the exhaust gas, some studies removed carbon dioxide from the inlet air. Campbell et al., 1990a removed carbon dioxide from the air intake by granular sodium hydroxide. Magalhaes et al. (1993) used activated coconut charcoal (Supelco Orbo-32) tube and 5 N NaOH solution to remove volatilized organic compounds and $CO_2$, from air before it entered the system.

**Moisture control**

The following equation can be used to calculate the moisture content of the material in a composting reactor:

$$\text{Moisture content (\%)} = \frac{W_{Wet} - W_{Dry}}{W_{Wet}} \times 100 \qquad (2.1)$$

Where $W_{Wet}$ is the weight of the fresh compost sample and $W_{Dry}$ is the weight of sample after drying in 70 °C for a period of time that the weight becomes constant.

Different methods have been used to control the moisture content during composting. The frequently used method is to adjust the moisture content of raw materials. Mixing the raw materials with dry materials such as dry tree leaves, saw dust, and wheat/rice straw (Lu et al.,

2008; Kalamdhad et al., 2009; Karnchanawong and Suriyanon, 2011) or drying material with natural air drying (Xiao et al., 2009) can reduce the moisture of wastes with a high initial moisture content.

To keep the desired moisture content and inhibit excessive drying of the composting mass during composting, continues water addition and waster sparing as well as air humidification prior to delivery air to the system have been reported (Suler and Finstein, 1977; MacGregor et al., 1981; Hogan, et al., 1989; Campbell et al., 1990b; Magalhaes et al., 1993; Miyatake and Iwabuchi, 2005; Fontenelle et al., 2011).

**Exhaust gas control**

The composition of exhaust air can be a good index to evaluate the composting process and the quality of the compost production. Ammonia is one of the main compounds in the exhaust gas which is responsible for generation of offensive odours and atmospheric pollution. Carbon dioxide is another compound of exhaust gas that can cause adverse effects on the environment (Pagans et al., 2006).

Techniques to identify and monitor the exhaust gas include individual or multigas analysis and chemical trap. Sulfuric acid ($H_2SO_4$) (Kim et al., 2009; Puyuelo and Sánchez, 2010) and boric acid ($H_3BO_3$) are normally used to trap ammonia, and NaOH is widely used to trap carbon dioxide (Puyuelo and Sánchez, 2010).

## 2.4 Parameters for evaluating compost maturity and stability

Maturity and stability are important indices for compost quality assessment and practical use of composted materials in agriculture (Mondini et al., 2004). Stability and maturity are both commonly used to define the degree of decomposition of organic matter during the composting process even if they are conceptually different (Benito et al., 2003). They are helpful to monitor the effectiveness of the biological degradation and process performance, and compare different composting systems (Cossu and Raga, 2008; Xiao et al., 2009).

Stability is related to the microbial activity and can be expressed by biological indicators like respiration index (oxygen uptake rate or $CO_2$ evolution rate), heat release as a result of microbial activity (ATP), enzyme activity and total microorganisms count (Wu et al., 2000; Benito et al., 2003; Bernal et al., 2009). In stable compost, readily biodegradable material was decomposed and converted to humic-like substances so the matter cannot sustain the microbial activity anymore (Xiao et al., 2009). Thus the oxygen consumption reduced and odour cannot be produced. The rate of energy release due to microbial degradation of the organic matter equals the rate of energy loss to the environment, and temperature of the compost thus equals that of the ambient temperature (Zmora-Nahum et al., 2005). The stability of given compost can determine the potential impact of the material on nitrogen availability in soil or growth media and maintain consistent volume and porosity in container growth media (Grigatti et al., 2011).

Maturity refers to the decomposition degree where compost does not pose any adverse effects on plants and growth of various crops (Zmora-Nahum et al., 2005; Castaldi et al., 2008). It is commonly associated with plant-growth potential or phytotoxicity. Mature compost contains negligible or acceptable concentrations of phytotoxic compounds such as $NH_3$ or short-chain

organic acids and a high proportion of humic substances. Maturity has been evaluated based on chemical parameters correlated with plant response (Bernal et al., 2009, Xiao et al., 2009).

Immature and poorly stabilized composts may cause a number of problems during storage, marketing and use. During storage of unstable compost, anaerobic conditions can result in odour, fire, or toxic compounds (California compost quality council, 2001). During the usage of immature and unstable compost, due to the ongoing microbial activities and decomposition, a competition between plants and the microbial biomass for oxygen exist (Benito et al., 2003; Chukwujindu et al., 2008; Grigatti et al., 2011). This may constrain the availability of oxygen to roots, suppress plant growth and produce $H_2S$ and NO (Chukwujindu et al., 2008; Grigatti et al., 2011). The consumption of soil nitrogen by microbial biomass can produce a serious nitrogen deficiency in soil and deprive roots of N (Iglesias Jiménez and Perez Garcia, 1989; Chukwujindu et al., 2008; Grigatti et al., 2011). High C/N ratio of applied immature compost may immobilize soil mineral nitrogen, leading to the degradation of the excessive carbon by soil microorganisms, and thus decreasing $O_2$ concentration and soil Eh (Redox potential). The reducing condition at the root system due to the low Eh can increase the solubility of some heavy metals, the sulphate formation, and the heavy metal precipitation. The soluble heavy metals can be absorbed more by plants (Iglesias Jiménez and Perez Garcia, 1989). Quick decomposition in the rhizosphere will increase the temperature which will inhibit seed germination and decrease root respiration, and nutrient uptake of the plant (Bernal et al., 2009). Accumulation of excess nitrogen, phosphorus and other nutrients is the other negative effect of unstable compost application (Hutchinson et al., 2008). Although phytotoxicity can be caused by other factors such as excess soluble salts or high heavy metal concentrations (Said-Pullicino et al., 2008 ), decomposition of unstable composting also produces phytotoxic substrate like phenolic compounds, ethylene oxide, low-molecular

weight organic acids, ammonia and toxic nitrogen compounds which could inhibit root growth (Zucconi et al., 1981).

To characterize compost maturity and stability, several factors have been studied including microbial respiration activity ($CO_2$ evolution) (Wu et al., 2000; Benito et al., 2003; Hutchinson et al., 2008), specific oxygen uptake rate (SOUR) (Lasaridi and Stentiford, 1998; Cabañas-Vargas et al., 2005; Scaglia et al., 2007; Mokhtari et al., 2011) Dissolved Organic Carbon (DOC) concentration (Wu et al., 2000; Mondini et al., 2004; Zmora-Nahum et al., 2005; Grigatti et al., 2011), seed germination tests (Zucconi,et al., 1981; Cabañas-Vargas et al., 2005; Zmora-Nahum et al., 2005; Said-Pullicino et al., 2008; Komilis et al., 2011; Guo et al., 2012), $NH_4^+$-N and $NO_3^-$ - N concentration (Benito et al., 2003; Francou et al., 2005; Chikae et al., 2006; Gao et al., 2010; Mokhtari et al., 2011; Guo et al., 2012), neutral degradable fiber and lignin (Hutchinson et al., 2008), enzyme activity including protease (Benitez et al., 1999; Goyal et al., 2005; Castaldi et al., 2008; Kayikçioğlu and Okur, 2011), urease (Godden et al., 1983; Benitez et al., 1999, Castaldi et al., 2008), cellulose (Godden et al., 1983; Castaldi et al., 2008), β-glucosidase (Benitez et al., 1999; Mondini et al., 2004; Kayikçioğlu and Okur, 2011), dehydrogenase activities (Benito et al., 2003; Tiquia, 2005; Barrena et al., 2008; Castaldi et al., 2008), and phosphatase (Godden et al., 1983; Mondini et al., 2004; Kayikçioğlu and Okur, 2011), Cation Exchange Capacity (CEC) (Iglesias Jiménez and Perez Garcia, 1992; Gao et al., 2010), humification parameters [Humic Acid (HA), Fulvic Acid (FA)] (Wu and MA, 2002; Francou et al., 2005, Tiquia, 2005, Cavani et al., 2008), Total Organic Carbon (TOC) (Francou et al., 2005; Gao et al., 2010, 2012), microbial biomass (Mondini et al., 2004), Biological oxygen demand (BOD) and Chemical Oxygen Demand (COD) (Cossu and Raga, 2008), non-cellulosic polysaccharides, phenolic compounds (Said-Pullicino et al., 2007), and water-soluble organic

matter (Said-Pullicino et al., 2008). Threshold for maturity indices have been defined by several studies and summarized in below:

Table 2.2. Threshold for maturity parameters

| Index | Threshold | Units | Reference |
|---|---|---|---|
| **respiration rates** | <2 | mg CO- C g compost $C^{-1}$ $d^{-1}$ | Brewer and Sullivan (2003) |
| **Water-soluble organic matter** | <2.2 | g/litre | Garcı´a et al. (1991) |
| **Water-soluble carbon/WSN** | <2 | - | Garcı´a et al. (1991) |
| **WSC/ORG.N** | <5 | - | Garcı´a et al. (1991) |
| **index of biodegradability** | <2.4 | - | Garcı´a et al. (1991) |
| **C/N** | 20 | - | Iglesias Jiménez and Perez Garcia, (1989) |
| **WSC/N** | <0.5 | - | Iglesias Jiménez and Pérez García, (1992); Pascualet al (1997) |
| **NH4+-N** | 0,04% | | De Bertoldi (1983) |
| **$NH_4^+$-N/$NO_3^-$-N** | <0.16 | | Bernai et al. (1998) |
| **$NH_4^+$-N/$NO_3^-$-N** | 1.9 | | Benito et al. (2003) |
| **DHA(dehydrogenase activity)** | 800 | mg TPF $kg^{-1}d^{-1}$ | Tiquia et al. (2002) |
| **GI (high phytotoxicity)** | <50% | | Zucconi et al. (1985) |
| **GI(no phytotoxicity)** | 50%-80% | | Zucconi et al. (1985) |
| **dynamic respiration index** | 500 | mg O2 $kg^{-1}$ (VS) $h^{-1}$ | Adani et.al, (2004) |
| **DOC** | <17 | g kg-1 | Bernal et al. (1998) |
| **DOC** | ≤10 | g $kg^{-1}$ | Hue and Liu (1995) |
| **water soluble carbon (WSC)** | <0.5% | | Garcı´a et al. (1991) |
| **water soluble carbon (WSC)** | <1% | | Hue and Liu (1995) |
| **water soluble carbon (WSC)** | <1.7% | | Bernal et al. (1998) |
| **C/N** | 12 | | Bernal et al. (2009); |

| | | | |
|---|---|---|---|
| | | | Iglesias Jiménez and Perez Garcia, (1992) |
| **Water extractable organic carbon(WEOC)** | <0.4 | mg $mL^{-1}$ | Zmora-Nahumet al. (2005) |
| **DOC (dissolved oxygen content)** | 4 | g $kg^{-1}$ | Zmora-Nahum et al (2005) |
| **C/N** | <15 | | Saidi at al. (2009) |
| **NH4+-N** | < 400 | mg/kg | Saidi at al. (2009) |
| **CO2-C** | < 2000 | mg $CO_2$-C/kg | Saidi at al. (2009) |
| **dehydrogenase activity** | < 1 | mg TPF/g dry matter | Saidi at al. (2009) |
| **germination index (GI)** | > 80% | | Saidi at al. (2009) |
| **Electrical conductivity** | 3000 | µs $cm^{-1}$ | Soumaré et al. (2002) |

Katia et al. (1998) showed that SOUR increased with age of compost and presents a consistent trends and highly significant correlations with processing time, thus respiration was suggested as a suitable indicator for compost stability (Lasaridi and Stentiford, 1998).

We et al. (2000) express that TKN, Total P, TVS%, C/N ratio, and HA /FA cannot be considered as a promising indication of compost maturity and stability, because they did not show a consistent trend for different waste feedstock. They found that the respiration test and bioassay test represent different properties of compost, and both $CO_2$ evolution and seed germination test are needed to be able to assess the compost stability and maturity (Wu et al., 2000).

Benito et al. (2003) showed that CEC increased due to humification, the concentration of $NH_4^+$-N decreased due to its conversion to $NO^{-3}$- N or volatilisation, the $CO_2$ Evolution stay steady after active phase (Benito et al., 2003).

To evaluate the maturity and stability of compost effectively, easy, rapid, and reliable testing methodology for all kind of composts should be developed and applied (California compost quality council, 2001; Castaldi et al., 2008). Since maturity and stability are not described by a single property and the origins of compost are different, the combination of multiple parameters is desired for a comprehensive evaluation (California compost quality council, 2001; Scaglia et al., 2007).

### 2.4.1 Evaluation of Carbon and Nitrogen relevant parameters

A number of parameters related to determination of organic matter especially different forms of carbon and nitrogen such as water soluble carbon (WSC), total carbon, total organic carbon, water soluble nitrogen (WSN), $NH_4^+ - N$, and $NO_3^- - N$ have been proposed for testing compost stability and maturity.

WSC is an indication of water-soluble fraction of organic matter of compost. It is the most accessible organic nutrient to microorganisms because it consists of sugars, hemicellulose, and phenolic substances, amino acids, peptides, and other easily biodegradable substances during composting. It has been frequently used as maturity index in the literature (Gajalakshmi and Abbasi, 2008; Paradelo et al., 2010b).

Ammonium and nitrate are the forms of N, which could be changed during composting. Poor aeration during composting resulted in excessive ammonium (Paradelo et al., 2010b). The $NH_4^+/NO_3^-$ ratio has also been proposed to estimate the compost stability. At the end of the composting process, the content of $NO_3^-$ should be higher than that of $NH_4^+$, indicating that the process has been performed under adequate aeration conditions (Grigatti et al., 2011).

García et al. (1991) measured the content of WSC, total organic carbon content, total nitrogen content, nitrate nitrogen, ammoniacal nitrogen in the water extract of the compost. They noticed

that water soluble carbon and WSN decreased significantly with time in all the samples during composting. Also the water soluble carbon/water soluble nitrogen showed a decline by proceeding composting. The WSC, WSN, and WSC/WSN can be considered as suitable parameters to reflect maturity of compost. It was suggested that the value of WSC/WSN should be less than 2 in the final matured product of composting.

Paradelo et al. (2010b) measured the TOC, total N, WSC, WSN, total alkali-extractable carbon in compost. The WSC/N should be less than 0.5 for mature compost great differences were observed for the ratio $NH_4^+ - N/\ NO_3^- - N$ among the composts. It has been concluded that at least three parameters including seed germination, microbial activity or water soluble organic matter, and degree of humidification should be measured to assess the maturity of final product of compost (Paradelo et al., 2010b).

Said-Pullicino et al. (2008) found that the total organic C to organic N (TOC: N) ratio decreased with composting time. The variation in the water-extractable organic C to soluble organic N (WEOC: ON) ratio during the process showed a similar trend to that observed for the TOC: N ratio. The WEOC: ON ratio is generally lower than TOC: N ratio due to the faster degradation of the soluble C with respect to soluble organic N. It could be derived that when the concentration of organic C in the germination media is 1.85 mg $mL^{-1}$, the phytotoxicity disappeared. Also the ratio of hydrophobic to hydrophilic water extractable organic C could represent the solubilisation and mineralization, that are responsible for the attainment of stability (Said-Pullicino et al., 2008).

### 2.4.2 Evaluation of enzyme activities

Enzyme is a biocatalyst which controls the rate of substrates degradation or accelerates the rate of biological reactions. In degradative processes, enzymes act as the main mediators (Castaldi et al., 2008; Kayikçioğlu and Okur, 2011; Valsange et al., 2012). They are responsible for the breakdown of several organic compounds characterised by a complex structure, finally leading to the solubilisation of simple water-soluble compounds (Castaldi et al., 2008). Due to the role played by enzymes in the biological and biochemical processes during composting, enzyme activity can indicate the ability of microbes to degrade a wide range of common organic substrates (Tiquia, 2002; Mondini et al., 2004, Castaldi et al., 2008). The presence of a high content of degradable organic compounds in the initial mixture might stimulate microbial growth and enzyme synthesis (Castaldi et al., 2008).

Characterising and quantifying specific enzyme activities during composting could provide information of dynamics of the composting process. They can reflect the rate of transformation of organic residues and nitrogen, as well as the stability and maturity of end products (Mondini et al., 2004; Raut et al., 2008). Moreover, the determination of enzyme activity, in contrast to other analytical techniques used for compost stability evaluation is easy, fast, and relatively inexpensive (Mondini et al., 2004). Important enzymes involved in the composting process include dehydrogenase for substrate oxidization by a reduction reaction, β-glucosidases for glucoside and amide hydrolysis, as well as phosphatases and arylsulphatase for phosphate and sulphate removal from organic compounds (Mondini et al., 2004). Other enzymes in composting process are celluloses for cellulose depolymerisation, proteases and urease involved in N mineralization (Mondini et al., 2004).

Dehydrogenases are enzymes belonging to the oxido-reductase group which catalyse the oxidation of organic substances (Kayikçioğlu and Okur, 2011). They participate in the metabolic reactions producing energy in the form of ATP through the oxidation of organic matter (Barrena et al., 2008). Dehydrogenases involve in the detachment of electrons from the substrate and their binding with protons (Kayikçioğlu and Okur, 2011). The microbial activity during composting, when defining by the dehydrogenase activity, reflects the role of enzymes on the oxidative phosphorylation process and their involvement in the respiratory chain of all organisms (Castaldi et al., 2008; Vargas-Garcia et al., 2010, Kayikçioğlu and Okur, 2011). Barrena et al. (2008) used dehydrogenase activity to monitor the composting process. Temperature and dehydrogenase profiles were very similar during the thermophilic stage; both showed a rapid increase in the first days of composting. However, maximum values of dehydrogenase (0.54 mg TPF gdry matter$^{-1}$h$^{-1}$) were observed at the end of thermophilic stage or at the beginning of mesophilic stage. They concluded that dehydrogenase is a useful parameter to follow the evolution of the biological activity of the composting process, since it correlates well with the temperature profile in the reactor (Barrena et al., 2008).

Phosphatase is group of enzymes that catalysis the hydrolysis both esters and anhydrides of $H_3PO_4$ (Page, 1982). Phosphatase has agronomic value because it hydrolyses compounds of organic phosphorus and transforms them into different forms of inorganic phosphorus assimilable by plants. The phosphatase activity is due to the presence of phosphorylated compounds, a substrate for the microorganisms to synthesize phosphatase. It is considered as a general microbial indicator. Phosphatase is an enzyme for the characterization of microbial activities during composting, since it can only be synthesized by microorganisms but is not

originated from plant residues (Raut et al., 2008). Phosphatase includes phosphomonoesterases. phosphomonoesterases or phosphoric monoester hydrolases include acid and alkaline phosphomonoesterase (which hydrolyse monoester bonds including mononucleotides and sugar phosphates). Acid and alkaline phosphomonoesterases do not hydrolyse phosphates of phytic acid (myo-inositol hexaphosphates) but they can hydrolyse lower-order inositol phosphates (Bunemann et al., 2011).

β-Glucosidase is one of the key enzymes governing the C-cycle. It hydrolyses reducing terminations of b-D-glucose chains and form b-glucose. Its activity is therefore indicative of the presence of these terminations, which come from the labile organic matter (Vargas-Garcia et al., 2010; Kayikçioğlu and Okur, 2011).

Garcia et al. (1993) characterized biochemically three groups of urban wastes used in agriculture, (fresh municipal solid waste, fresh sewage sludge, and the composted products of both). Five hydrolase activities in the cycles of C (β-glucosidase), N (urease and protease) and P (phosphatase) were determined. Total urease activity was found to be the highest in the sewage sludge, with variable values being observed in the fresh MSW and low values in the compost. Protease-BAA showed quite low values in all cases. They confirmed that the hydrolytic enzymes were biomarkers of the state and evolution of the organic matter.

Kayikcioglu and Okur (2011) evaluated the enzyme activities during composting of tobacco waste (TW), a mixture of TW and grape pomace (GP), and a mixture of TW and olive pomace (OP). They found that the maximumvalues of dehydrogenases activity probably corresponded to the end of the thermophilic stage or the beginning of mesophilic stage, as the highest temperature in the composts was determined at the second week of composting processes. β-Glucosidase

activity increased during the first 5 weeks and then the activity in TW and TW+GP composts decreased until the 17th week. Results indicated that this enzyme activity was related to the type of humic compounds and humic enzyme complexes which are resistant to microbial attack accumulated.

## 2.5 Introduction to factorial design

Most experiments involve several factors that may affect the response(s). To study the effect of these factors on the response(s), a factorial design is considered to be the most efficient method available. Factorial design can screen the significant factors, which can then be used to develop a model to optimize and predict the response. Factorial design has several advantages over the traditional one-factor-at-a-time approach. For example, the effect of one factor can be assessed at several levels of the other factors so that different combinations can be evaluated simultaneously; fluctuation of the responses can be monitored when the level of factors changes; the number of runs is less than the one-factor-at-time method giving a more efficient design in time and cost; and most importantly, factorial designs allow the evaluation of the interaction effects among the factors especially when the interaction has a high impact on the result (Montgomery, 1997).

The most common factorial design is two-level (or $2^k$) factorial design. In the $2^k$ factorial design, 2 indicates the number of levels and k indicates the number of factors. Each factor has only two levels, and these levels can be qualitative or quantitative. The main effect is the average differences in response at high and low levels of the factor, and the interaction is the average difference in response of the effect of one factor at high and low level of the other factors. The statistical model for a $2^k$ design would include k main effects, $\binom{k}{2}$ two-factor interactions, $\binom{k}{3}$ three-factor interactions, and one k-factor interaction. That is, the complete model would

contain $2^{k-1}$ effects for a $2^k$ design. The treatment combinations may be written in standard order. For example, the standard order for a $2^4$ design is (1), a, b, ab, c, ac, bc, abc, d, ad, bd, abd, cd, acd, bcd, and abcd, and it comprises 2x2x2x2=16 treatment combinations (Montgomery, 1997).

The minus and plus sign for the contrast constants of the $2^4$ fractional factorial design are shown in Table 2.3. The contrast of the effect is calculated to determine the effect or sum of squares for an effect. The contrast is determined by the following formula:

$$\text{Contrast}_{AB....k} = (a \pm 1)\,(b \pm 1) \ldots (k \pm 1) \qquad (2.1)$$

The sign in each set of parentheses is negative if the factor is included in the effect and positive if the factor is not included. For example, in a $2^5$ design, the contrast for ABCD would be

$\text{Contrast}_{ABCD}$= (a - 1) (b -1) (c - 1) (d - 1) (e - 1)

= abcde + cde + bde + ade +bce

+ ace + abe + e + abcd + cd +bd

+ ad + bc + ac + ab + (1) - a- b - c

- abc - d - abd - acd - bcd -ae

- be - ce -abce - de - abde - acde –bcde (2.2)

Effect and the sum of the square for an effect can be computed after calculating the contrast:

$$AB\ldots K = \frac{2}{n2^k}\,(\text{contrast}_{AB....K})$$

$$SS_{AB....k} = \frac{1}{n2^k}\,(\text{contrast}_{AB...K})^2 \qquad (2.3)$$

Where n denotes the number of replicates (Montgomery, 1997)

Table 2.3. Matrix of $2^4$ factorial design

| No. | Standard Order | A | B | C | D |
|---|---|---|---|---|---|
| **1** | (1) | - | - | - | - |
| **2** | a | + | - | - | - |
| **3** | b | - | + | - | - |
| **4** | ab | + | + | - | - |
| **5** | c | + | - | - | - |
| **6** | ac | + | - | + | - |
| **7** | bc | - | + | + | - |
| **8** | abc | + | + | + | - |
| **9** | d | - | - | - | + |
| **10** | ad | + | - | - | + |
| **11** | bd | - | + | - | + |
| **12** | abd | + | + | - | + |
| **13** | cd | - | - | + | + |
| **14** | acd | + | - | + | + |
| **15** | bcd | - | + | + | + |
| **16** | abcd | + | + | + | + |

The statistical significance of the calculated effects can be tested using an analysis of variance (ANOVA). The null hypothesis for the ANOVA assumes that the mean of the treatment combinations (no treatment effects of the factors or interactions) are equal and the alternate hypothesis states that at least the mean of one of the treatment combinations is different.

$H_0$: the mean of every group is identical (no treatment effects for either factor or interaction), versus

$H_1$: at least one mean differs (Helsel and Hirsch, 1992).

An ANOVA table is used to formally test for the significance of main and interaction effects. The total sum of squares of the response can be written partitioned into two parts:

$SS_{Total} = SS_{Effects} + SS_{Error}$

Where $SS_{Total}$ is the sum of squares of Total, $SS_{Total}$ = Total sum of (effect estimate)$^2$– (Total effect estimates )$^2$ , $SS_{Effects}$ is the sum of squares due to effects (i.e., between effects) $SS_{Effects}$= (Contrast $_{effects}$)$^2$/ ($2^k$n), and $SS_{Error}$ is the sum of squares due to error (i.e., within effects), $SS_{Erroe}$ = $SS_{Total}$–$SS_{Effects}$ . $SS_{Total}$ has ($2^K$ n)-1 degree of freedom (d.f), $SS_{Effects}$ has 1 degree of freedom and $SS_{Error}$ has $2^K$ (n-1) degree of freedom.

Table 2.4. ANOVA table for $2^k$ Design

| Source of variation | Sum of square | Degree of freedom | Mean square (MS) | $F_0$ |
|---|---|---|---|---|
| Main Effects | $SS_{effects}$ | 1 | $SS_{effect}$ /1 | $MS_{effect}$/ $MS_{error}$ |
| Interactions | $SS_{interaction}$ | 1 | $SS_{interaction}$ /1 | $MS_{Interaction}$/ $MS_{error}$ |
| Error | $SS_{error}$ | $2^k$(n-1) | $SS_{error}$ | |
| Total | $SS_{Total}$ | $2^k$n -1 | $SS_{Total}$ | |

The test statistic for ANOVA is F value. To reject the null hypothesis, $F_0$ should be greater than the critical $F_\alpha$

$F_0 > F_\alpha$ ,$d.f_{effect}$, $d.f_{error}$

The α-value, or significance level, is the probability of incorrectly rejecting the null hypothesis (rejecting $H_0$ when it is in fact true, called a "Type I error") (Helsel and Hirsch, 1992). It can be concluded that main factor or interaction has a significant effect on the response and at least one variable has a nonzero effect. Also p-Value can be used to determine the significant factors. The p-value is the probability of obtaining the computed test statistic, or one even less likely, when the null hypothesis is true. The smaller the p-value, the less likely is the observed test statistic when $H_0$ is true. When the p-value is less than the decision criteria (the α-level), $H_0$ is rejected, when the p-value is greater than α, $H_0$ is not rejected (Helsel and Hirsch, 1992).

There are other methods to screen for the significant factors such as half-normal plot, Pareto chart, and Lenth's method. The half-normal plot is a plot of the absolute value of the effect

estimates against their cumulative normal probabilities. The straight line on the half-normal plot always passes through the origin and should also pass close to the fiftieth percentile data value. In the half-normal plot, effects do not fall near a straight line and look like an outlier will be selected as significant factors. In Pareto chart, decision lines are added for the margin of error (ME) and the simultaneous margin of error (SME). A contrast that extends beyond the SME line is significant; one that exceeds the ME line but not the SME line should be viewed with some caution (Lenth, 2006).

Based on the ANOVA, the significant factors are determined and they are used to produce the regression model. The regression model representation of a $2^5$ factorial experiment can be written as

$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_i x_i + \hat{\beta}_{ij} x_i x_j + \hat{\beta}_{ijk} x_i x_j x_k + \hat{\beta}_{ijkl} x_i x_j x_k x_l + \hat{\beta}_{ijklm} x_i x_j x_k x_l x_m + \varepsilon$, i=1,2,…,5, j=1,2,…,5, k=1,2,…,5, l=1,2,…,5, m=1,2,…, (2.4)Where $\hat{Y}$is the response, $\hat{\beta}_0$ is the mean of all treatment combinations,$\hat{\beta}_i$, $\hat{\beta}_{ij}$ ,$\hat{\beta}_{ijk}$ , $\hat{\beta}_{ijkl}$ , $\hat{\beta}_{ijklm}$ are half of the effect estimated corresponding to significant effects, $x_i x_j x_k x_l x_m$ are coded variables that represent significant effects take on values between 1 and +1, and ε is a random error term. The random error terms are assumed to have a normal distribution, a constant variance, and are independent.

In order to build the regression model, insignificant factors should not be included in the model and the model should have hierarchy. This means that if a high-order interaction is included in the model; all lower-orders which are in the high-order should be included in the model. For example, if BCD is included in the model, B, C, D, BC, CD and BD should be included in the model. To select the model, $R^2_{predicted}$, $R^2$, adjusted $R^2$ and Prediction Error Sum of Squares (PRESS) can be calculated and compared. The $R^2$ measures the proportion of total variability explained by the model, adjusted $R^2$ is a statistic that is adjusted for the "size" of the model, that

is, the number of factors. The adjusted $R^2$ can actually decrease if insignificant terms are added to a model. The PRESS statistic is a measure of how well the model will predict new data. A model with a small value of PRESS indicates that the model is likely to be a good predictor. Also, a model with a large value of $R^2_{predicted}$ indicates that the model can describe the variability in the new predicted data. Model adequacy checking is the next step after selecting the model. If the model is correct, residuals should reveal a normal distribution and the residuals should be structureless in the plot of residuals versus the fitted values. If the assumption of ANOVA has been met, the model can be presented in the graphical form such as a three dimensional graph which is called a response surface plot, or a contour plot (Montgomery, 1997).

The number of the runs will increase by increasing the number of factors. For example, the number of runs required for 5 factor with two levels ( $2^5$ ) is 32, only 5 degree of 32 degree of freedom is related to main effect, 10 degree is related to two-factor interaction, 10 degree related to three-factor interaction, 5 degree related to four-factor interaction and 1 degree related to five-factor interaction. If the high order interactions can be assumed negligible, a fraction of the runs can be used to estimate the main effects and low order interactions. Thus the $2^{5-1}$ fractional factorial design has 5 factors with 2 levels with 16 runs of treatment combinations ($2^{5-1}= 2^4 =16$).

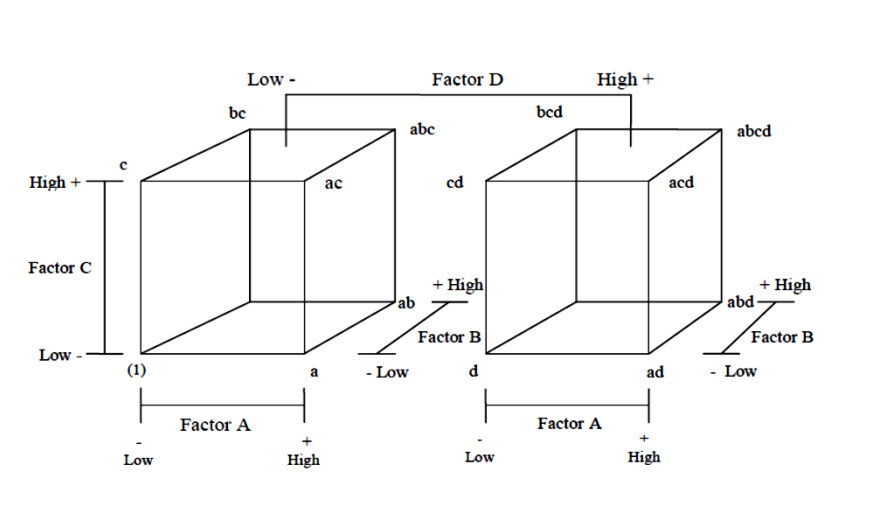


Figure 2.4. Geometric view of a $2^4$ full factorial design

The successful use of fractional factorial designs is based on three key ideas:

1. The sparsity of effects principle. When there are several variables, the system or process is likely to be driven primarily by some of the main effects and low-order interactions.

2. The projection property. Fractional factorial designs can be projected into stronger (larger) designs in the subset of significant factors.

3. Sequential experimentation. It is possible to combine the runs of two (or more) fractional factorials to assemble sequentially a larger design to estimate the factor effects and interactions of interest (Montgomery, 1997).

The half-normal probability plot and Lenth's method will be used to select the significant factors. In the process of the selection of the significant factors, if the main effects are considered as significant effects, their aliased interactions also should be included in the significant effects. Also, all the aliased interactions with the insignificant main factors should not be included in the significant effects. The rest of the calculation for the ANOVA and regression model will be like the full factorial design (Montgomery, 1997).

**Design of experiments in composting**

Many factors can influence composting process and the quality of the end product. Design of experiments is an effective tool to research the effect of these factors and their interaction. Although in the literature the effect of one factor at time has pronominally been used to conduct the experiments, some literature used different methods of experimental design to perform the experiments (Antony, 2003).

Liang et al. (2003) investigated the influence of temperature and moisture contents on the aerobic microbial activity of bio-solid (municipal wastewater treatment sludge) composting using 2 factorial design method with six temperatures and five moisture contents. They concluded that the moisture content can affect microbial activity so that a higher microbial activity accrues at higher moisture content.

The effect of bulking agent/sludge ratio, bulking agent particle size and composting volume on the compostibility of the municipal wastewater sludge has been studied by a full factorial design (Leiva et al., 2003). The mixture 1:1 of sludge and wood chips was indicated as the optimum value for laboratory scale sludge composting. They concluded that the experimental design is a valid tool to determine the initial operation condition for the composting of raw sludge.

Paradelo et al. (2010a) used $3^3$ fractional factorial design to study the optimal condition for the composting of the Hydrolyzed Grape Marc and Vinification Lees, in which three dependent variables (temperature, addition of vinification lees, and addition of $CaCO_3$ were assayed at three levels. The proportion of vinification lees in the mixtures was the factor with the main influence in the final nutritive properties of the composts. The result of the DOE suggested 1:1 mixture of hydrolyzed grape marc and vinification lees, amended with no more than 5 g of $CaCO_3$ per 100 g of hydrolyzed as the optumim vales. Central composite experimental design was used by Bueno et al. (2008) to study the influence of moisture, aeration, particle size and time on the nitrogen conservation during legume trimming residues composting.

## 2.6 Summary

This chapter started by introducing municipal solid waste composting followed by factors affect the municipal solid waste composting process including temperature, pH, C/N ratio, moisture content and aeration rate. Available commercial and lab-scale composting systems with

associated parameters have been reviewed. Temperature, aeration, moisture content, and exhaust gas were hence concluded as operational parameters for laboratory-simulated composting systems. Enzyme activity and parameters related to carbon and nitrogen are good indicators of compost maturity and stability. Subsequently, the application of factorial design in composting was reviewed. In most of the previous studies, effects from individual impact factors on enzyme activity and (GI) during composting process were analyzed, however, interactive effects from multiple factors were seldom investigated. This study will examine the interactive effects of operational parameters on enzyme activities and GI.

# 3 Material and Methods

## 3.1 $2^4$ Factorial design for the present study

Factorial design method was used to design the experiments in this research. In total, 4 factors with 2 levels and 16 runs were examined. Sixteen runs are combinations of the low and high levels of 4 factors. Four factors investigated include C/N ratio, moisture content, aeration rate, and bulking agent. The high and low level of factors are presented in the Table 3.1. Experimental design is presented in Table 3.2.

Table 3.1. Design factors and their high and low level

| Factor | High level | Low level |
|---|---|---|
| **A-Aeration rate (L/min.kg)** | 0.5 | 0.3 |
| **B-Moisture content (%)** | 70 | 55 |
| **C-Bulking agent** | Peat | sawdust |
| **D-C/N ratio** | 17 | 12 |

Table 3.2. Experimental Design

| Std | Run | A:Aeration | B:Moisure | C:BA | C/N |
|---|---|---|---|---|---|
| **1** | 1 | 0.3 | 55 | Sawdust | 12 |
| **4** | 2 | 0.5 | 70 | Sawdust | 12 |
| **8** | 3 | 0.5 | 70 | Peat | 12 |
| **14** | 4 | 0.5 | 55 | Peat | 17 |
| **11** | 5 | 0.3 | 70 | Sawdust | 17 |
| **7** | 6 | 0.3 | 70 | Peat | 12 |
| **15** | 7 | 0.3 | 70 | Peat | 17 |
| **10** | 8 | 0.5 | 55 | Sawdust | 17 |
| **16** | 9 | 0.5 | 70 | Peat | 17 |
| **2** | 10 | 0.5 | 55 | Sawdust | 12 |
| **12** | 11 | 0.5 | 70 | Sawdust | 17 |

| | | | | | |
|---|---|---|---|---|---|
| **3** | 12 | 0.3 | 70 | Sawdust | 12 |
| **13** | 13 | 0.3 | 55 | Peat | 17 |
| **6** | 14 | 0.5 | 55 | Peat | 12 |
| **5** | 15 | 0.3 | 55 | Peat | 12 |
| **9** | 16 | 0.3 | 55 | Sawdust | 17 |

## 3.2 Composting Materials

To keep the homogeneity and consistency of the substrate, the synthetic food waste was used as substrate in this research. Synthetic food consists of potato, carrot, meat, rice, cabbage, and soybean, which was shredded with food processor to approximately 5 mm in diameter. Physical and chemical characteristics of the substrate such as pH, carbon content, nitrogen content, C/N ratio, dry matter, and ash content were analysed. The moisture content and aeration rate was adjusted based on the experimental design; and bulking agent was then added to the material. The compositions of composting mixture for 17 runs are presented in Table 3.3.

Table 3.3. Composition of composting mixtures (unit: kg)

| | Run (3,6,14,15) | Run (4,7,9,13) | Run (1,2,10,12) | Run (5,8,11,16) |
|---|---|---|---|---|
| **Meat** | 0.5 | 0.3 | 0.5 | 0.3 |
| **Rice** | 1.5 | 2.2 | 1.3 | 2 |
| **Carrot** | 1.5 | 2.2 | 1.3 | 2 |
| **Potato** | 1.4 | 1.1 | 1.4 | 1.1 |
| **Lettuce** | 0.1 | 0.2 | 0.1 | 0.2 |
| **Soybean** | 1.4 | 0.4 | 1.8 | 0.8 |
| **Peat** | 0.6 | 0.6 | - | - |
| **Sawdust** | - | - | 0.6 | 0.6 |

## 3.3 The composting system

The composting reactor (50×20×25 cm) was made of acrylic sheets. The inlet and outlet were made of ABS-M30 (Acrylonitrile/Butadiene/Styrene). Six mixers were installed to mix the material in the rectangular composting container. Reactor was sealed with the rubber tape. The size of the rectangular inlet was 13x12 cm. Also, an inlet was designed for air with a 1.2 cm diameter on the first end which will be connected to a vacuum pump (Thermo Fisher Scientific, Model No. 420-2901) to provide the air. Over the aeration distribution part which has 5 cm height, the perforated plate with 0.6 cm diameter holes was installed. To prevent the dropping of raw material into the aeration part, the holed plate was covered by a screen. The aeration rate was monitored by a flowmeter (Acrylic block flowmeter, FR2000, VWR). The exhaust gas outlet was designed at the top of the tunnel. The gas was discharged through a vinyl pipe into a flask containing $H_2SO_4$ solution (1 M) to absorb the $NH_3$, and then primarily monitored by gas monitoring system (Industrial Scientific Multi-Gas Monitor, model M40) and released into the lab ventilation system. The leachate outlet was designed at the second end with a 1.2 cm internal diameter which will be connected to the beaker to collect the outcome leachate from the raw material. The top of the reactor can be opened for feeding and after feeding, the arm in the feeding part can push the waste forward along the tunnel. To monitor the temperature, a thermometer hole was designed at the top with a 2 cm internal diameter. The thermometer (Bi-metal dial thermometer, H-B Instrument Company) was used to monitor the temperature and was sealed by a rubber stopper. To prevent the heat loss, the heat insulating material was used to cover the reactor; initially a layer of aluminum foil was applied to reflect the heat radiant, then two layers of foil insulation “reftectix bubble pack” which is filled with 3.5 inch fibreglass covered the reactor thoroughly.

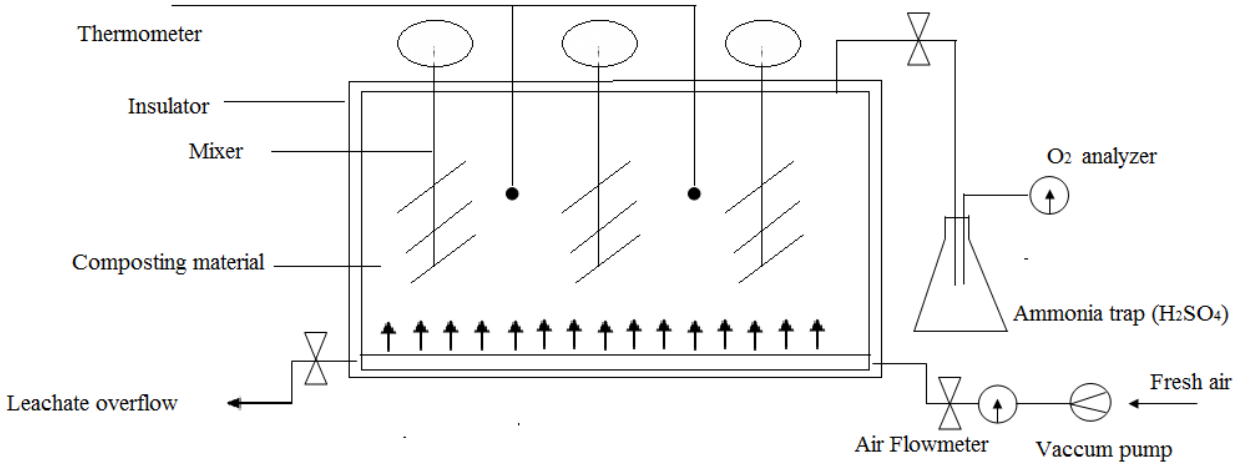



Figure 3.1. Schematic diagram of the composting system

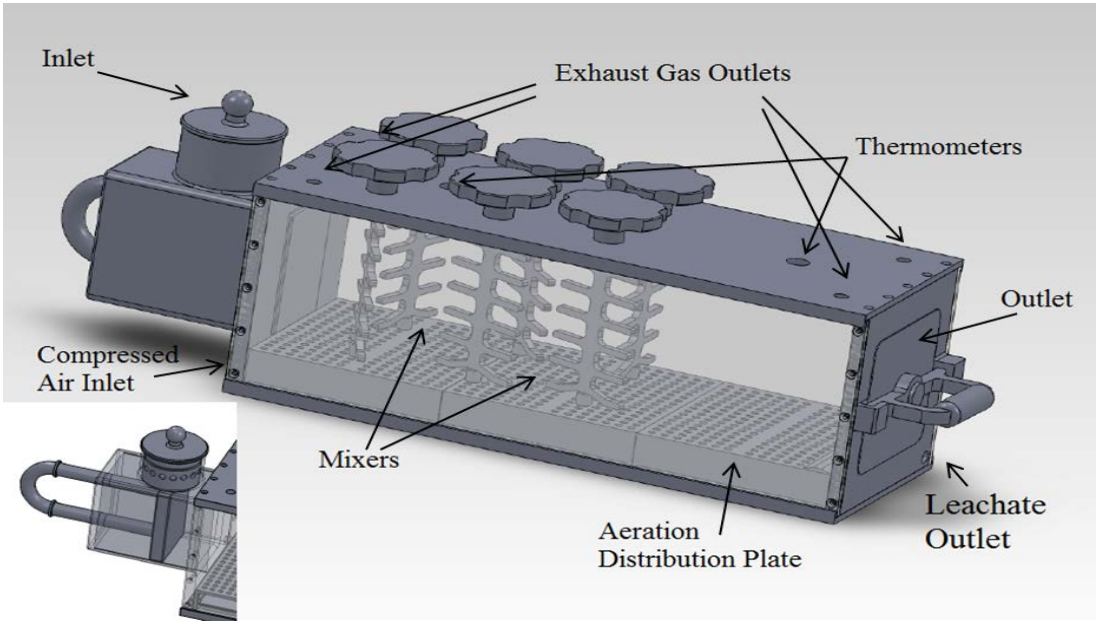



Figure 3.2. 3D view of the designed composting system

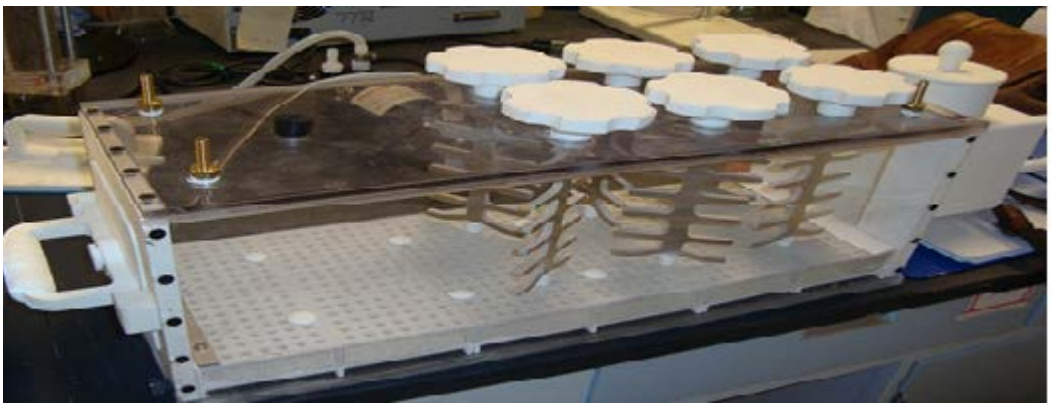


Figure 3.3. Photos of the composting system

## 3.4 Sampling

Composting material was turned with mixers twice a day in order to get homogenized samples. After turning, approximately 120 g compost was collected randomly from the 3-4 different

points in the pile, and was then mixed in a beaker. The collected sample was divided into different sub-samples to measure pH, electrical conductivity (EC), C/N ratio, moisture content, ash content and organic matter content, enzyme activity assay, and germination test.

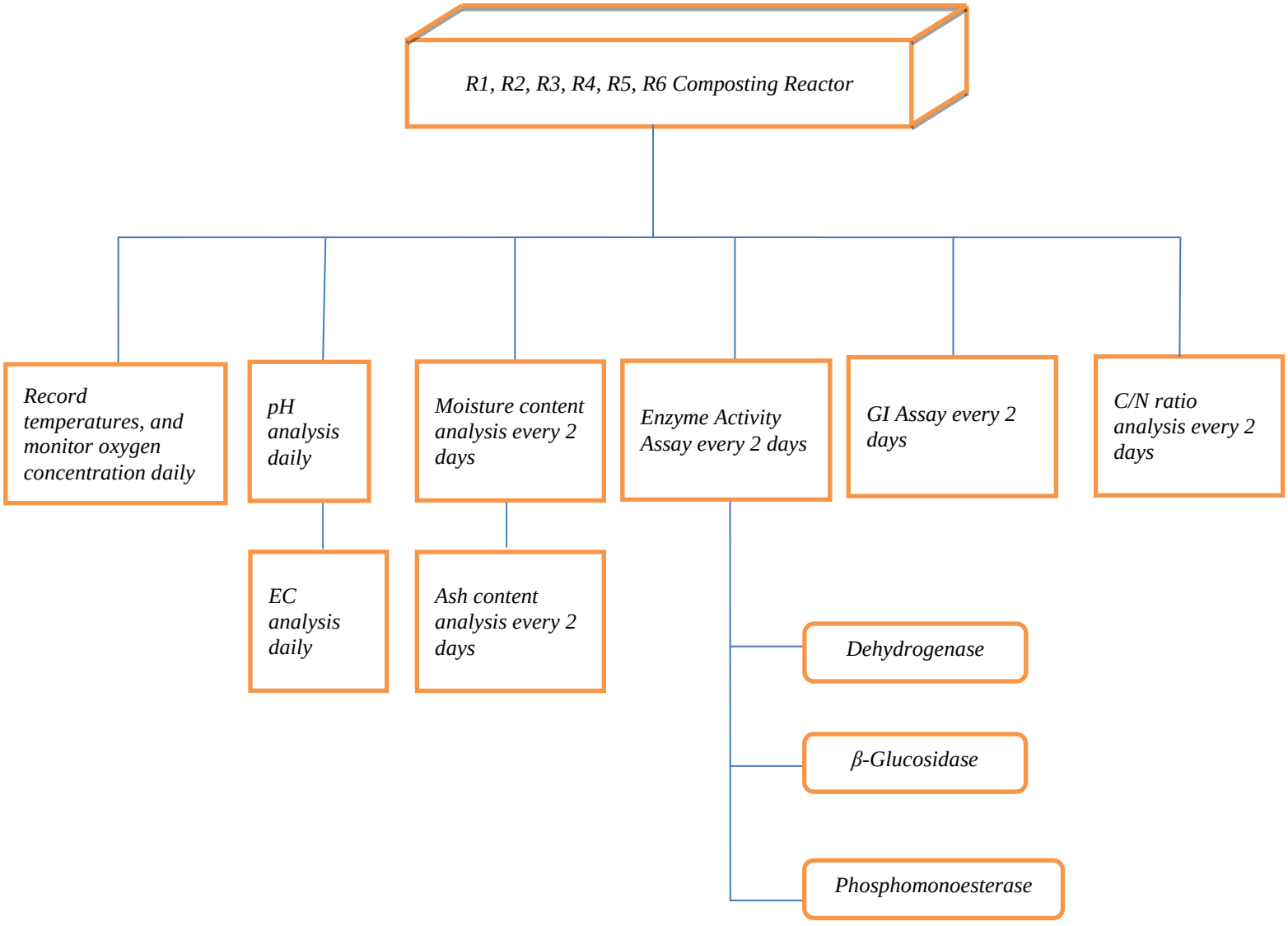



Figure 3.4. Sampling scheme of composting materials

## 3.5 Physical and chemical analysis

### 3.5.1 PH and EC

A bench top pH meter (EL20, Mettler Toledo) was used to measure the pH in a mixture of compost and water with 1:2 ratio (Thomas, 1996). Ten gram of compost was weighted and placed in a flask and then 20 ml water was added to the flask. The flask was stirred for 15 seconds and stayed for 30 minutes. The pH meter was calibrated once a day before reading and adjusted to the temperature of the solution. The pH was read by an electrode tip (EL 407, Mettler Toledo). The same solution was used to measure the EC of the samples with bench top EC meter (Orion Star A222 and A322, Thermo Scientific).

### 3.5.2 Temperature

A bi-metal dial thermometer (H-B Instrument Company, PA) was placed in a hole on the top of the reactor and inserted in the compost material. The temperature was recorded every 12 hours.

### 3.5.3 Moisture content

Gravimetric method was used to measure the moisture content (Black, 1965). The weight of a crucible which have been dried at 105 °C in the oven overnight to a constant weight was recorded ($W_{Crucuble}$), and 5 g compost placed in the crucible and the weight of the fresh compost and crucible was recorded ($W_{Crucuble} + W_{Fresh}$ ). The fresh compost placed in the crucible settled in the oven at 70 °C until reaching constant. Then it was taken out of the oven and cooled in the desiccator to room temperature. The weight of the crucible and the dried compost were recorded$\left(W_{Crucible} + W_{Dry}\right)$. The moisture content of the sample can be calculated as follows:

$$\text{Moisture content} = \frac{(W_{Crucuble} + W_{Fresh}) - (W_{Crucible} + W_{Dry})}{(W_{Crucuble} + W_{Fresh}) - (W_{Crucuble})} \quad (3.1)$$

The average of two replications was used as moisture content.

### 3.5.4 Ash content and organic matter content

Ignition method was used to measure the ash content (Black, 1965). After measuring the moisture content, the dried samples in crucible placed in the muffle-furnace at 550 °C for 4 hr, then cooled in the desiccator to room temperature. The weight of the ignited sample and crucible was recorded ($W_{Crucible} + W_{Ignited}$). The ash content and organic matter content could be calculated as follows:

$$\text{Ash content (\%)} = \frac{(W_{Crucible} + W_{Ignited}) - (W_{Crucible})}{(W_{Crucible} + W_{Fresh}) - (W_{Crucible})} \times 100 \quad (3.2)$$

### 3.5.5 Oxygen Uptake Rate

The outlet oxygen concentration in compost exhaust gas was monitored by passing the air through a M40 Multi-Gas Monitor (Industrial Scientific Corp., Oakdale, PA, USA) and was recorded was recorded as $O_{2\ out}$ (%) after stabilizing the monitor of the multi gas analyzer . The oxygen concentration in the inlet air ($O_{2in}$ (%)) was 20.9% at different airflow rate (L/min) which is injected to the system.

$$\text{Oxygen Uptake rate (OUR)} = (O_{2\ out}\ (\%) - O_{2\ in}\ (\%)) \times \text{airflow rate (L/min)} \quad (3.3)$$

### 3.5.6 Enzyme Activity

**(1) Dehydrogenase activity**: TTC method (Thalmann, 1968; Alef and Nannipieri, 1995)

It is clear that enzyme activity in respiratory chain could be used as oxidative activity of cell, therefore dehydrogenase activity has been used as a measure of overall microbial activity (TMECC, 2001). This method is based on the estimation of the TTC reduction rate to TPF in soils after incubation at 30 $^{o}$C for 24 hr.

Reagents:

- Tris-HCl Buffer (100 ml)

  Dissolve 12.1 g of Tris (hysroxy methyl-aminomethane) in 700 ml distilled water, adjust with HCl to pH 7.8 for acid soils with pH values less than 6, to pH 7.6 for neutral soils with pH values ranging from 8 to 7.5, and to pH 7.4 for alkaline soils with pH values higher than 7.5. Bring up with distilled water to 1000 ml.

- TTC Solution

  Depending of the soil type, 0.1-1.5 g TTC was dissolved in 80 ml of Tris buffer. Bring up with the same buffer to 100 ml.

Extractant:

- Acetone (analytical grade)
- TPF standard solution

  Dissolve 50 mg of TPF in 80 ml acetone (500 µg TPF ml$^{-1}$) and bring up with acetone to 100 ml.

Procedure:

Because of the light sensitivity of TTC and TPF, all procedure should be performed under diffused light. Fresh sample (5 g) was weighted into the test tubes and mixed with 5 ml of TTC solution. The tubes were sealed with rubber stoppers and incubated for 24 hr at 30$^{o}$C. The control contains only 5 ml Tris buffer without added to, and were shaken thoroughly and further incubated at room temperature in the dark for 2 hr. The soil suspension (15 ml) is then filtered, and the optical density of the clear supernatant was measured against the blank at 546 nm.

Calibration curve

Pipette 0, 0.5, 1.0, 2.0, 3.0 and 4.0 ml of TPF standard solution to 50-ml volumetric flasks ), and then add 8.3 ml Tris buffer (pH 7.6) and bring up with acetone to 50 ml to obtain the following concentrations: 0, 5, 10, 20, 30, and 40 µg TPF ml$^{-1}$, respectively.

Calculation

Obtain the TPF concentration (µg/ml) from the calibration curve, correct for the control value, and calculate the dehydrogenase activity as follows:

$$\text{Dehydrogenase activity TPF (µg/dwt (g))} = \frac{TPF\frac{\mu g}{ml} \times 45}{dwt \times 5} \qquad (3.4)$$

Where dwt is the dry weight of 1 g moist soil, 5 is the moist soil used (g) and 45 is the volume of solution added to the soil sample in the assay.

**(2) β – glucosidase activity** (Tabatabai 1982, Eivazi and Tabatabai 1988; Alef and Nannipieri, 1995)

This method is based on the determination of the released p-nitrophenol after incubation of soil with p-nitrophenylglucoside solution for 1 hr at 37 $^{o}$C.

Reagents:

- Toluene
- Modified universal buffer (MUB), pH 6.0

  Dissolve 12.1 g of Tris, 11.6 g of maleic acid, 14 g of citric acid, and 6.3 g of boric acid ($H_2BO_3$) in about 500 ml of NaOH (1M) and dilute the solution to 1000 ml with distilled water, store at 4$^{o}$C.

- Modified universal buffer, pH 6

  Titrate 200 ml of MUB stock solution to pH 6.5 under continuous stirring with HCl (0.1 M) and dilute to 1000 ml with distilled water.

- $CaCl_2$ (0.5 M)

  Dissolve 73.5 g of $CaCl_2 \cdot H_2O$ in distilled water and dilute with distilled water to 1000 ml.

- Tris buffer (0.1 m, pH 10)

  Dissolve 12.2 g of Tris (Hydroxy methyl amino methane) in 800 ml distilled water and dilute to 1000 ml with distilled water.

- Tris buffer (0.1 m, pH 12)

Dissolve 12.2 g of Tris (Hydroxy methyl amino methane) in 800 ml distilled water. Adjust to pH 12 under continuous stirring with NaOH (0.1 M) and dilute to 1000 ml with distilled water.

- p-Nitrophenol standard solution

  Dissolve 2.927 g of dicodium p-nitrophenyl phosphate tetrahydrate in about 40 ml MUB (pH 6.5 or 11) and bring up to 50 ml with the buffer of same pH. Store at 4 $^{o}$C.

- p-Nitrophenyle- β-D glucoside (PNG) solution (25 mM)

  Dissolve 0.377 g of PNG in 40 ml of MUN buffer and dilute to 50 ml with the same buffer. Store at 4 $^{o}$C.

Procedure

Place 1 g of moist sample in an Erlenmeyer flask (50 ml), add 0.25 ml of toluene, 4 ml of MUB solution, 1 ml of PNG solution, stopper the flasks and mix the contents thoroughly and incubate for 1 hr at 37 $^{o}$C. After the incubation, add 1 ml of $CaCl_2$ solution, 4 ml of Tris buffer, pH 12, swirl the flasks and filter the soil suspensions immediately (Whatman filter 2v). Measure the color intensity at 400 nm. If the optical intensity is too high, dilute the filtrate with Trisbiffer pH 10. To prepare the blanks, make the addition of the substrate PNG at the incubation before adding $CaCl_2$ and Tris buffer.

Calibration curve

Dilute 1 ml of the standard p-nitrophenol solution to 100 ml with distilled water in a volumetric flask. Then pipette 0, 1, 2, 3, 4, and 5 ml aliquots of this diluted standard solution into Erlenmeyer flask (50ml). Adjust the volume to 5 ml by addition of distilled water, and proceed as described for p-nitrophenol analysis of the incubated sample.

Calculation

Correct the results for the control and calculate the p-nitrophenol per millilitre of the filtrate by reference to the calibration curve.

$$\text{p-nitrophenol } (\mu g\ g^{-1} dwt\ h^{-1}) = \frac{C \times v}{dwt \times SW \times t} \qquad (3.5)$$

Where C is the measured concentration of p-nitrophenol (µg ml $^{-1}$ filtrate), dwt is the dry weight of 1 g moist sample, v is the total volume of the sample suspension in millilitres, SW is the weight of sample used (1 g), and t is the incubation time in hours (1 hr).

**(3) Phosphomonoesterase activity** (Tabataai and bremner, 1969; Ebivazi and Tabatabai, 1977)

This method is based on the determination of p-nitrophenol released after the incubation of sample with p-nitrophenyle phosphate for 1 h at 37 $^{o}$C.

Reagents

- Toluene
- Modified Universal buffer (MUB) stock solution

Dissolve 12.1 g of Tris, 11.6 g of maleic acid, 14 g of citric acid, and 6.3 g of boric acid ($H_2BO_3$) in about 500 ml of NaOH (1M) and dilute the solution to 1000 ml with distilled water, store at 4$^{o}$C.

- Modified universal buffer, pH 6.5 and 11

Titrate 200 ml of MUB stock solution to pH 6.5 under continuous stirring with HCl (0.1 M) and dilute to 1000 ml with distilled water. Titrate another 200 ml of the MUB stock solution to pH 11 by using NaOH (0.1 M) and dilute to 1000 ml with distilled water.

- p-Nitrophenyle phosphate solution (PNP, 15 mM)

Dissolve 2.927 g of dicodium p-nitrophenyl phosphate tetrahydrate in about 40 ml MUB (pH 6.5 or 11) and bring up to 50 ml with the buffer of the same pH. Store at 4 $^{o}$C.

- $CaCl_2$ (0.5 M) solution

Dissolve 73.5 g of $CaCl_2 \cdot H_2O$ in distilled water and dilute with distilled water to 1000 ml.

- NaOH (0.5 M) Solution

Dissolve 20 g of NaOH in distilled water and bring up with distilled water to 1000 ml.

- NaOH (0.1 M) solution

Dissolve 4 g of NaOH in distilled water and dilute with distilled water to 1000 ml.

- Standard p-nitrophenol solution

Dissolve 1 g p-nitrophenol in about 70 ml of distilled water and dilute the solution to 1000 ml with distilled water store at 4 $^{o}$C.

Procedure

Place 1 g of sample in an Erlentmeyer flask (50 ml) and treat with 0.25 ml of toluene, 4 ml of MUB, and 1 ml of p-nitrophenyl phosphate solution made in the same buffer. After stopping the flask, the content was mixed and incubated for 1 hr at 37 $^{o}$C. After the incubation, add 1 ml of $CaCl_2$ (0.5 M) and 4 ml of NaOH (0.5m). Mix the contents and filter the soil suspension through a Whatman no.2v folded filter paper. Measure the absorbance at 400 nm. To perform the controls, add 1ml of PNP solution after the additions of $CaCl_2$ (0.5 M) and 4 ml of NaOH (0.5 M) and immediately before filtration of the soil suspension.

Calibration curve

Dilute 1 ml of the standard p-nitrophenol solution to 100 ml with distilled water in a volumetric flask. Then pipette 0, 1, 2, 3, 4, and 5 ml aliquots of this diluted standard solution into Erlenmeyer flask (50ml). Adjust the volume to 5 ml by addition of distilled water, and proceed as described for p-nitrophenol analysis of the incubated sample.

Calculation

Correct the results for the control and calculate the p-nitrophenol per millilitre of the filtrate by reference to the calibration curve.

$$\text{p-nitrophenol } (\mu g\ g^{-1}\text{dwt } h^{-1}) = \frac{C \times v}{dwt \times SW \times t} \qquad (3.6)$$

Where C is the measured concentration of p-nitrophenol (µg ml $^{-1}$ filtrate), dwt is the dry weight of 1 g moist sample, v is the total volume of the sample suspension in millilitres, SW is the weight of sample used (1 g), and t is the incubation time in hours (1 hr).

### 3.5.7 C/N ratio

The total carbon and nitrogen contents of the composting sample were determined by the LECO TruSpec CN Determinator (LECO Corporation, St. Joseph, MI).

(1) Sample preparation

Weigh approximately 5 g of the compost sample in a crucible and then acidify the sample by pouring in 3 ml 0.1M $H_2SO_4$ over the entire sample before drying, in order to avoid $NH_4^+$ loss. Let the sample be oven dried at 105 °C for 24 hr. Grind the dry sample to homogeneous powder and store it in a desiccator till the measurements could be performed. Weigh 0.1500 to 0.2000 g of dry sample in a tin foil cup; twist and seal it to a capsule. Record the mass of the sample, and then analyze the sample for C/N ratio using the LECO TruSpec CN Determinator.

(2) Testing procedure

Perform system check and leak check before operating the CN Determinator. Login and analyze blank samples till the instrument is stabilized and a plateau is reached (typically ± 0.001%). Set blank calibration by analyzing five blank samples. Weigh 10 EDTA standard samples in a mass range of 0.1500 to 0.2000 g, and make them into tin capsules. Login and analyze the EDTA samples, and perform the standard calibration. Place each sample capsule in the carousel auto-sampler in order and perform the analysis. Insert the EDTA standard sample for every 10 samples (for quality control).

## 3.6 GI analysis

In this method (TMECC, 2001), germination rates of cucumber seed subjected to a compost extract solution was compared to the germination rate of cucumber seed in deionized water.

Add 10 parts distilled water to 1 part fresh sample in an Erlenmeyer flask. Stop and shake the flask for 1 hr. Filter mixture through filter paper. Collect approximately 10 ml and place in a 9 cm diameter Petri dish, and place 10 cucumber seed on the filter paper in Petri dish. For control experiments, replace the sample extract with distilled water. Place the petri dish in the area with 20 ± 2 $^{o}$C for 7 days. Compare cucumber seed germination time and root length in assays conducted with compost extract to those conducted with distilled water, on day 5.

$$(GI) = \frac{\text{Seed germination x Root length of the treatment x 100}}{\text{Seed germination x Root length of the control}} \qquad (3.7)$$

# 4 Experimental Results and Discussions

The variations in physicochemical parameters including temperature, OUR, pH, EC, moisture and ash content, GI, Enzyme activity, and C/N ratio will be provided in this chapter.

## 4.1 Temperature

The temperature of the composting pile expresses the breakdown of the organic matter and the quality of the compost, since the rise of temperature is the result of readily available organic matter and nitrogen compounds decomposition by microorganisms (Ros et al., 2006; Lee et al., 2007). Temperature is one of the important indices to evaluate compost efficiency (Lee et al., 2007) because it affects the biological reaction rate, the population dynamic of microbes, and the physiochemical characteristics of the compost (Hu et al., 2009). The microbial activity and the organic matter breakdown rate decreased when the organic matter becomes more stabilized and consequently the temperature drops to the ambient temperature (Ros et al., 2006). Generally, the composting process occurs in 2 stages: the biooxidative stage and the maturing stage. The biooxidative stage can be divided into three phases: (i) in the mesophilic phase, mostly bacterial and fungi degrade simple organic matter such as sugar, amino acids, and proteins. (ii) In the thermophilic phase, fats, cellulose, and hemicellulose are degraded by themophilic microorganisms and the pathogens are suppressed. (iii) In the last step, cooling phase, the deficiency of the biodegradable material lead to reduction of microbial activity and decrease in temperature (Bernal et al., 2009). The highest sanitation, maximum biodegradation rate, and the greatest diversity of microorganisms have been observed at temperature over 55°C, between 45

and 55°C, and between 35 and 45 °C, respectively (Lee et al., 2007; Kayikçioğlu and Okur, 2011).

The temporal variation of the temperature, oxygen uptake rate, pH, and EC are presented in Figures 4.1 to 4.16. On run 1, as the composting proceeded, the temperature of the decomposing waste rose rapidly and reached to a maximum of 58 °C after 2 days as it is shown in Figures 4.1. The active decomposition phase lasted for 3 days and then temperature reduced gradually and reached air temperature when the microorganism consumed the organics matters. As revealed in figure 4.2, the microbial activity started in initial hours of composting caused an increase in the temperature on second day and peaked after 3 days on run 2. Temperature stayed around 60 °C for 4 days. It is known that the highest thermophilic activity in composting system was maintained in temperature between 52-60 °C (Liang et al., 2003; Kalamdhad et al., 2009). After 14 days the temperature became equal to ambient. For run 3, an initial temperature of 25 was recorded. The maximum temperature was observed on day 3 of composting, reaching 68 °C. The temperature stayed between 58 and 68 °C for 4 days, and then decreased gradually. This drop indicates the end of the active phase of the composting process. Compared to the other runs, run 3 took longer time to reach the thermophilic phase. The mixture heated up rapidly on run 4, reaching a temperature of 58°C at the second day of composting. The first temperature peak, 68°C, as a result of aerobic biodegradation of the fast decomposing organic matter in the food waste appeared on the third day. The second peak was observed after 9 days as a result of the degradation of slowly decomposed material.

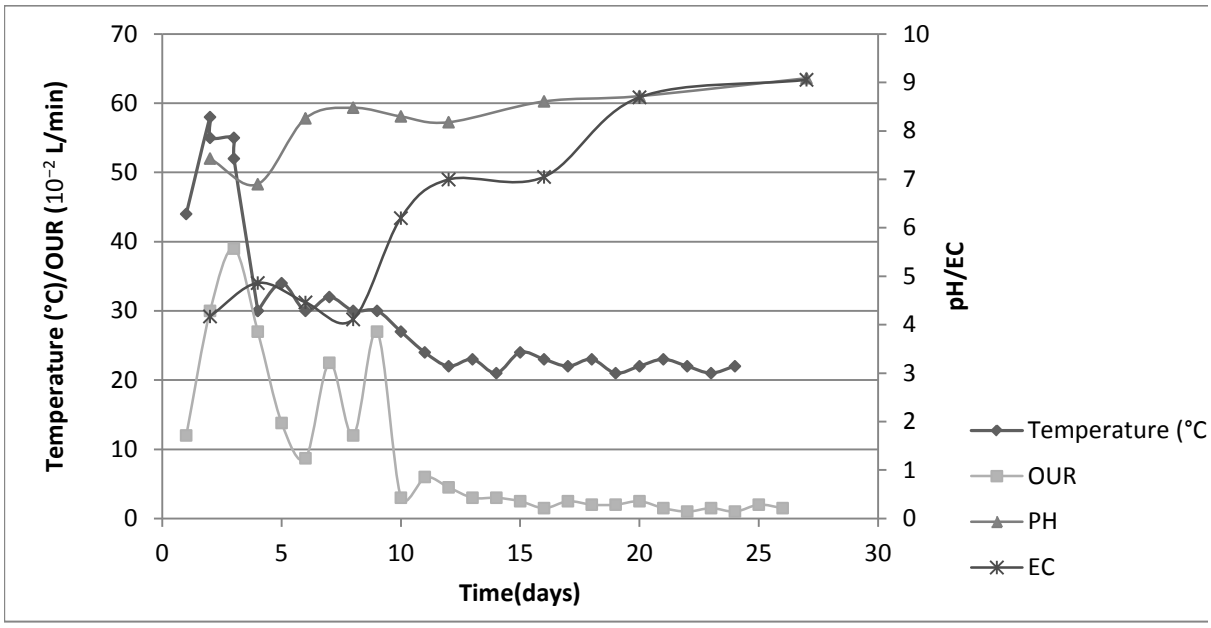



Figure 4.1. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 1)

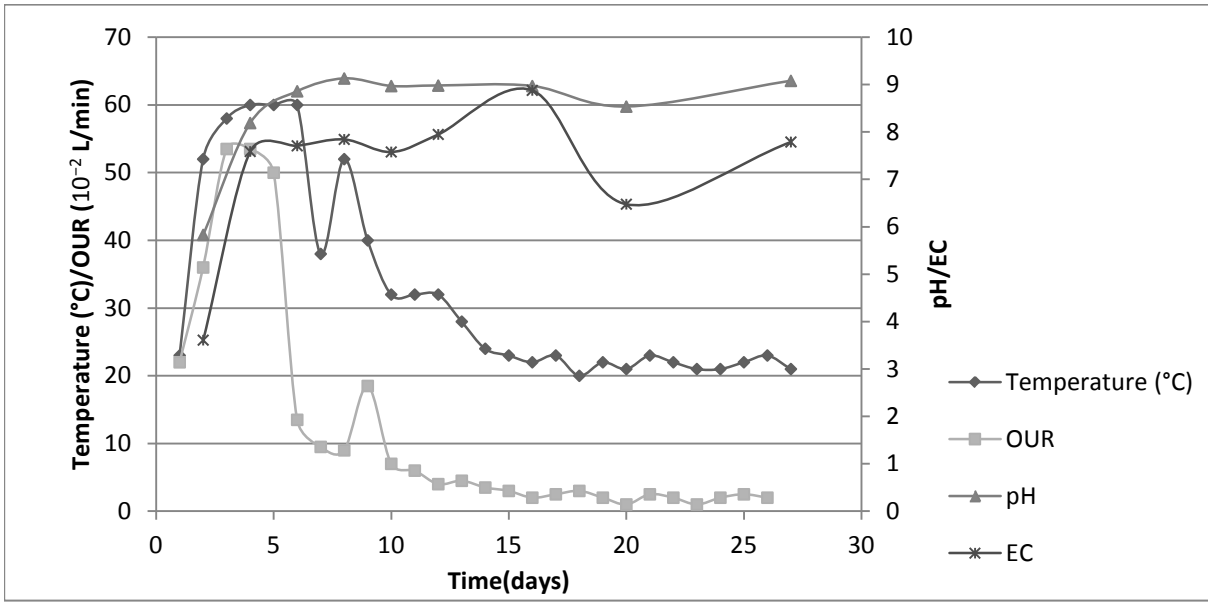



Figure 4.2. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 2)

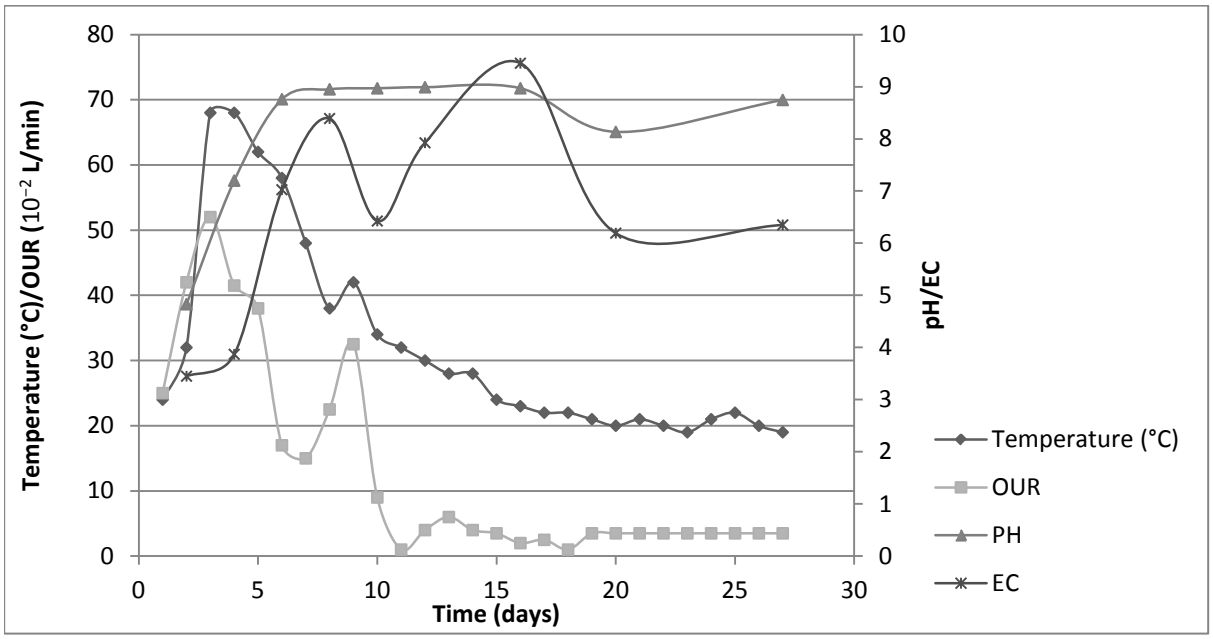



Figure 4.3. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 3)

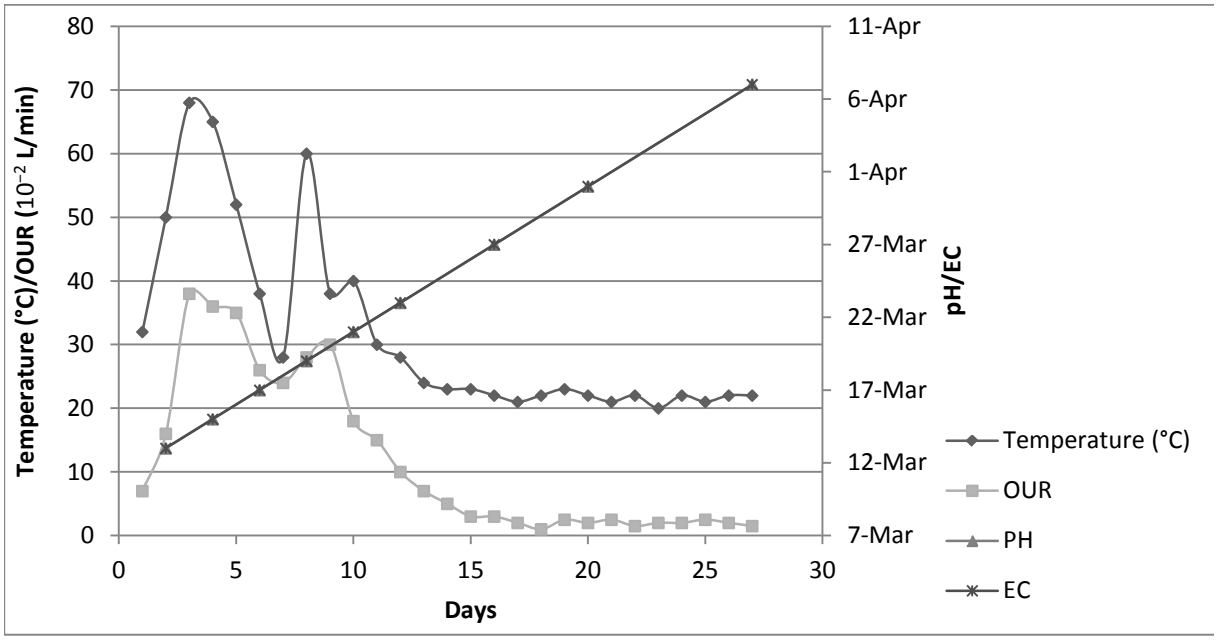



Figure 4.4. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 4)

The temperature of the matrix on run 5 increased rapidly to 52°C on day 2. A peak temperature 70°C was obtained after only 3 days. The matrix temperature was greater than 55°C for more than 3 days. The minimum requirement for a proper disinfection of waste material from pathogens was met. A rapid increase in temperature was observed on run 6, indicating a dramatic microbial activity. The thermophilic phase lasted 2 days and the maximum temperature inside the reactor was 68° C. After this phase, microbial activity and organic matter decomposition rates slowed down and the temperature decreased gradually. Thermophilic range of the temperature was quickly achieved and maintained for 8 days on run 7. The thermopilic range was followed by a marked drop and the temperature pattern was corresponding to the typical composting temperature profile at the laboratory scale reactor. On run 8, the temperature reached a maximum of 58°C after 2 days of operation and remained above 50°C for 2 days; afterward the temperature diminished to levels less than 40°C. The sanitation requirement was not fulfilled because the temperature was not maintained above 55°C for 3 days.

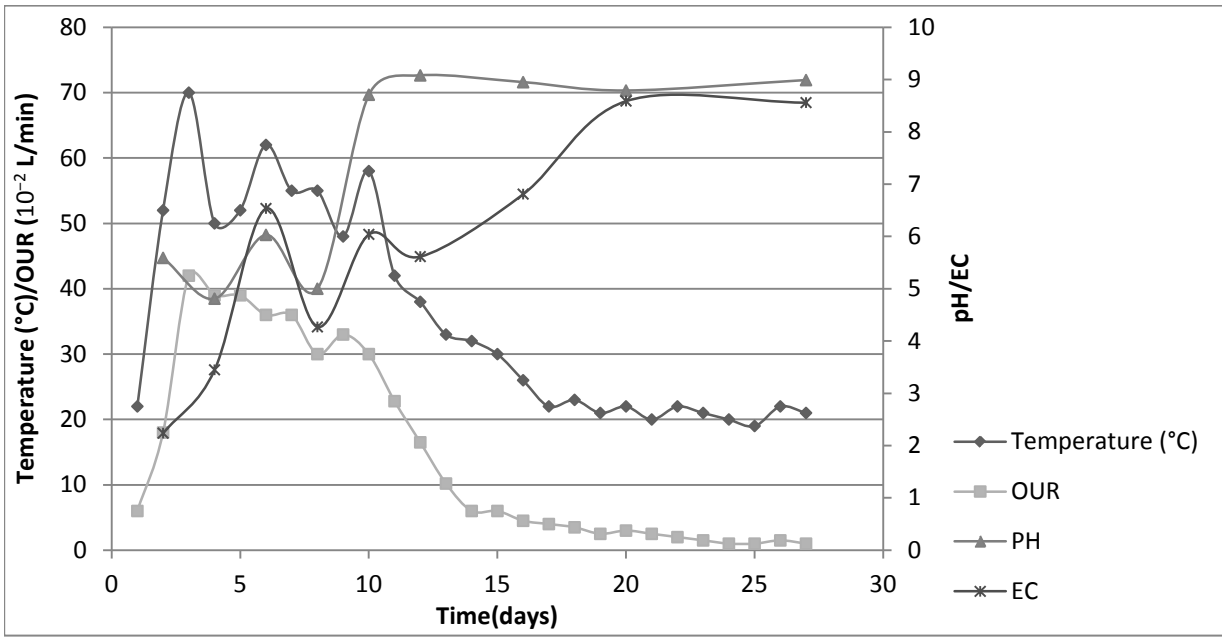



Figure 4.5. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 5)

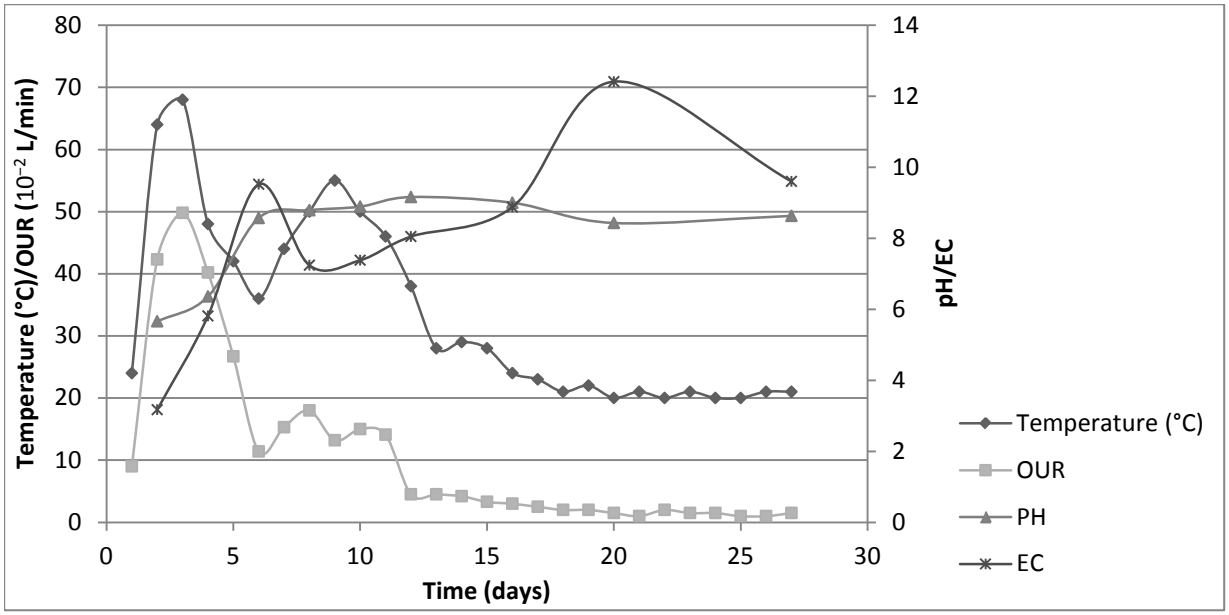



Figure 4.6. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 6)

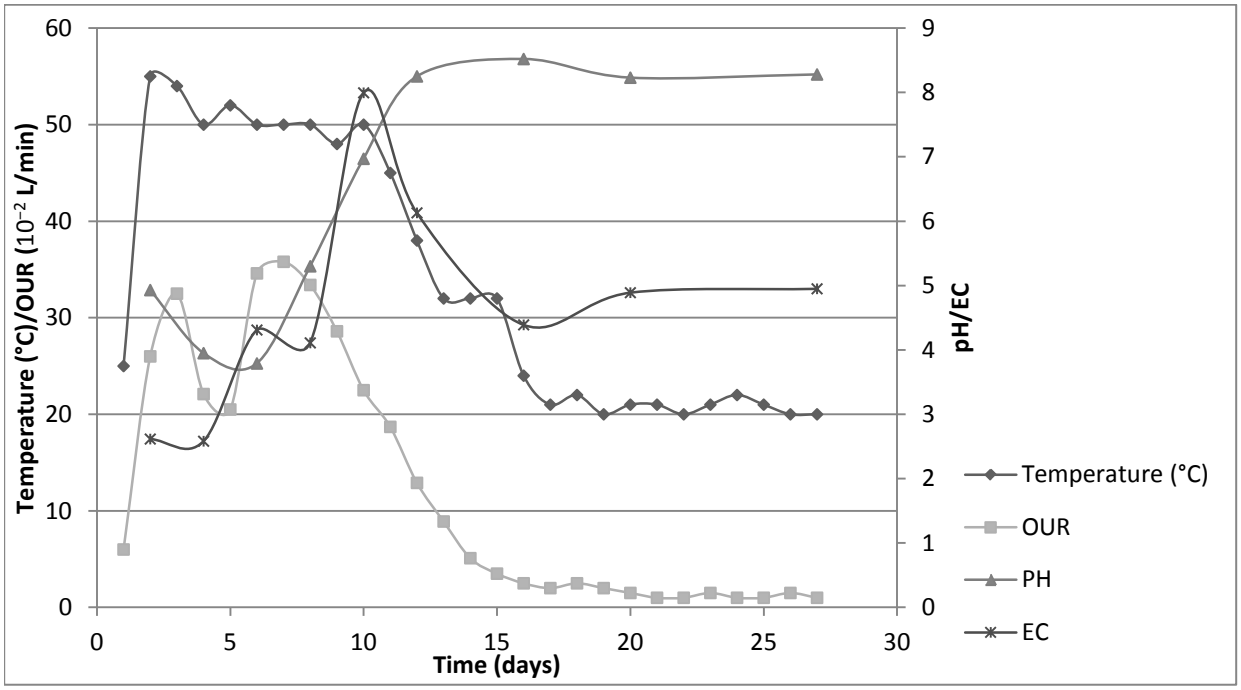



Figure 4.7 Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 7)

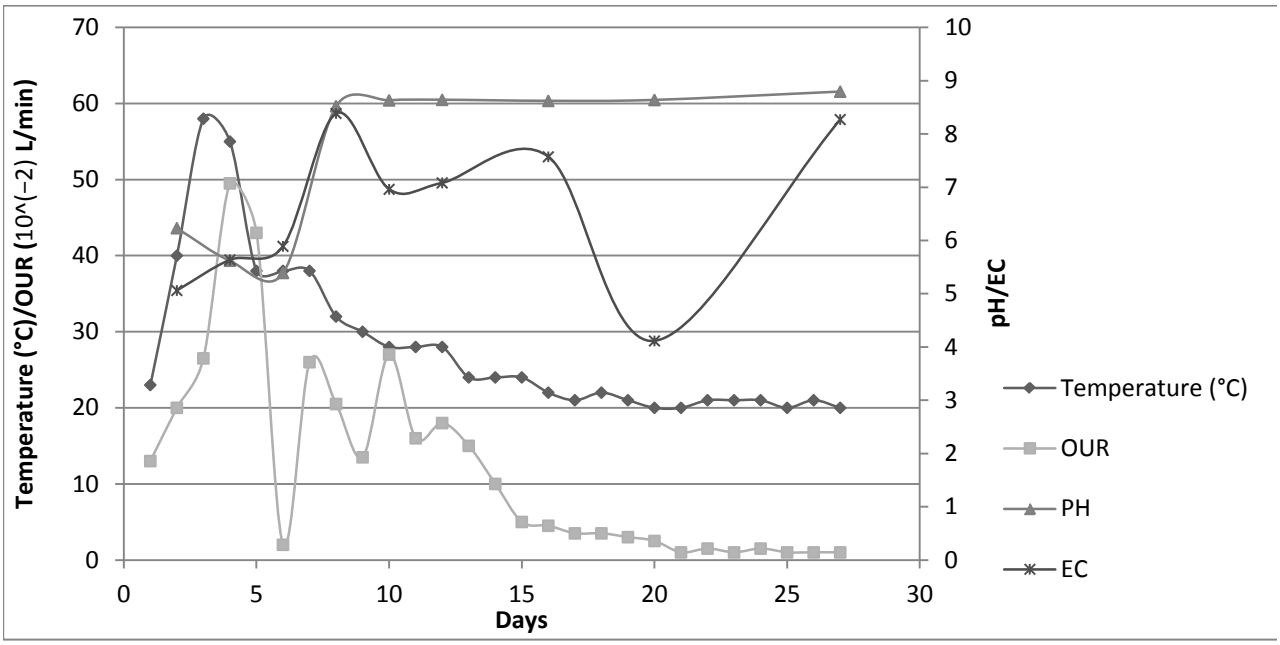



Figure 4.8. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 8)

Thermophilic phase maintained through self-heating of the microorganism on the second day on run 9. The highest temperature recorded was 68°C and the period of the temperature above 55 °C was not enough to sanitize the end product. The temperature increased rapidly to the termophilic phase by the second day and persisted for 4 days on run 10, so the high temperature ensured the elimination of all pathogens since only 3-4 days at 55°C was sufficient for elimination of pathogens (Rasapoor et al., 2009). Although the temperature of compost showed an increase to 52°C on run 11, the highest temperature on compost was not sufficient to ensure the hygiene safety of the end product. It could be due to the fact that the composting reactor was relatively small, but in the full scale reactor the sanitation can be assured (Pagans et al., 2006). Temperature increased very fast due to the rapid breakdown of the organic matter and nitrogen compounds by microorganism on run 12. A maximum temperature of 67°C was observed on day 3 and the temperature was above 55 °C for more than 3 days.

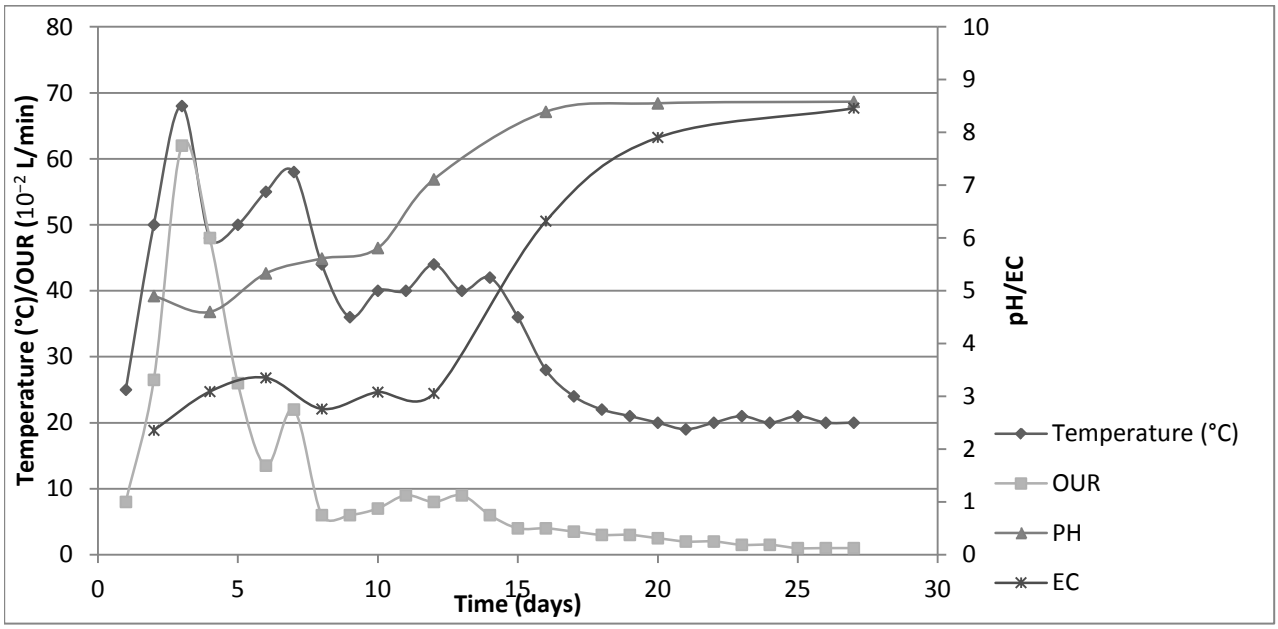



Figure 4.9. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 9)

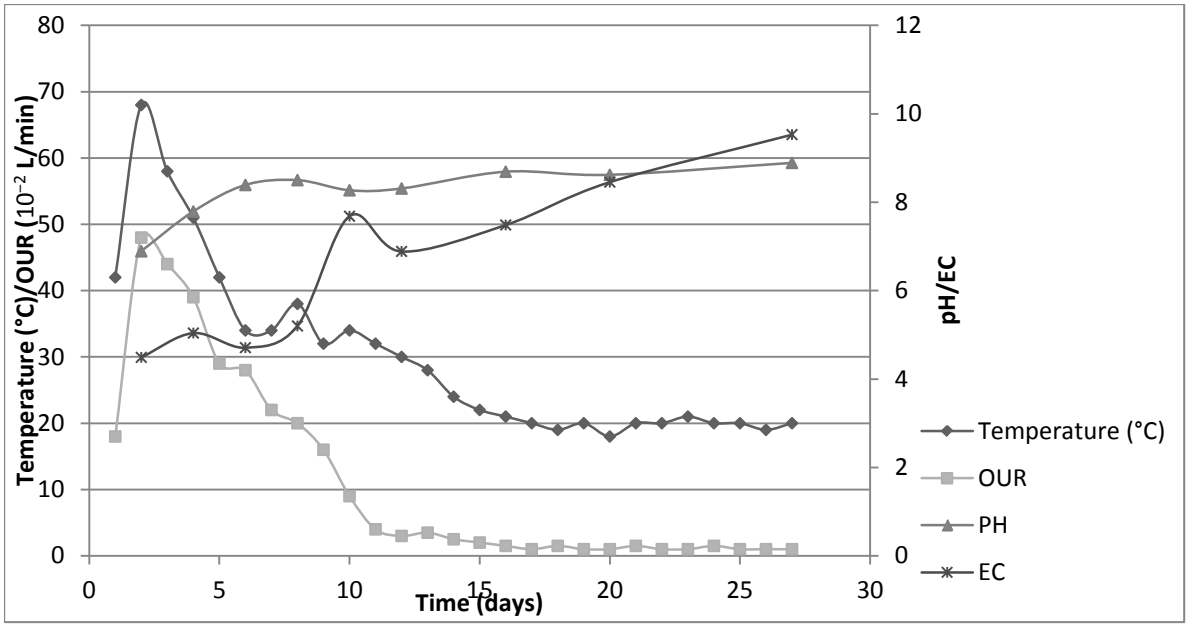
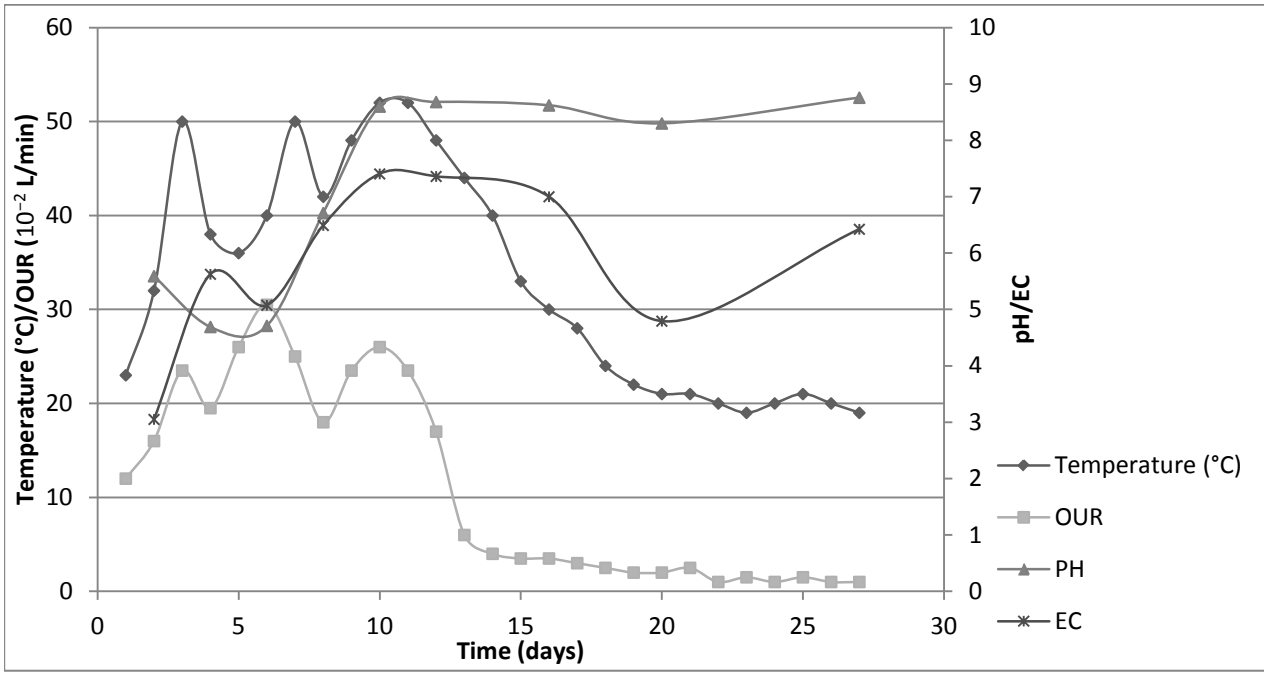



Figure 4.10. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 10)




.Figure 4.11. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 11)

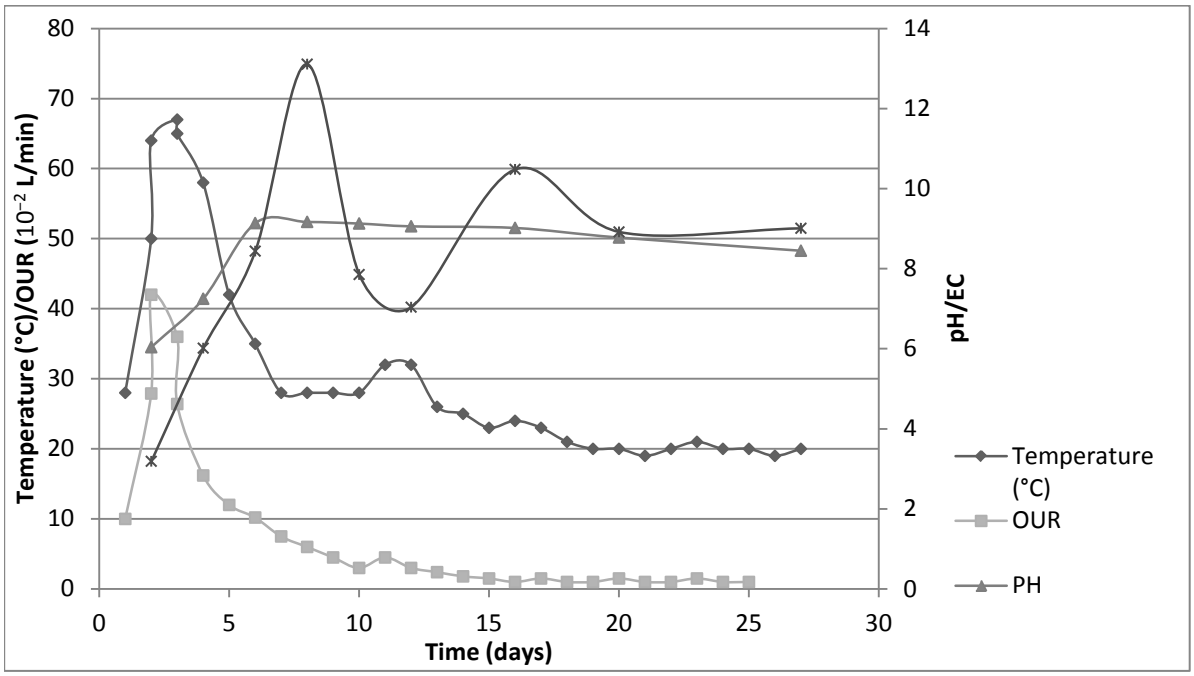



Figure 4.12. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 12)

The sharp increase of the temperature to 66°C at the second day indicated the comparatively high microbial activity on run 13. Temperature was high for 4 days and then a marked decrease was observed. The composting system regained temperature and then again decreased to the ambient temperature. The temperature rose to 66°C on the second day and diminished to 30°C on day 6 on run 14. The establishment of the thermophilic phase indicated there were sufficient waste materials available to support aerobic microorganisms. Temperature reached a maximum of 67°C on the third day on run 15 and then fell off to the ambient temperature after 12 days. On run 16, 55 °C was the highest temperature observed. The process was mostly mesophilic rather than thermophilic. The appearance of the temperature peak depended on the composition of the waste material which affects the microorganism growth.

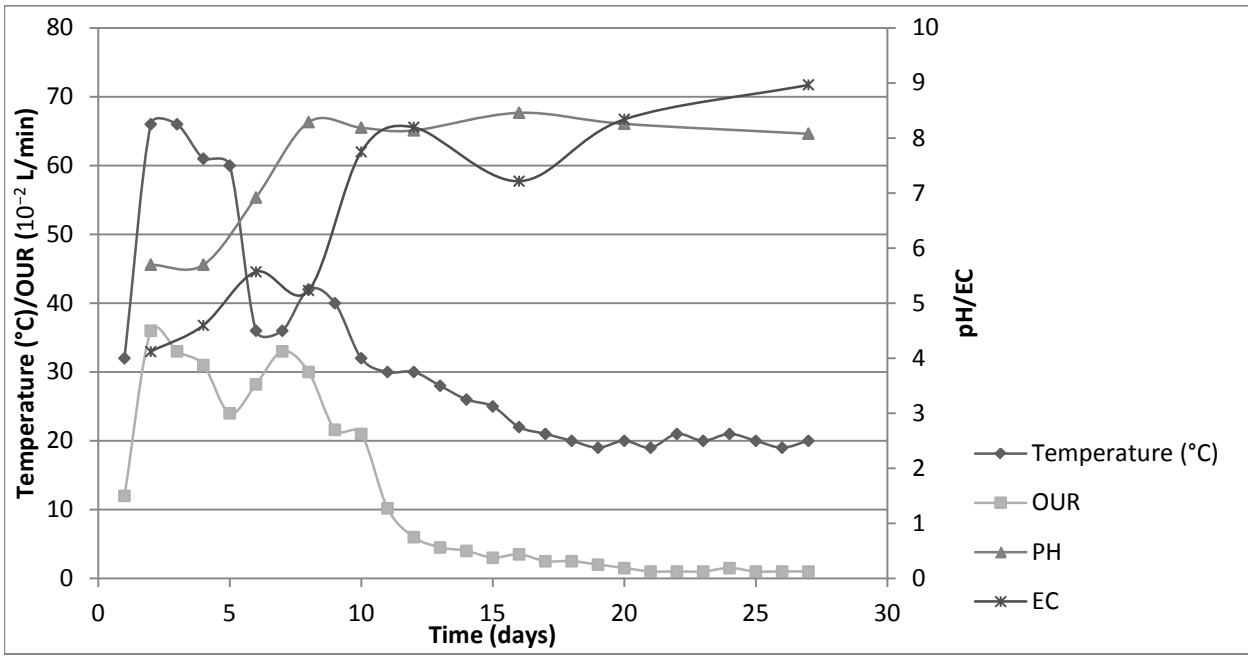



Figure 4.13. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 13)

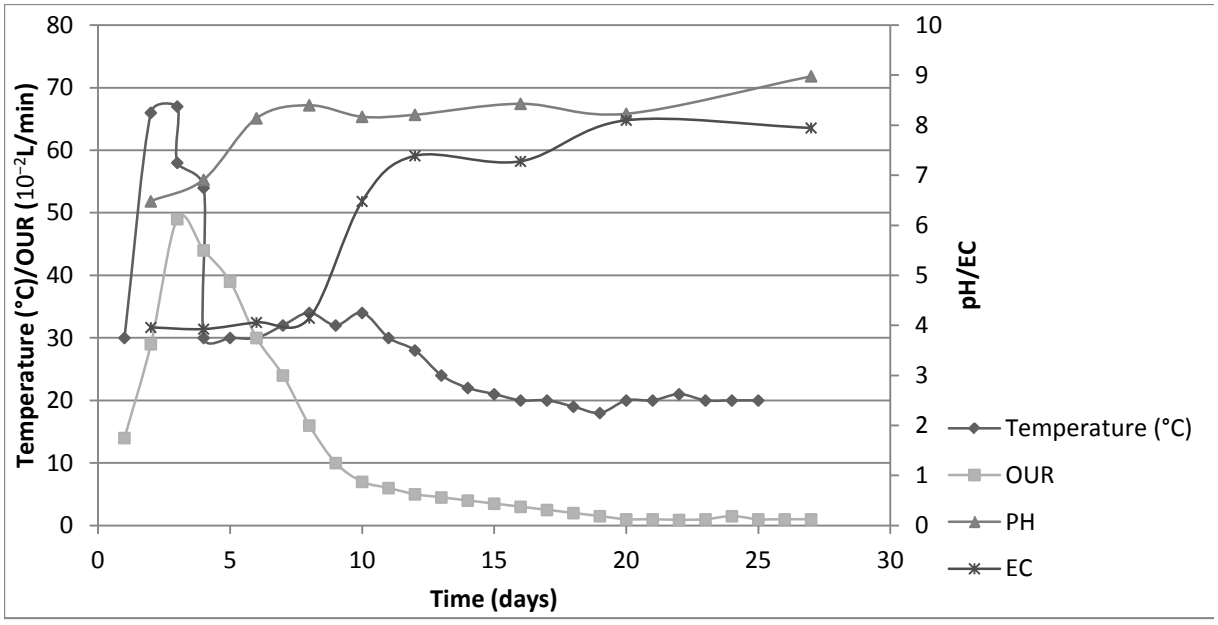



Figure 4.14Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 14)

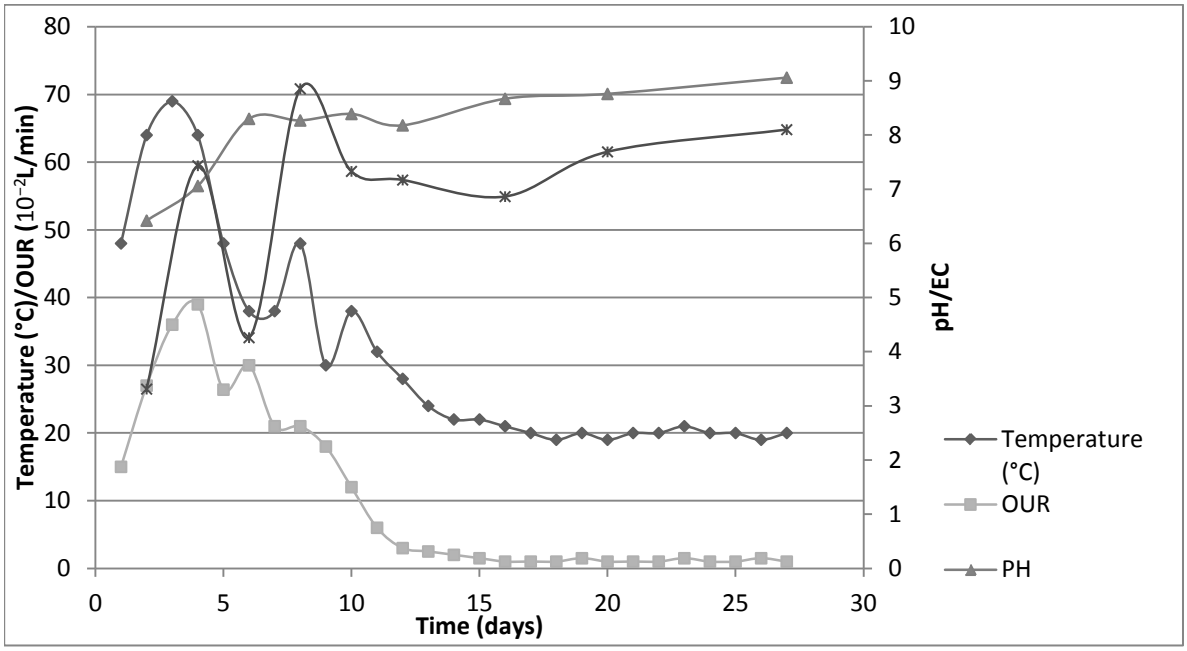



Figure 4.15. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 15)

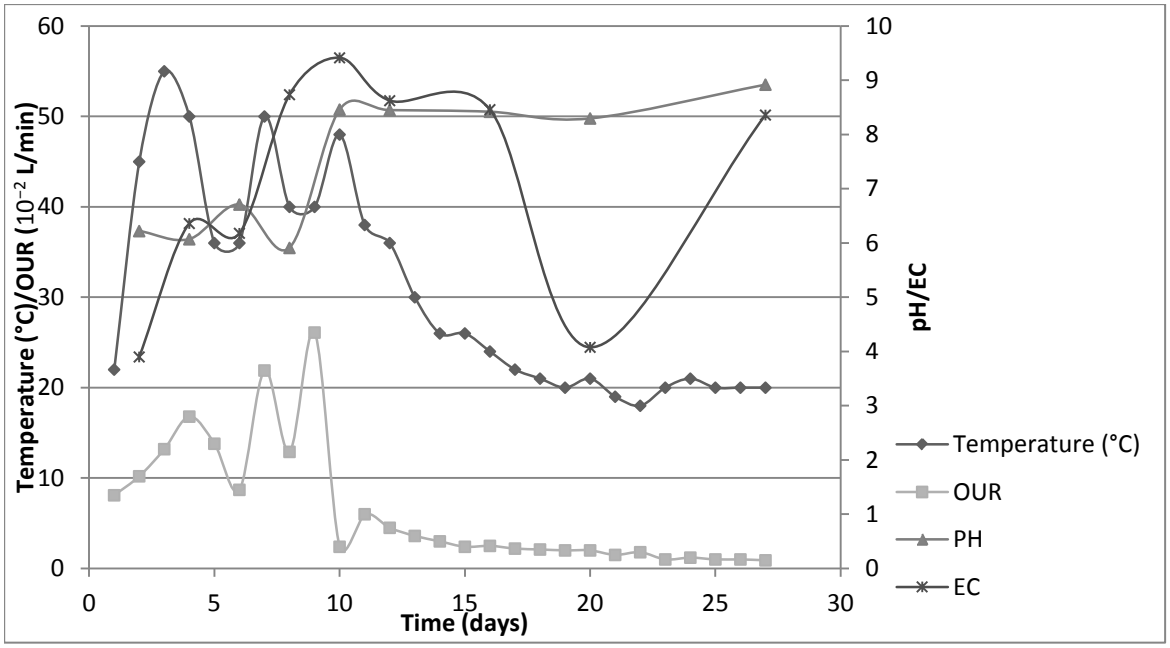



Figure 4.16. Temporal variations of temperature, oxygen uptaking rate, pH, and EC level (Run 16)

Generally, the lowest temperature was between 19 and 22°C and the highest was between 52 and 70°C. The mesophili, thermophilic, and cooling phase were on day 1-2, 2-3, and 12-18, respectively. The highest temperature recorded on run 2 and the longest thermophili activity occurred on run 5 which was 10 days. Run 3 and 11 reached the themophilic phase later than the others. The aeration rate and the composition of the starting matter affect the temperature profile of the composting process. Temperature variations were almost corresponding to the temperature pattern of the composting process.

## 4.2 OUR

Microbial respiration has been used to measure the microbial activity during composting. Also, it has been used to assess the evolution of the composting process and maturity of the final product (Ros et al., 2006). High OUR indicates organic matter are available for microorganisms to be degraded, and therefore the material is not stabilized yet. Low OUR indicates organic matter are more stabilized and most of the organic matter has been decomposed by microorganisms (Said-Pullicino et al., 2008). The pattern of OUR in all runs was similar to the pattern of the temperature. The highest OUR was recorded during the thermophilic phase, when the temperature rises. High OUR indicates higher biological activity. The maximum values of OUR was between 26 and 62 ($\frac{10^{-2}L}{min}$). The maximum OUR was observed on run 9. After the active phase, the OUR decreased and reached the steady state. A strong correlation has been found between temperature and OUR (r = 0.812, p=0.000).

The first peak of OUR which is visible in most of the runs is attributed to the consumption of the readily available organic matter by microorganism, and the later peaks are related to providing organic matter through the breakdown of the large organic molecules to support microbial respiration. On run 16, the maximum OUR was observed on day 7, which can be due to the low pH at the beginning of the composting. The low pH inhibits microbial growth and microbial activity and consequently reduces the OUR. Also, the absence of the oxidative microbial community to oxidize the organic matter or presence of the particular compounds which inhibits the effective mineralization of the organic matter can lead to the low OUR during composting process (Said-Pullicino et al., 2008).

## 4.3 pH

The pH value of the compost is one of the important factors to evaluate compost stability and maturity due to its influence on the physical-chemical and microbiological reactions in the compost (Banegas et al., 2007). Compost with low pH indicates lack of the maturity due to the short composting time of occurrence of the anaerobic process (Iglesias Jiménez and Perez Garcia, 1989).

As a result of organic acids contained in the food waste the initial pH of all runs was slightly acidic (Smårs et al., 2002; Adhikari et al., 2009). The pH variation of run 2, 3, 4, 6, 9, 10, 11, 12, 13, 14, 15, and 16 followed almost the same trend. The pH values of these runs started to increase as a result of high microbial activity which used the organic acids as a substrate (Adhikari et al., 2009). The increase continued during the themophilc phase. The increase during the active phase of composting can be attributed to the accumulation of $NH_4^+$ due to the proton

assimilation during ammonification and N mineralization as a result of microbial activity (Dresbøll and Thorup-Kristensen, 2005; Rasapoor et al., 2009).

The initial pH value for run 1, 5, 7, 8, and 11 decreased. This decrease in pH was due to the loss of ammonium through the volatilization and nitrification, and accumulation of organic acid and $CO_2$ during decomposition of the simple organic matter like carbohydrates (Banegas et al., 2007; Chukwujindu et al., 2008; Kayikçioğlu and Okur, 2011). Organic acids degradation by microorganisms at the later stage elevated acidic pH to slightly basic pH (Adhikari et al., 2009; Karnchanawong and Suriyanon, 2011).

On run 3, 4, 5, 6, and 12, pH decreased after the thermophilic phase. The pH reduction after active phase can occur either as a result of the nitrification process because during nitrification, nitrifying bacterial by liberation of hydrogen ions reduces the pH or accumulation of organic acids reflects high rate of OM degradation (Dresbøll and Thorup-Kristensen, 2005; Chukwujindu et al., 2008; Kalamdhad et al., 2009, Rasapoor et al., 2009).

On run 8 and 9, the initial phase of low pH was longer, it could be due to the rapid increase of temperature to the thermophilic phase. Microorganisms cannot tolerate high temperature and low pH at the same time. Thermophilic bacterial are not acid tolerant so the low pH led to a decline in microbial activity and the low microbial activity resulted in low degradation rate and longer period of the acidic pH (Sundberg et al., 2004). In this situation, mesophilic control of temperature or addition of yeast, which can eliminate organic acids, can increase the process activity and eliminate the decline in microbial activity especially at the large scale composting systems in which despite low pH and low microbial activity, temperature rises to thermophilic phase due to self-insulation of large scale composting (Smårs et al., 2002; Sundberg et al., 2004).

The initial pH of all runs was between 4.8 and 7.4. The maximum values were between 8 and 9.16. The highest value was 9.16 on run 17. The pH values were negatively correlated with temperature ($r = -0.598$, $p = 0.000$), and OUR ($r = - 0.597$, $p = 0.000$).

## 4.4 EC

Compost EC affects microbial population and organic matter transformation. Also, high EC values of compost may have phytoxicity effects on the plant and negatively influence the growth and seed germination (Banegas et al., 2007; Kalamdhad et al., 2009, Arslanet al., 2011). Kayikçioğlu and Okur (2011) stated that the initial EC values of the composting were the most important factor that affects the EC change during composting. The EC values of all runs on the second day of composting were between 2.02 to 5.05 mS/cm. Generally, EC values increased for all runs during composting. This increase could be due to the release of mineral cation concentration such as ammonium ions and phosphate which did not bind to the stable organic complex or went out of the system through leachate (Francou et al., 2005; Kalamdhad et al., 2009). On some runs, for a short period of time slight decrease were observed, this decrease may be attributed to the reduction of water soluble substances such as organic acids during the composting process (Arslanet al., 2011). In addition, the decrease was seen in the later stage in some runs such as 8, 11, and 16, which can be attributed to volatilization of ammonia and the participation of mineral salt (Rasapoor et al., 2009).

EC values were between 5 and 9.68 mS/cm at the end of the process. Positive correlation was found between pH and EC ($r = 0.668$, $p = 0.000$). Also EC negatively correlated with temperature ($r = -0.512$, $p = 0.000$), and OUR ($r = -0.525$, $p = 0.000$).

## 4.5 Moisture content

Moisture content variation is shown in figure 4.17 and 4.18 which are categorized based on their initial values. As it is revealed in the figure, moisture content showed descending trends in all runs. The combination of evaporation because of high temperature and aeration lead to moisture content decrease during composting, especially at the thermophilic phase (Said-Pullicino et al., 2008; Lashermes et al., 2012). Run 7, 10, 12, 13, and 15 showed corresponding trends, as temperature increased and moisture decreased. Decrease of the moisture content during composting is an indication of decomposition of organic matter (Kalamdhad et al., 2009; Arslanet al., 2011). On the first 6 days, except run 9, high temperature had positive effect on moisture reduction. Although in general, moisture showed reducing trend in all runs, temperature was not high enough to evaporate the water produced through microbial activity and moisture showed temporary increasing trend for a short period of time on some runs such as run 6, 8, 9, and 11. Moisture content of run 9 and 11 exceeded 70% at some points, which is undesired for composting because it is capable of creating anaerobic condition (Tiquia and Tam, 1998). The highest reduction was observed on run 7 which could be due to the long period of high temperature. Huag (1993) suggested 40% as the minimum moisture content to continue microbial activity. Moisture content at the end of experiments, in all runs with 70% initial moisture content, was above 40%. In contrast, moisture content in runs with 55% initial moisture content, reached under 40% except run 4 and run 8.

Moisture content showed positive correlation with temperature ($r = 0.364$, $p=0.000$) and OUR ($r = 0.306$, $p=0.000$). It is also negatively correlated with pH ($r = -0.447$, $p = 0.000$) and EC ($r = -0.308$, $p = 0.000$).

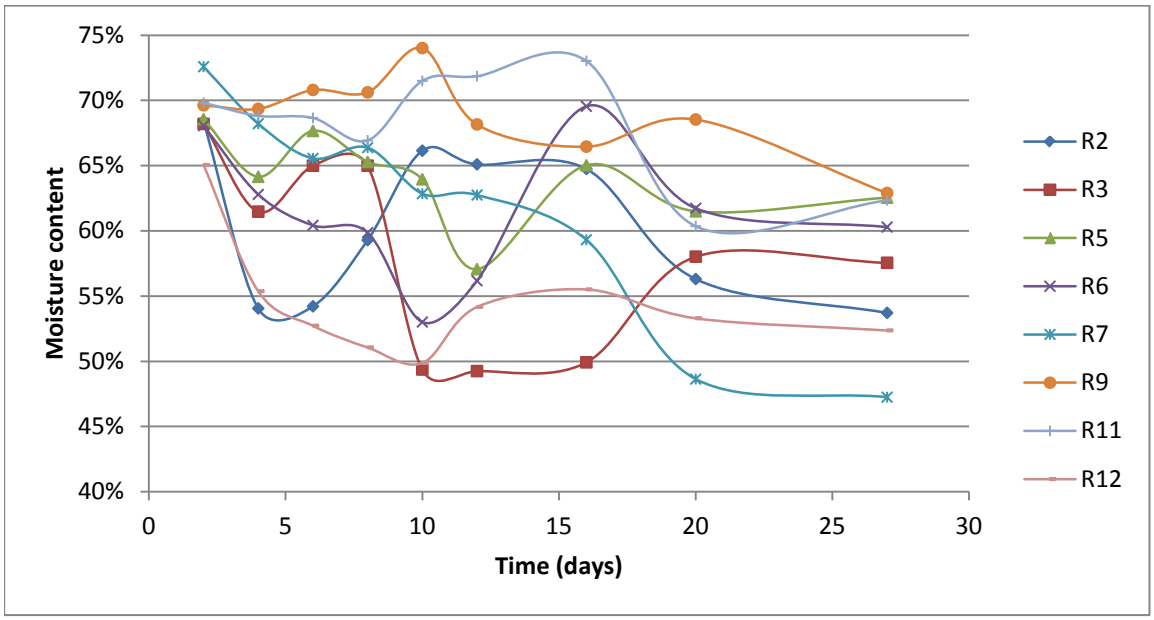



Figure 4.17. Temporal variations of moisture content for runs with 70% initial moisture content

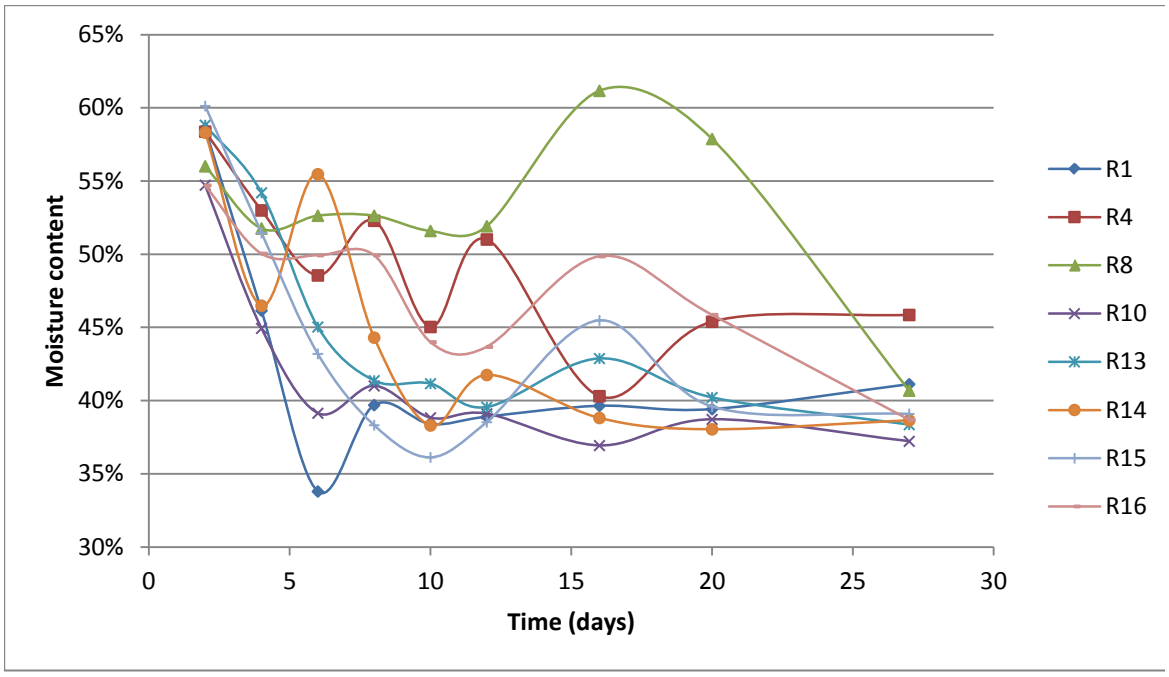



Figure 4.18. Temporal variations of moisture content for runs with 55% initial moisture content

## 4.6 Ash Content

The ash content profile of the compost is shown in Figure 4.19 and 4.20. The amount of ash increased consistently in all runs. The ash content increasing trend had large slope at the thermophilic stage, and then the slope became smoother when temperature dropped. During composting the organic matter was decomposed into volatile compound, and consequently the final compost has lower organic matter and higher ash content (Kalamdhad et al., 2009).

The Ash content of the samples at the beginning of experiment was between 0.8 % and 1.2%. At the end of the experiments, the ash content increased to 2.1% to 5.5%. The highest increase happened in run 7 which could be due to the long thermophilic phase. Ash content strongly correlated with temperature ($r = - 0.634$, $p=0.000$), OUR ($r = - 0. 570$, $p=0.000$), and moisture content ($r = -0. 577$, $p=0.000$). It also positively correlated with pH ($r= 0.636$, $p=0.000$) and EC ($r = 0.470$, $p=0.000$).

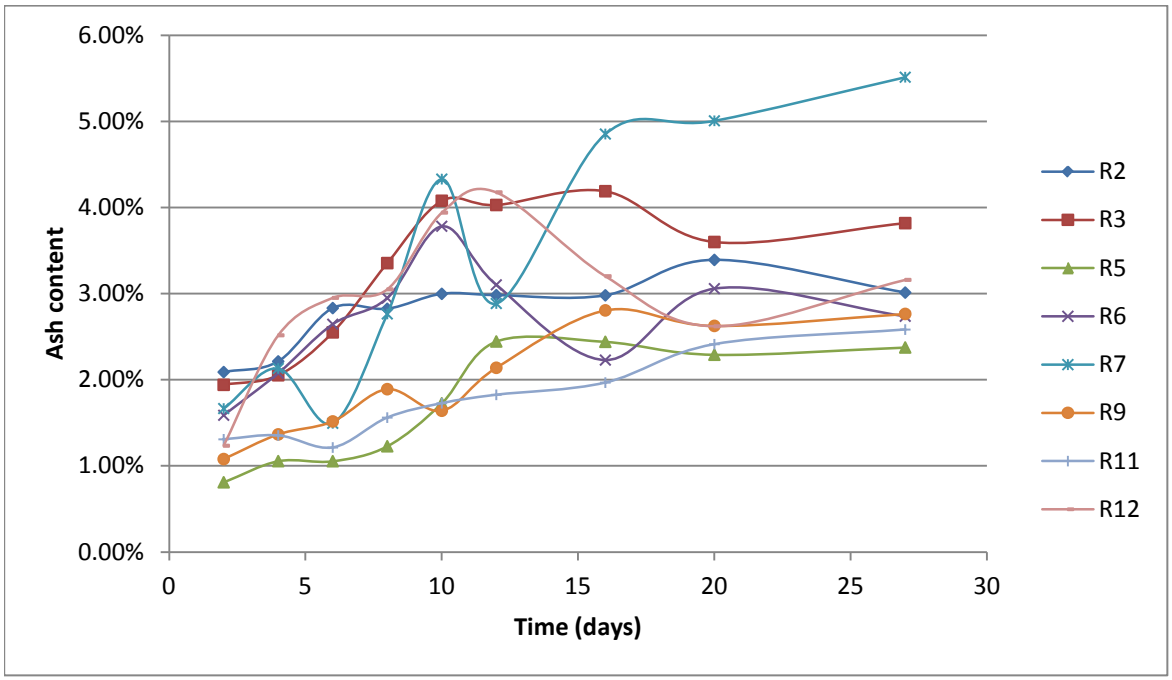



Figure 4.19. Temporal variations of ash content for runs with 70% initial moisture content

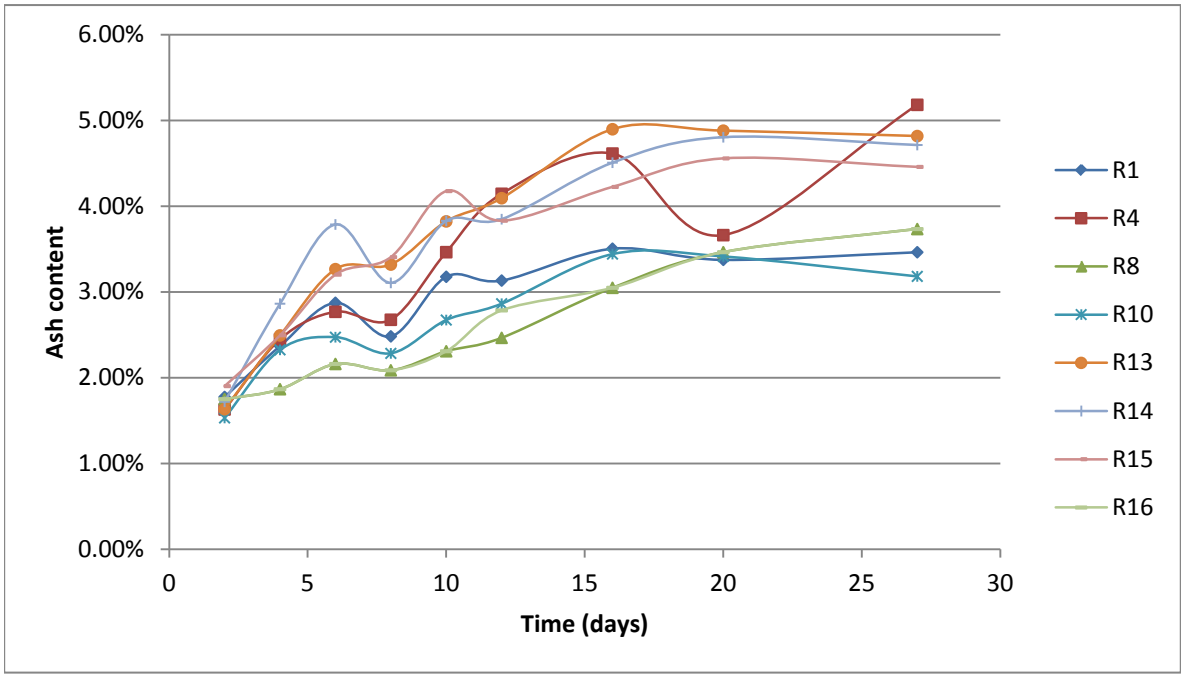



Figure 4.20.Temporal variations of ash content for runs with 55% initial moisture content

## 4.7 GI

Figures 4.21 to 4.24 show the variation of GI. Seed germination test helps to evaluate the efficiency of the composting process for plant growth and seed germination (Banegas et al., 2007). In this study, the raw material is synthetic food waste, which does not contain any toxic material for plant growth. Consequently, the germination indices in most of the runs at the beginning were very high. In some runs such as run 7, 10, and 13, low germination indices at the beginning can be a result of the fast starting of biological activity and the formation of toxic compounds such as alcohols, phenolic compound, and organic acids which inhibits seed germination (Cabañas-Vargas et al., 2005). GI decreased during the thermiphilic phase and during the transition of tehmophilic to mesophilic phase. Although the phytotoxicity of composts can be attributed to high EC content (> 4 $\mu S/cm^{-1}$) (Allison, 1973; Wu et al., 2000) or said low pH (Tiquia and Tam, 1998), in this research the high EC did not influenced the GI in most of the runs. In the majority of the runs, GI started to increase after 3 weeks of composting. It has been suggested that a GI over 80% indicates the absence of phytotoxicities in compost (Tiquia and Tam, 1998). Only GI of runs 5, 7, 8, 11, and 17 raised over 80%, in other runs the low GI can be associated to the stage of the composting. Run 3, 12, and 14 showed very low GI after 4 weeks. EC can affect adversely seed germination in these runs.

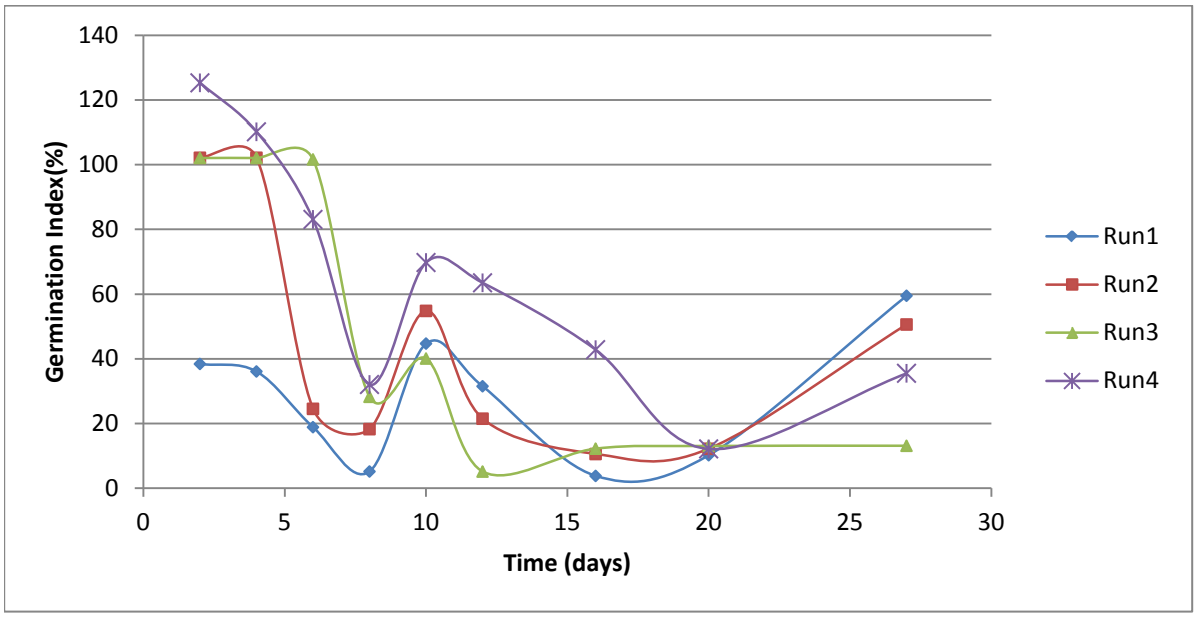



Figure 4.21. Germination Index for runs 1, 2, 3, and 4

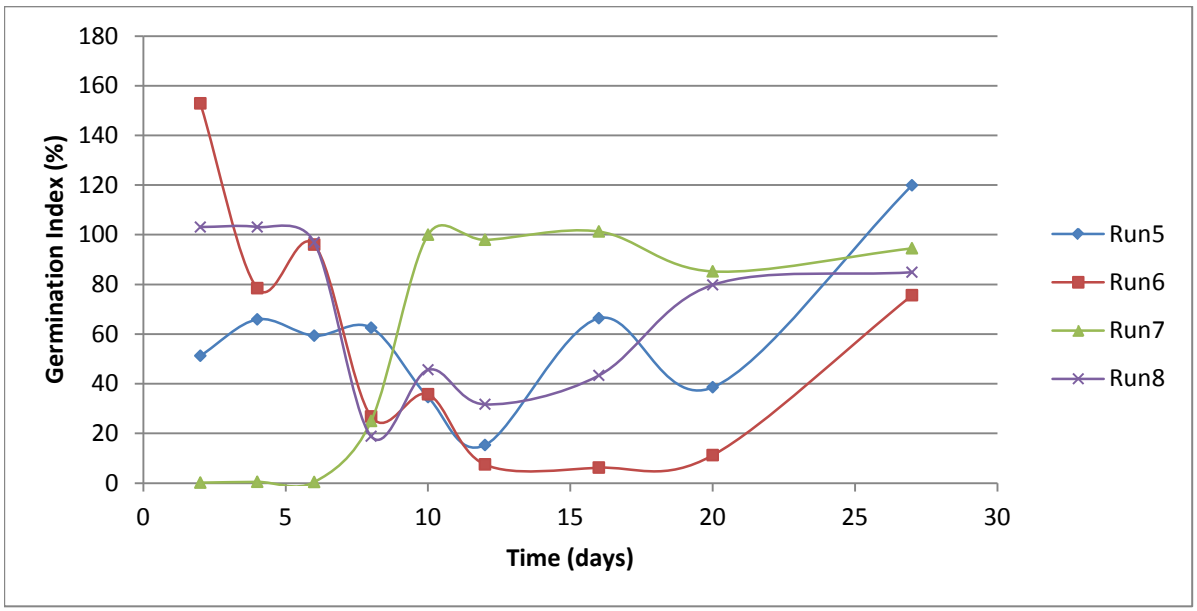



Figure 4.22. Germination Index for runs 5, 6, 7, and 8

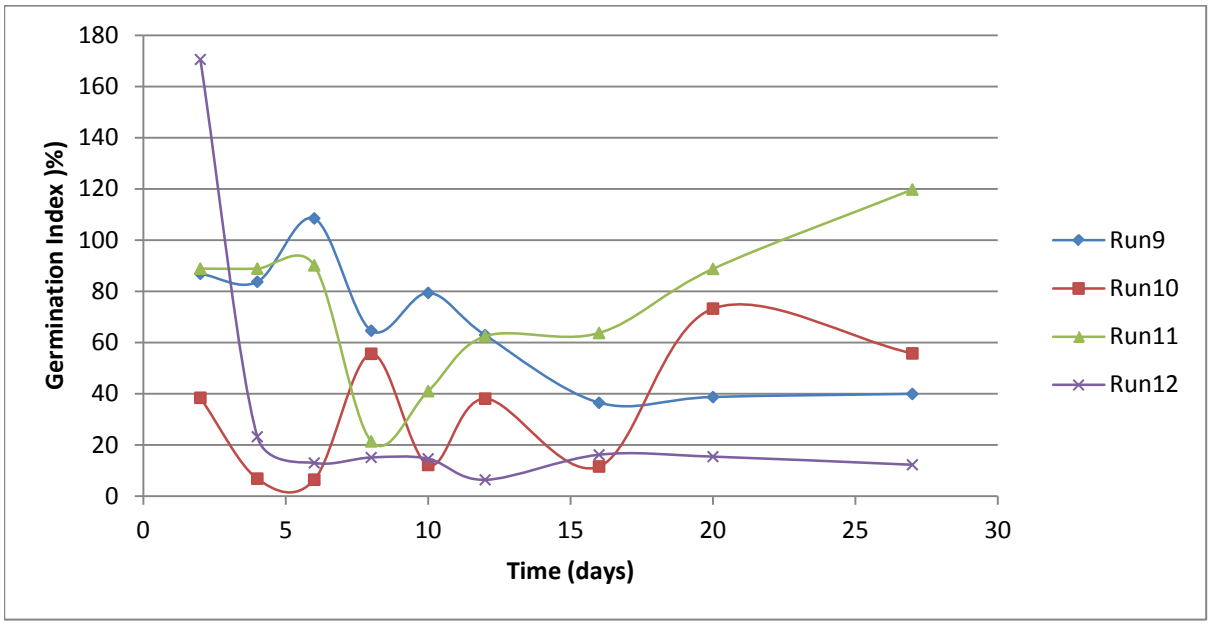



Figure 4.23. Germination Index for runs 9, 10, 11, and 12

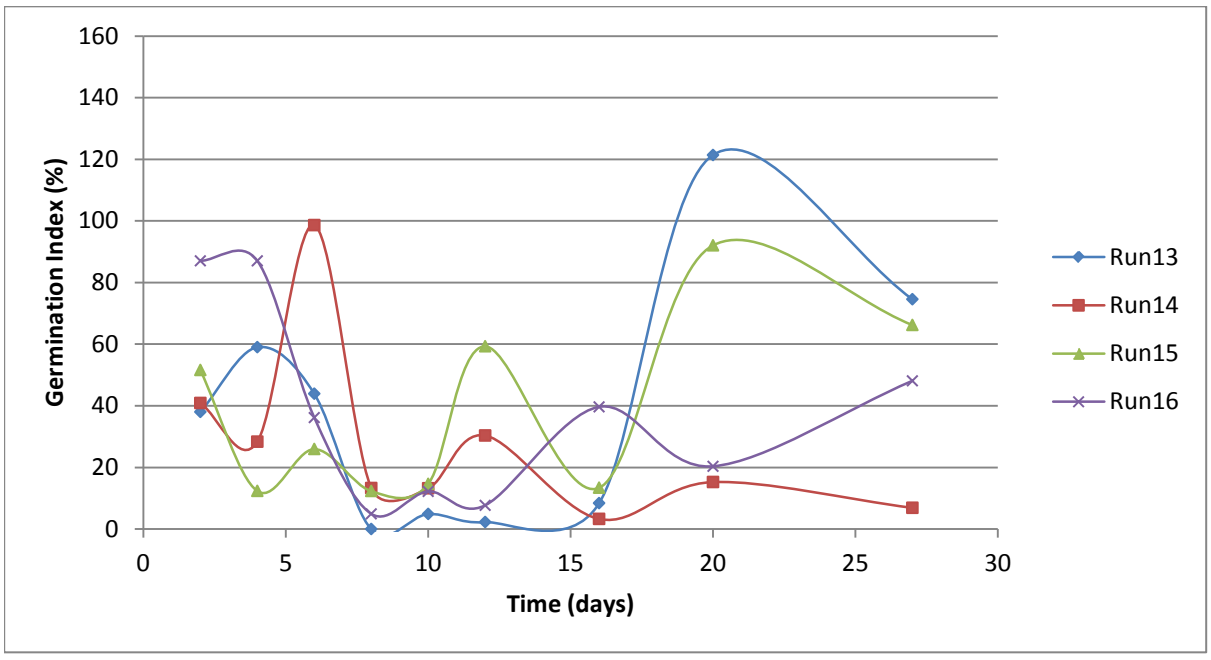



Figure 4.24. Germination Index for runs 13, 14, 15, and 16

## 4.8 Dehydrogenase activity

Dehysrogenase activity has been used to evaluate the microbial activity because it belongs to the group of the intercellular enzymes which catalyse the oxidation of compost organic matter (Iglesias Jiménez and Perez Garcia, 1992; Benito et al., 2003). Due to the relationship between dehydrogenase activity and temperature, Barrena et al. (2008) suggested to use dehydrogenase activity to describe the biological activity during the tehmophilic and mesophilic stage.

Dehydrogenase activity has shown in Figures 4.25 to 4.28. Dehydrogenase activity initially increased on run 1, 2, 3, 8, 10, 14, 13, 14, and 15 whereas run 4, 5, 6, 7, 9, 12, 11, and 16 showed initial decrease in the dehydrogenase activity. The dehydrogenase activity values at the beginning of runs which showed decrease in the initial phase were very high, which could be a result of the starting microbial activity during storage time. Although Kayikçioğlu and Okur (2011) and Barrena et al. (2008) found that the maximum values of dehydrogenase activity corresponded to the end of the thermophilic phase or the beginning of the mesophilic stage, In this study, run 1, 3, 4, 7, 8, 10, 11, 13, 14, and 16 showed different patterns and the peaks of temperature, OUR, and dehydrogenase activity appears simultaneously. Kayikçioğlu and Okur (2011) also mentioned that the high account of mesophilic and themiphilic bacteria accompanied high dehydrogenase vales. Vargas-Garcia et al. (2010) stated that the higher dehydrogenase activity values are related to the higher microbial activity and lower values associated to the maturation phase. After day 20, the dehydrogenase activity decreased, which means that most of the organic matter has been degraded by the microorganism and converted to the stable material and consequently the respiratory process slowed down (Benitez et al., 1999; Benito et al., 2003; Tiquia, 2005; Ros et al., 2006; Vargas-Garcia et al., 2010, Kayikçioğlu and Okur, 2011).

The maximum dehydrogenase activity was observed on run 5 which was 25000 (µg TPF g dry matter $^{-1}$). The final values of dehydrogenase activity were between 1935 and 9017 (µg TPF g dry matter $^{-1}$). Although other studies found strong correlation between dehydrogenase activity and other operational parameters such as SRI (static respiration index), temperature, pH, and EC (Barrena et al., 2008), dehydrogenase activity did not show any correlation with OUR or pH. It was correlated with moisture content ($r = 0.431$, $p=0.000$) and temperature ($r = 0.261$, $p=0.000$).

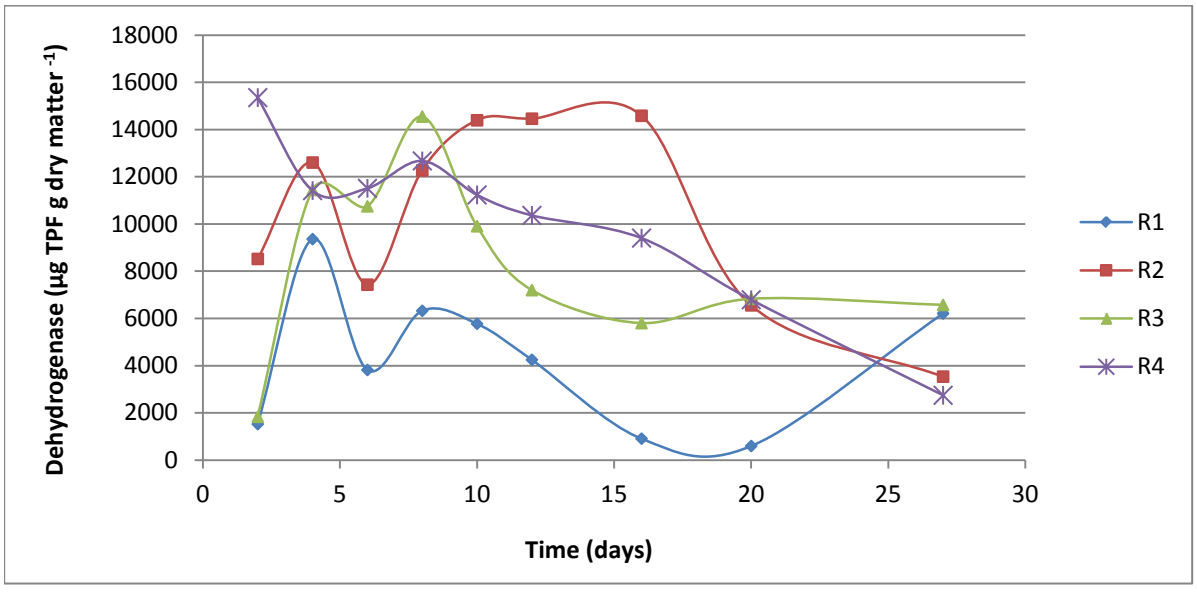



Figure 4.25. Dehydrogenase Activity for Runs 1, 2, 3, and 4

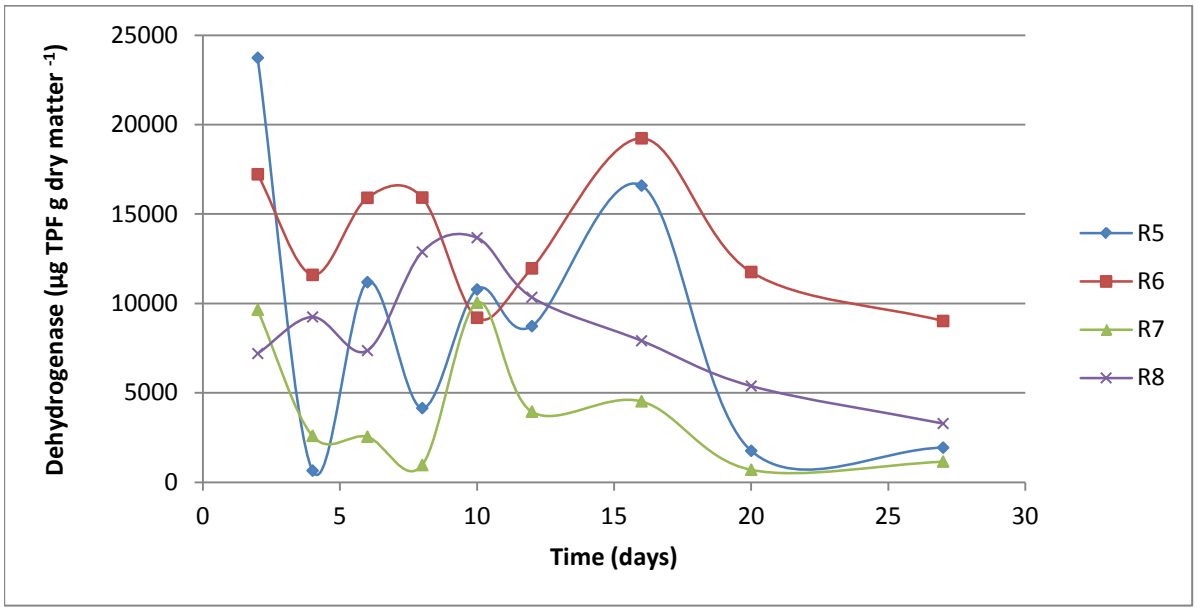



Figure 4.26. Dehydrogenase activity for Runs 5, 6, 7, and 8

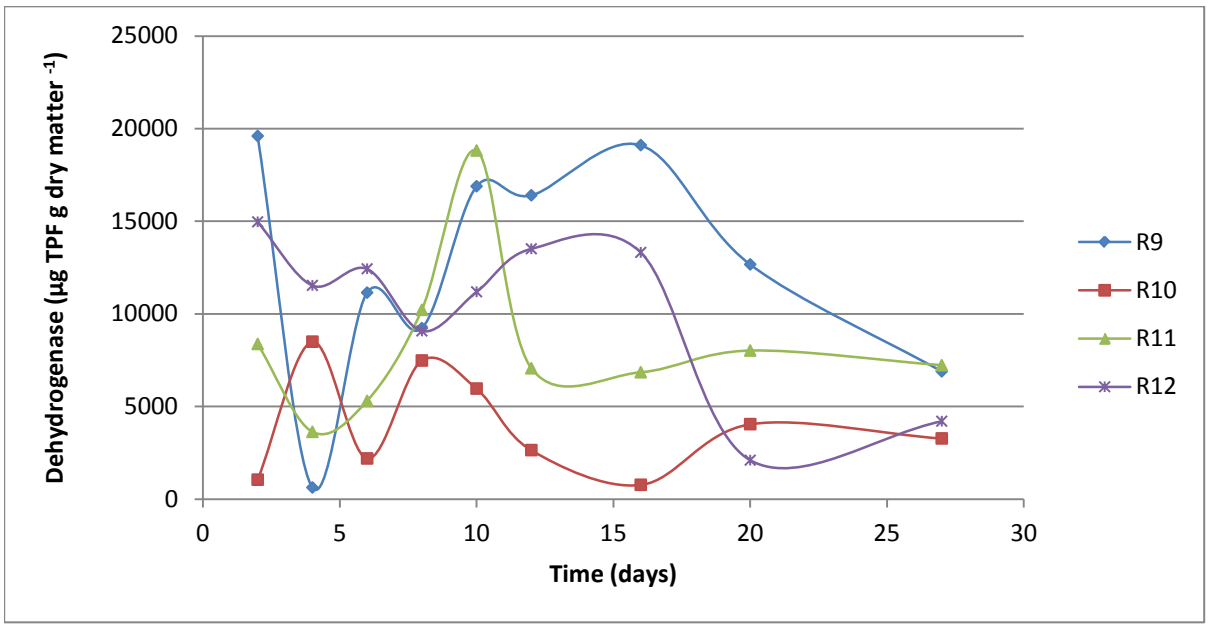



Figure 4.27. Dehydrogenase activity for Runs 9, 10, 11, and 12

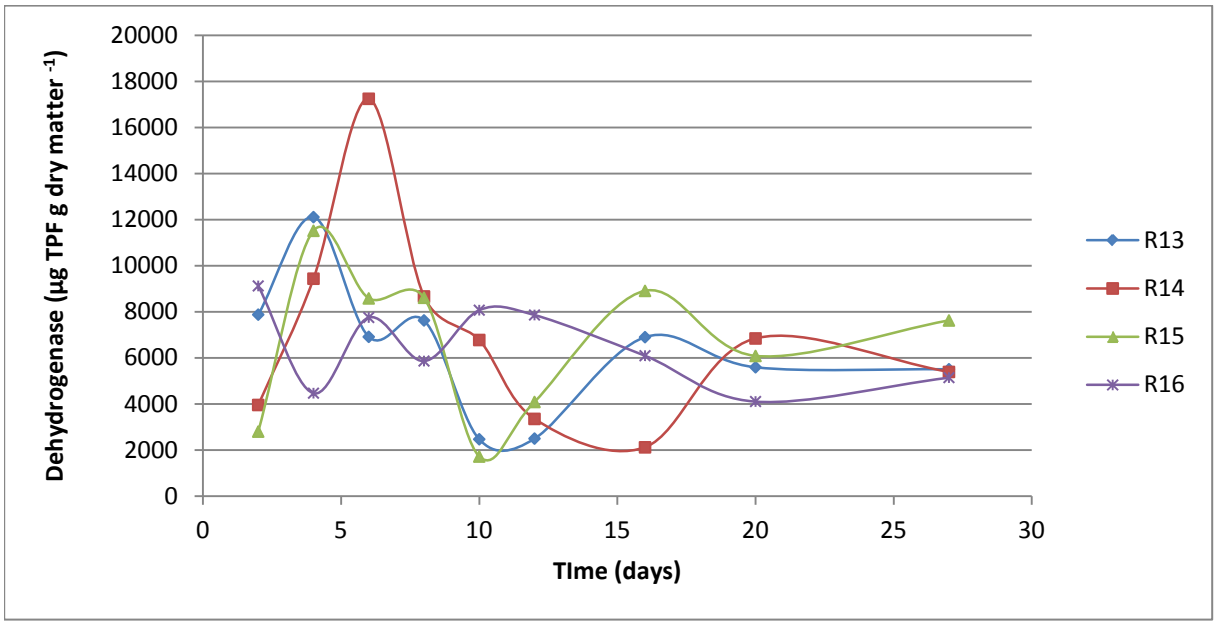



Figure 4.28. Dehydrogenase Activity for Runs 13, 14, 15, and 16

## 4.9 β-Glucosidase activity

β-Glucosidase catalyses the hydrolysis of the b-glucoside bonds of the carbohydrates, which contributes to the release of energy for microbial activity. β-Glucosidase activity was high at the initial phase of composting and later stage after thermophilic phase. High β-Glucosidase activity in the beginning is related to high amount of readily metabolizable substrates are available in the initial stage (Ros et al., 2006; Vargas-Garcia et al., 2010), and in the later stage, which is observed in this study too, may be related to the release of carbon compounds from the cellulytic and hemicellulytic activities, and lignin content after consuming of the easily metabolized carbon (Castaldi et al., 2008 and Vargas-Garcia et al., 2010).

Figures 4.29 to 4.32 reveals β-Glucosidase activities. The enzyme activity was high at the beginning of the composting; it decreased during first days and then showed an increase in all runs. After 3 weeks it declined slightly. Some other studies reported an increase of this enzyme activity during composting (Mondini et al., 2004, Castaldi et al., 2008). Nevertheless, other authors reported a decrease of GLU after an increase during composting different materials.

The value of the β-Glucosidase activity on the second day of composting was between 2037 and 21353 µg PNP g dry matterr$^{-1}$h$^{-1}$. The maximum value of β-Glucosidase activity observed during composting was related to run 7, 21903 µg PNP g dry matter$^{-1}$h$^{-1}$. Correlations were foundbetween β-Glucosidase activity and the moisture content ($r = 0.460$, $p = 0.000$) and ash content ($r = -315$, $p = 0.000$). Also, β-Glucosidase activity correlated with pH ($r = -0.311$, $p = 0.000$) and EC ($r = -0.334$, $p = 0.000$).

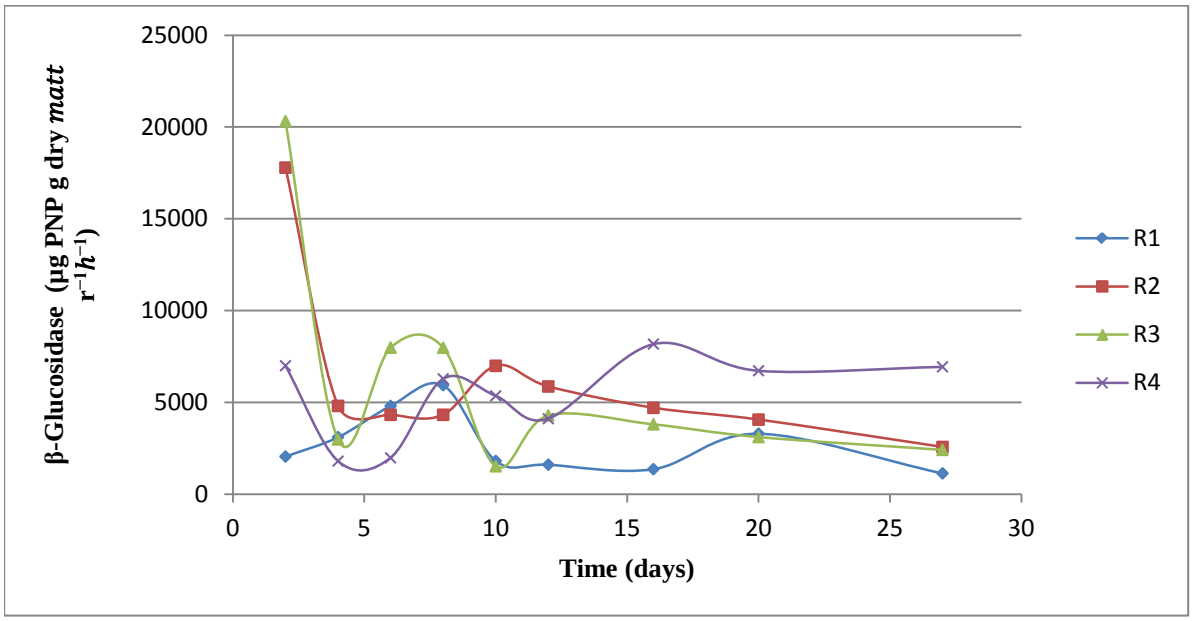



Figure 4.29. β-Glucosidase activity for Runs 1, 2, 3, and 4

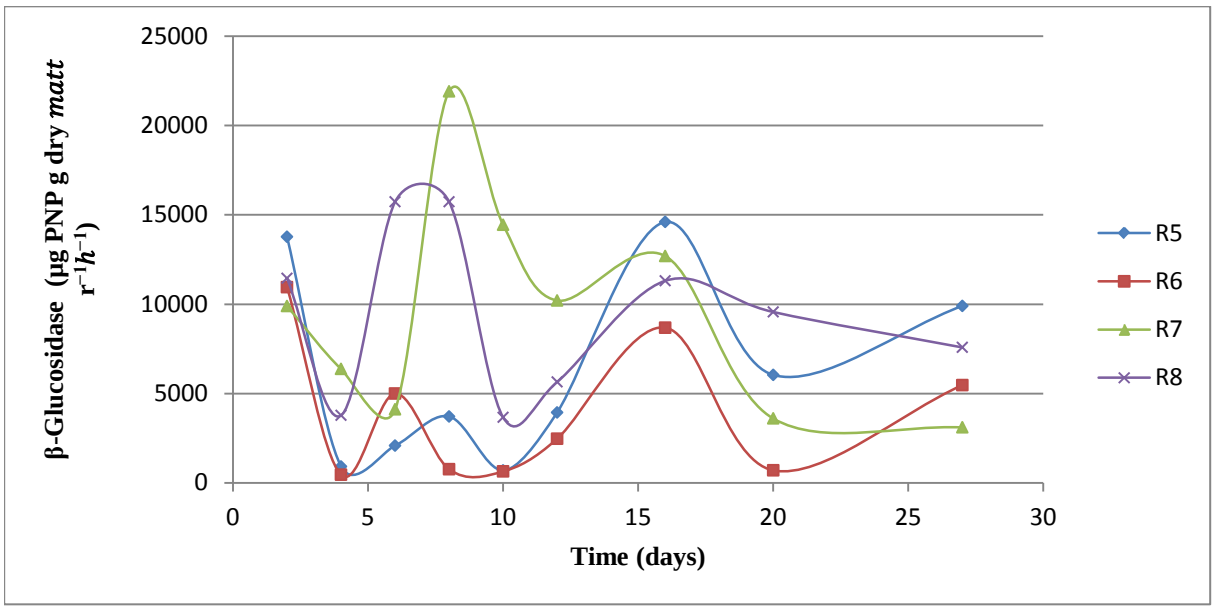



Figure 4.30. β-Glucosidase activity for Runs 5, 6, 7, and 8

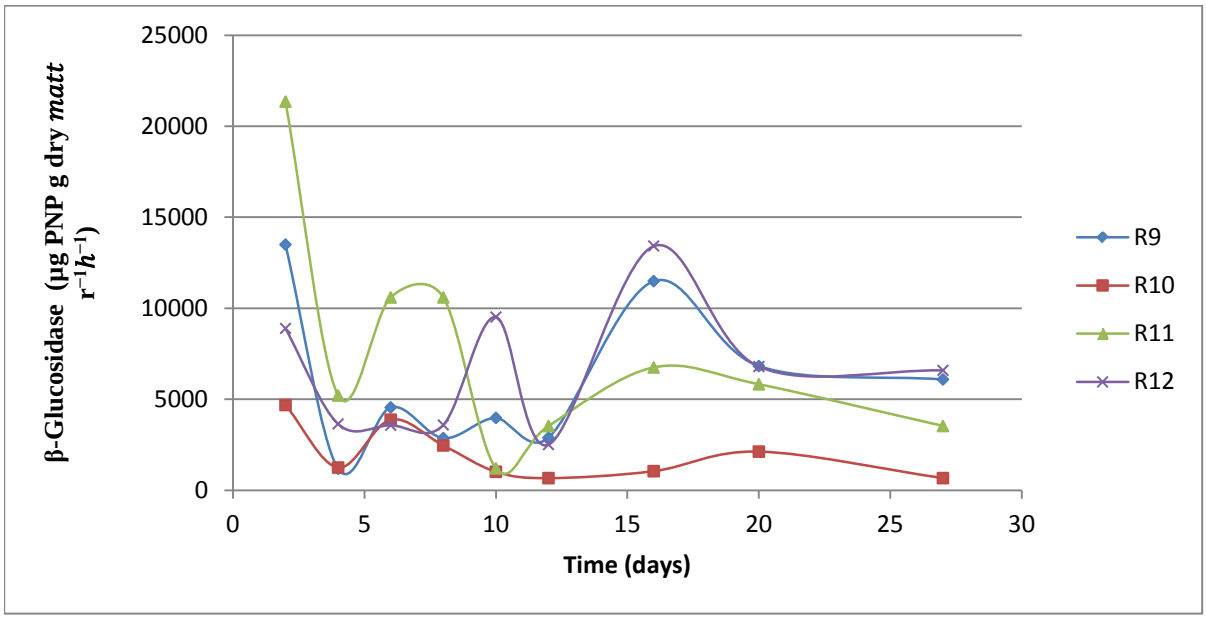



Figure 4.31. β-Glucosidase activity for Runs 9, 10, 11, and 12

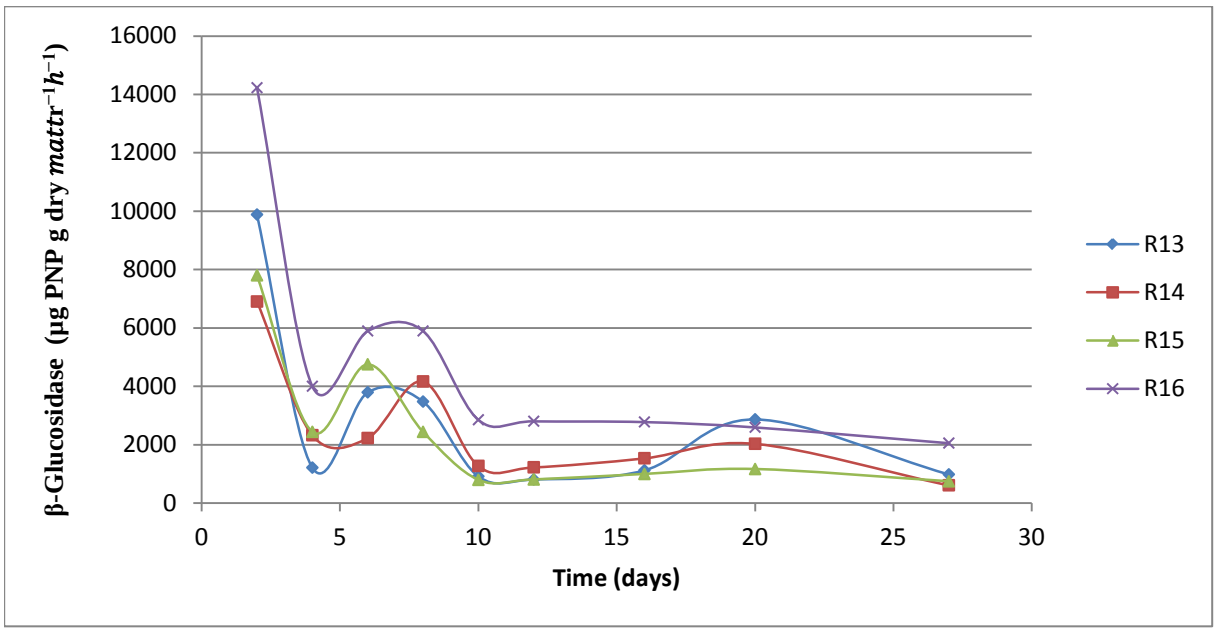



Figure 4.32. β-Glucosidase Activity for Runs 13, 14, 15, and 16

## 4.10 Phosphomonoestrase activity

Phosphomonoestrase catalyse reactions involved in the biochemical transformation of P and it is useful to assess the compost microbial activity and organic matter mineralization.

Figures 4.33 to 4.36 show the Phosphomonoestrase activity in 17 runs. Phosphomonoestrase activity decreased in most of the runs then it increased and reached maximum activity almost after a week and then it declined slightly until the end of the experiments. Activity varied between zero and 37000 µg PNP g dry matter$^{-1}$h$^{-1}$. The highest level was observed on run 7 and the strongest decrease was recorded on run 11. Phosphomonoestrase activity correlated with temperature (r = 0.208, p = 0. 010), OUR (r = 0.162, p = 0.045), Moisture content (r = 0.269, p = 0.001), and ash content (r = -0.173, p= 0.033).

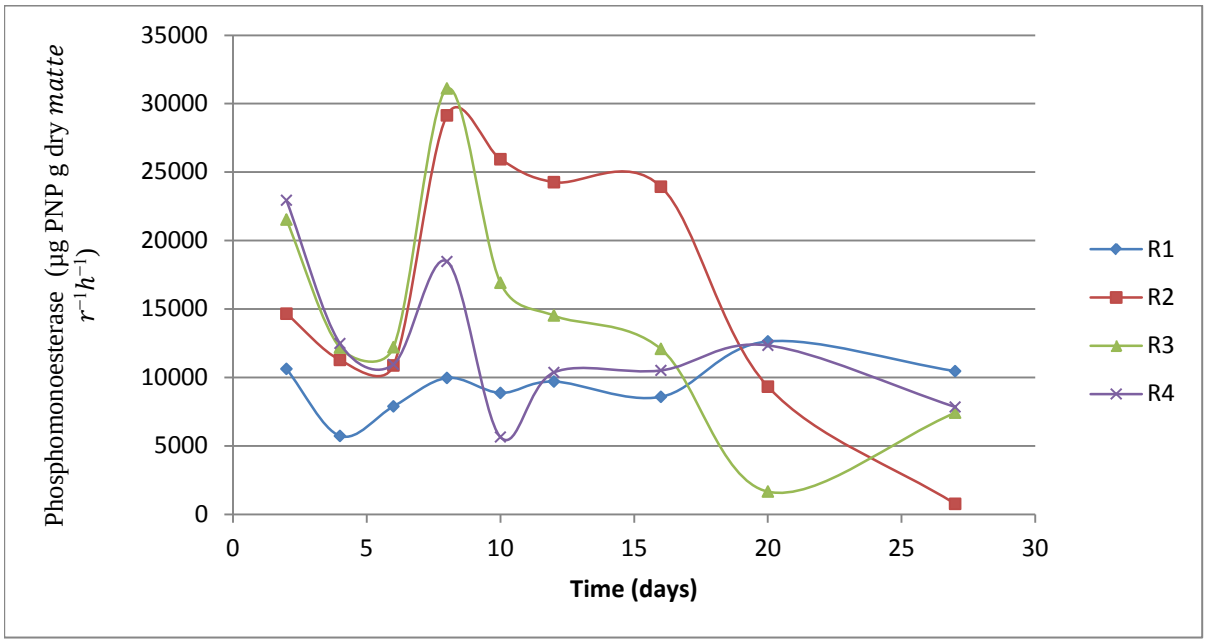



Figure 4.33. Phosphomonoestrase activity for Runs 1, 2, 3, and 4

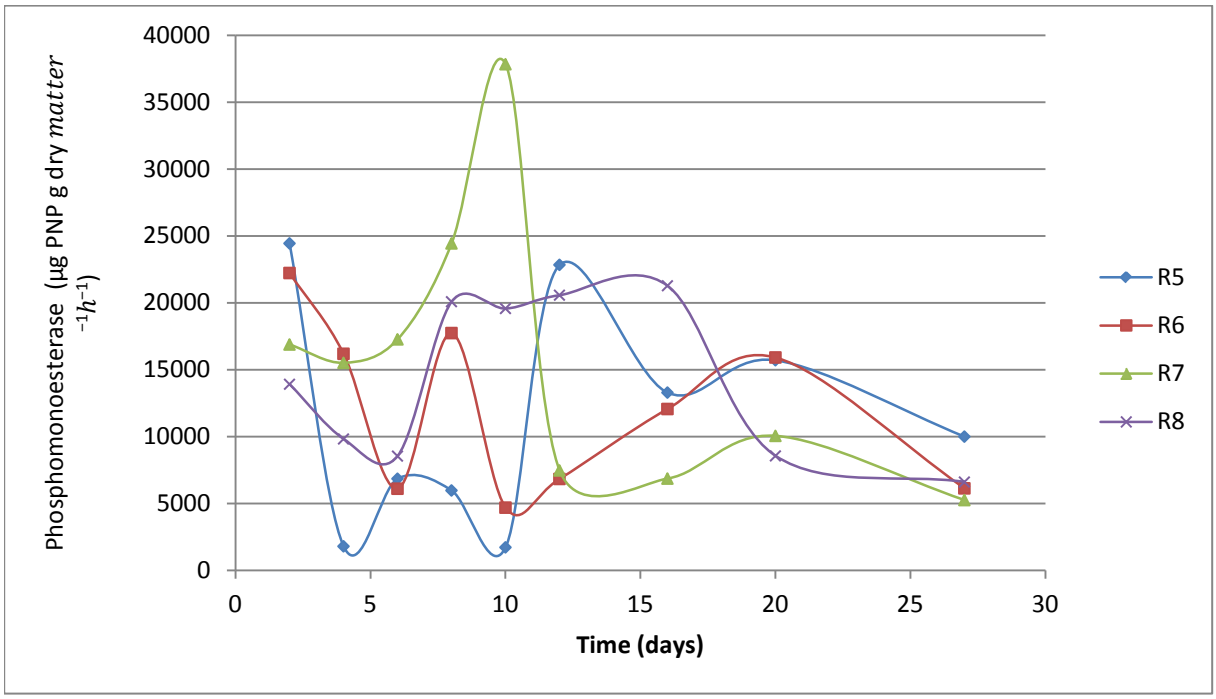



Figure 4.34. Phosphomonoestrase activity for Runs 5, 6, 7, and 8

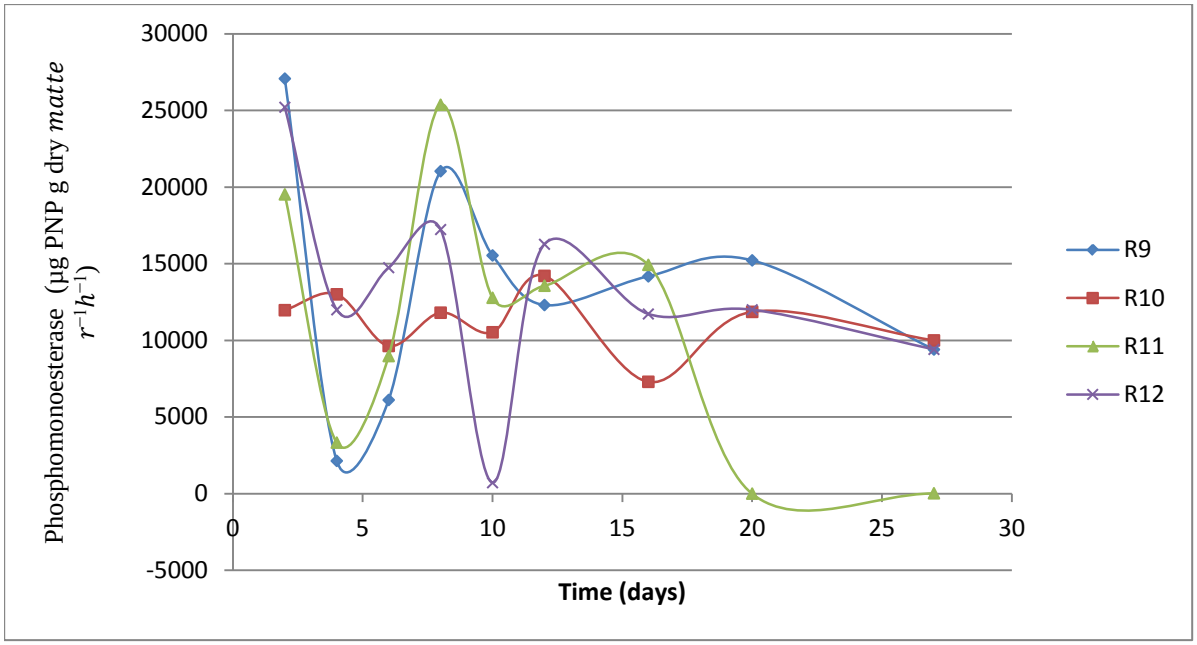



Figure 4.35. Phosphomonoestrase activity for Runs 9, 10, 11, and 12

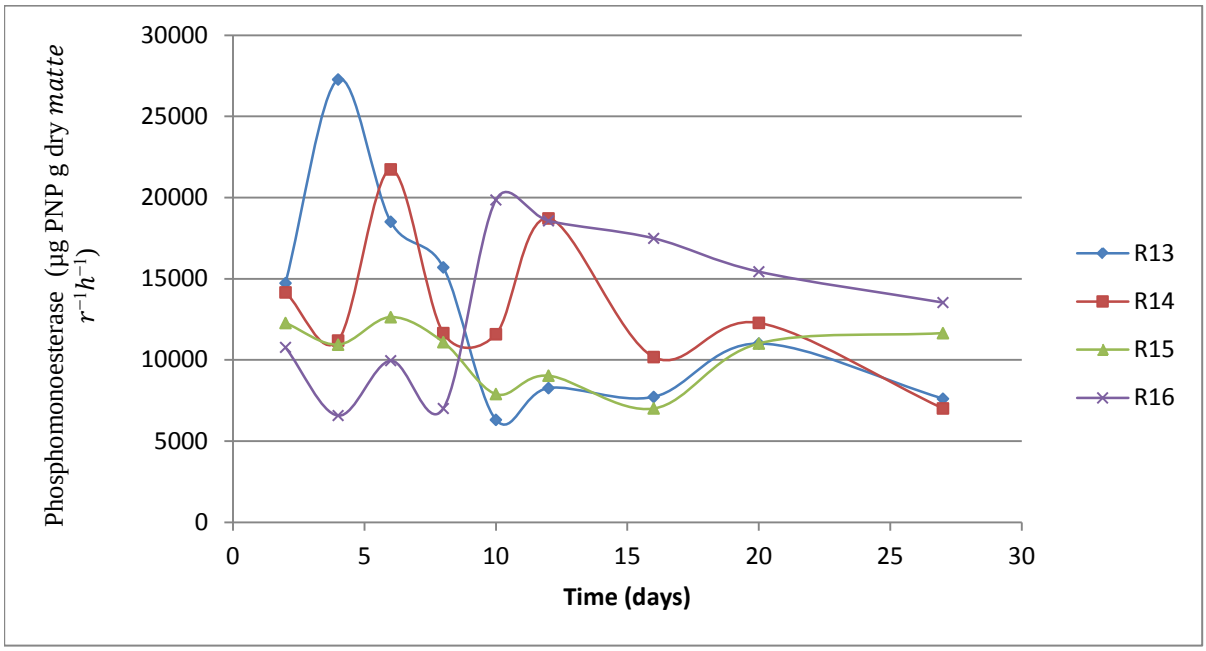



Figure 4.36. Phosphomonoestrase activity for Runs 13, 14, 15, and 16

## 4.11 C/N ratio

The Day 2 and final value of C/N ratio, total carbon, and total nitrogen of sixteen runs are presented in table 4.1. In all runs the C/N ratio decreased except for run 1, 2 and 6. On run 9 and 12 there was a slight decrease but the decrease at run 11 and 14 were dramatic. Carbon content has been increased on runs 1, 2, 8, 9, 10, 11, 12, 13, 14, and 15. The high OUR, temperature, and GI results show that large amounts of carbon were decomposed via microbial respiration to carbon dioxide ($CO_2$). Residual organic matter, such as celluloses and lignin, which resists degradation, may have been responsible for the increase in carbon content within the compost materials.

Table 4.1. Initial and final value of C/N ratio, total carbon, and total nitrogen in 16 runs

| Run | C/N-Design | C/N –Day 2 | C/N Final | TC-Day 2 | TN-Day 2 | TC Final | TN-final |
|---|---|---|---|---|---|---|---|
| **1** | 12 | 12.58 | 13.1 | 45.4 | 3.61 | 46.1 | 3.52 |
| **2** | 12 | 10.8 | 15.24 | 44.8 | 4.15 | 45.1 | 2.96 |
| **3** | 12 | 9.91 | 9.45 | 46.2 | 4.66 | 45.9 | 4.96 |
| **4** | 17 | 16.36 | 11.46 | 42.7 | 2.61 | 42.3 | 3.69 |
| **5** | 17 | 20.57 | 17.1 | 43.2 | 2.1 | 41.9 | 2.45 |
| **6** | 12 | 10.96 | 11.82 | 48.1 | 4.39 | 48.6 | 4.11 |
| **7** | 17 | 15.3 | 11.88 | 43.6 | 2.85 | 43.6 | 3.67 |
| **8** | 17 | 16.88 | 11.45 | 42.7 | 2.53 | 44.2 | 3.86 |
| **9** | 17 | 15.12 | 11.83 | 42.5 | 2.81 | 46 | 4.63 |
| **10** | 12 | 17.62 | 12.9 | 46 | 2.6 | 46.3 | 3.59 |
| **11** | 17 | 18.4 | 12.56 | 42.5 | 2.31 | 43.7 | 3.48 |
| **12** | 12 | 12.35 | 12.28 | 44.6 | 3.61 | 47.4 | 3.86 |
| **13** | 17 | 15.02 | 11.39 | 42.5 | 2.83 | 43.4 | 3.81 |
| **14** | 12 | 18.33 | 9.34 | 42.7 | 2.33 | 46.5 | 4.98 |
| **15** | 12 | 13.09 | 10.97 | 44.9 | 3.43 | 46.3 | 4.22 |
| **16** | 17 | 17.64 | 13.72 | 44.1 | 2.5 | 43.9 | 3.2 |

## 4.12 Quality control analysis

Statistical quality control (QC) charts are a simple but powerful tool for monitoring the stability of an analytical procedure (Mullins, 1994, Prichard and Barwick, 2007). Monitoring performance indicators through control charts enables the identification of trends. The laboratory can then addresses analytical problems and help improve the analytical process (González and Herrador, 2007). Conceptually, a standard material is measured regularly and the analytical responses are plotted in time order on a chart; if the chart displays other than random variation around the expected result it suggests that something has gone wrong with the measurement process (Mullins, 1994). The applicability of control chart techniques is based on the assumption that laboratory data approximate a normal distribution (González and Herrador, 2007).

For control chart, the CL (central line) is the average of the measurements considered to be in control. The control limits (UCL and LCL) and warning limits (UWL and LWL) are usually placed three and two times of standard deviation above and below central line, respectively. The average ($\bar{X}$) and standard deviation (S) for X individual measurements can be calculated through the following formula:

$$\bar{X} = \frac{\sum X_i}{n}, \quad S = \sqrt{\frac{\sum (X_i - \bar{X}}{n-1}} \qquad (4.1)$$

Where X is the individual measurement and n is the number of measurements.

If any of the following occur means there is a problem in the measuring or analysing system and an action is required: point falls outside of the control limits; seven points place above or below the central line continuously; eight consecutive points go upward or downward; or any other non-random pattern is observed (Prichard and Barwick, 2007). If the data are normally distributed, 95.5% of the data are within $\bar{X}$± 2S and 99.7% of the data are within $\bar{X}$± 3S (Mullins, 1994). Statistically only three out of 1000 measurements are thus located outside the action limits. If the control value is outside the action limits, there is a high probability that the analysis is in error (Hovind et al., 2005).

In order to control the quality of the data for enzyme activities, 10% of the samples were replicated for dehydrogenase, β-glucosidase, and phosphomonoestrase activities. Quality control charts for three enzymes are presented in Figures 4.37 to 4.39.

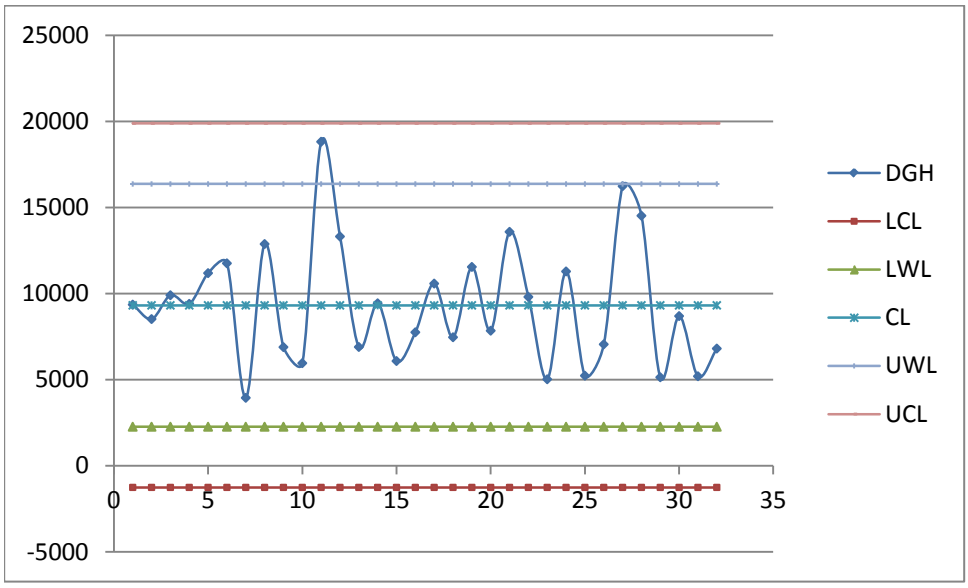



Figure 4.37. Quality control chart for dehydrogenase activity

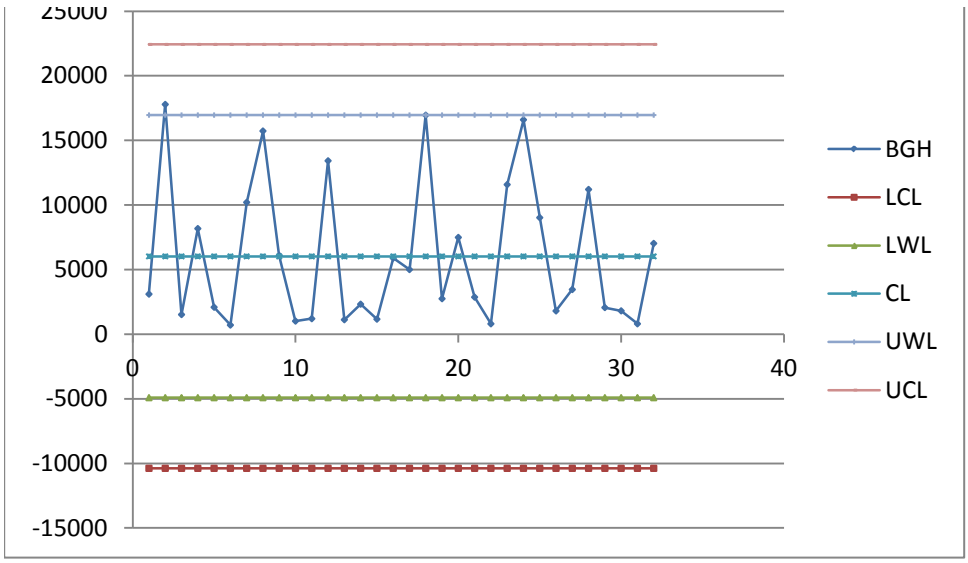



Figure 4.38. Quality control chart for β-glucosidase

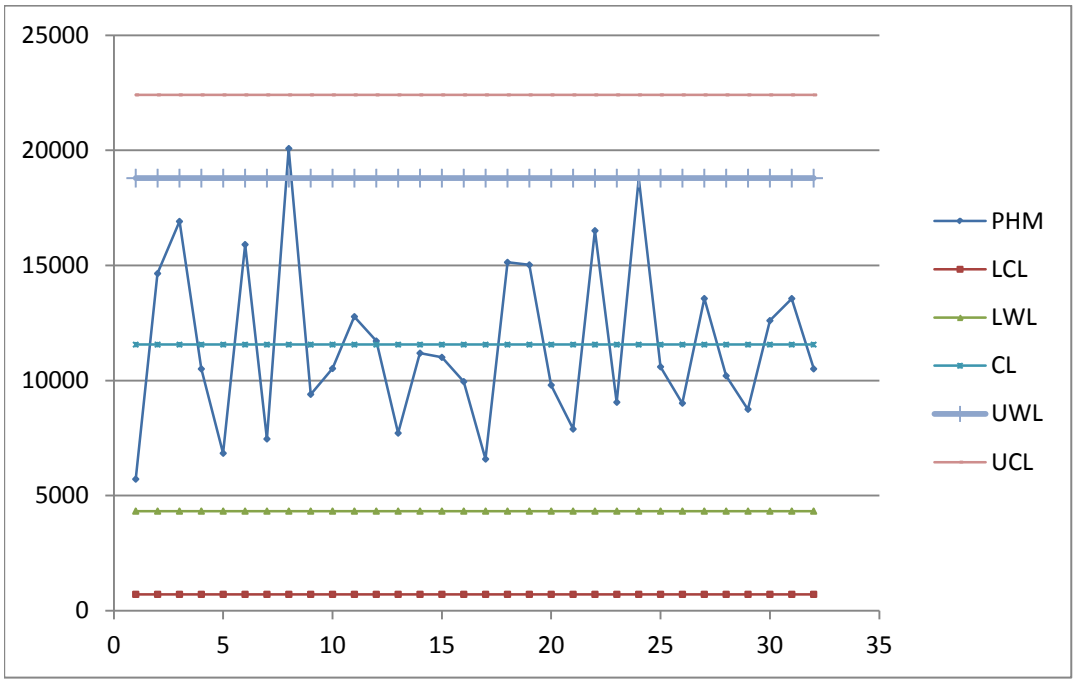



Figure 4.39. Quality control chart for phosphomonoestrase activity

All the data for enzyme activities meets the requirements and they do not violate the rules of the control charts for quality control. The distribution of the data are normal, only one point in each hart falls out of the warning area which means 96.87% of the data are between warning limits and 99.7% of the data are between control lines. Also, data are following random pattern, they are not continuously going upward or downward.

# 5 Statistical Analysis

## 5.1 Maximum temperature

(1) Factor Effect Estimates, Contrasts, and Sums of Squares

According to the experimental design, factor A, B, C, and D represent aeration rate, moisture content, bulking agents (peat and sawdust) and C/N ratio, respectively. Factor A, B, and D was considered quantitative or numeric with high and low values, and factor C has been considered as qualitative or categoric factor which can be peat or sawdust. The experimental design and maximum temperature as a response are shown in table 5.1.

Table 5.1. The $2^4$ factorial design

| Run | Aeration rate | Moisture content | Balking Agent | C/N ratio | Max. Temperature |
|---|---|---|---|---|---|
| **1** | 0.3 | 55 | Sawdust | 12 | 58 |
| **2** | 0.5 | 70 | Sawdust | 12 | 60 |
| **3** | 0.5 | 70 | Peat | 12 | 68 |
| **4** | 0.5 | 55 | Peat | 17 | 68 |
| **5** | 0.3 | 70 | Sawdust | 17 | 70 |
| **6** | 0.3 | 70 | Peat | 12 | 68 |
| **7** | 0.3 | 70 | Peat | 17 | 55 |
| **8** | 0.5 | 55 | Sawdust | 17 | 58 |
| **9** | 0.5 | 70 | Peat | 17 | 68 |
| **10** | 0.5 | 55 | Sawdust | 12 | 68 |
| **11** | 0.5 | 70 | Sawdust | 17 | 52 |
| **12** | 0.3 | 70 | Sawdust | 12 | 67 |
| **13** | 0.3 | 55 | Peat | 17 | 66 |
| **14** | 0.5 | 55 | Peat | 12 | 67 |
| **15** | 0.3 | 55 | Peat | 12 | 69 |
| **16** | 0.3 | 55 | Sawdust | 17 | 55 |

The minus and plus sign for the contrast constants of the $2^4$ fractional factorial design are shown in Table 5.2. From the definition of effect estimates explained in chapter 2, the effect is the difference between the average responses at high and low levels and could be estimated as follows:

Table 5.2. Contrast constants for the $2^4$ design

| Treatment | A | B | AB | C | AC | BC | ABC | D | AD | BD | ABD | CD | ACD | BCD | ABCD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | - | - | + | - | + | + | - | - | + | + | - | + | - | - | + |
| **a** | + | - | - | - | - | + | + | - | - | + | + | + | + | - | - |
| **b** | - | + | - | - | + | - | + | - | + | - | + | + | - | + | - |
| **ab** | + | + | + | - | - | - | - | - | - | - | - | + | + | + | + |
| **c** | - | - | + | + | - | - | + | - | + | + | - | - | + | + | - |
| **ac** | + | - | - | + | + | - | - | - | - | + | + | - | - | + | + |
| **bc** | - | + | - | + | - | + | - | - | + | - | + | - | + | - | + |
| **abc** | + | + | + | + | + | + | + | - | - | - | - | - | - | - | - |
| **d** | - | - | + | - | + | + | - | + | - | - | + | - | + | + | - |
| **ad** | + | - | - | - | - | + | + | + | + | - | - | - | - | + | + |
| **bd** | - | + | - | - | + | - | + | + | - | + | - | - | + | - | + |
| **abd** | + | + | + | - | - | - | - | + | + | + | + | - | - | - | - |
| **cd** | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + |
| **acd** | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - |
| **bcd** | - | + | - | + | - | + | - | + | - | + | - | + | - | + | - |
| **abcd** | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |

$$l_A = \frac{1}{8}\,[\,-58+60-68+68-70+68-55+58-68+68-52+67-66+67-69+55] = 5 \qquad (5.1)$$

$$l_B = \frac{1}{8}\,[\,-58-60+68+68-70-68+55+58-68-68+52+67-66-67+69+55] = -33 \qquad (5.2)$$

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$$l_{AB} = \frac{1}{8}\,[\,+58-60-68+68+70-68-55+58+68-68-52+67+66-67-69+55] = 3 \qquad (5.3)$$

Table 5.3 shows the estimates of the effects and the sums of the squares. The negative effect estimates shown in Table 5.3 means that an increase in those factors were resulted in a decrease in the maximum temperature. Conversely, when the effect estimates are positive, an increase in

factors level led to increase maximum temperature. Therefore, for the main effect estimates, factors B and D, with negative signs imply that increasing the moisture content and C/N ratio in the compost materials would decrease the maximum temperature by 0.125 and 4.125. In contrary, for the main effect of factor A, the aeration rate increase from 0.3 l/ min·kg to 0.5 l/min·kg would increase the maximum temperature by 0.125.

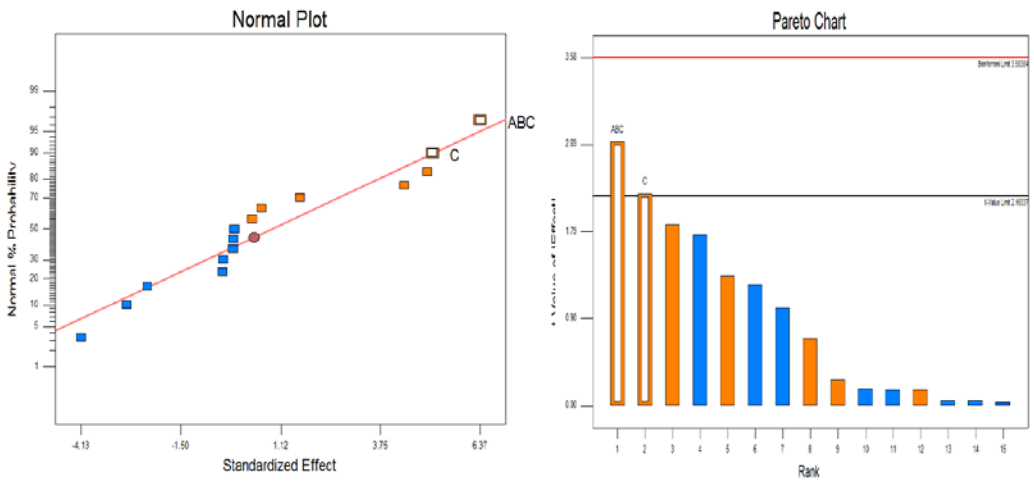
The percentage contributions are a rough but effective guide to the relative importance of each term, computed from a proportion of the sum of squares of each term to the total sum of squares of all terms (SS term/SS Σ terms) as percentage. Based on this, the main effects of C and the interaction effect of ABC are likely to have important impacts on the maximum temperature. Each term accounts for almost 20.0% of the total variability. For better evaluation of each factor and its interaction, a normal probability plot and a Pareto chart were made to discern the significant effects.

Table 5.3. Factor-effect estimates and sums of squares for maximum temperature

| Model term | Effects estimate | Sums of squares (SS) | Percent contribution |
|---|---|---|---|
| **A-Aeration** | 0.125 | 0.0625 | 0.011 |
| **B-Moisture** | -0.125 | 0.0625 | 0.011 |
| **C-BA** | 5.125 | 105.0625 | 18.966 |
| **D-C/N** | -4.125 | 68.0625 | 12.287 |
| **AB** | -3.125 | 39.0625 | 7.052 |
| **AC** | 3.125 | 39.0625 | 7.052 |
| **AD** | -0.125 | 0.0625 | 0.011 |
| **BC** | -2.625 | 27.5625 | 4.976 |
| **BD** | -0.375 | 0.5625 | 0.102 |
| **CD** | 0.375 | 0.5625 | 0.102 |
| **ABC** | 6.375 | 162.5625 | 29.347 |
| **ABD** | 0.625 | 1.5625 | 0.282 |
| **ACD** | 4.375 | 76.5625 | 13.822 |
| **BCD** | -2.375 | 22.5625 | 4.073 |
| **ABCD** | 1.625 | 10.5625 | 1.907 |

(2) Normal Probability Plot and Pareto Chart

In the normal probability plot, significant effects lie far from the line whereas all negligible effects lie along the line. In the Pareto chart, all the main and interaction effects of factors are presented as absolute values. There are two different t limits plotted on the Pareto chart - based on the Bonferroni corrected t-test and a standard t-test. The Bonferroni correction is an adjustment made to p-values when several dependent or independent statistical tests are being performed simultaneously on a single data set. To perform a Bonferroni correction, divide the critical p=value (α) by the number of comparisons being made. After selecting the effects which are obviously larger than the others: if the effect estimates are now above the Bonferroni Limit, they are almost certainly significant, if effects are now above the T-Value Limit, They are possibly significant and effects that are now below the T-Value Limit are not likely to be significant. Normal probability plot and Pareto chart of the effects for maximum temperature is presented in Figure 5.1.




(a) (b)

Figure 5.1. (a) Normal probability plot and (b) Pareto chart of the effects for maximum temperature

For maximum temperature, the significant factor is three order interaction ABC. The model in ANOVA can follow the hierarchy principle which means non-significant lower order terms have been included in a model because they were factors involved in significant higher order terms. Since three order interaction is significant factor, all the two order interactions and main effects can be included in the model, thus main factor A (aeration rate), B (Moisture content), C (Balking agent), and interactions AB, AC also are included in the hierarchal model and a non-hierarchical model consisting of terms: C and ABC, have to be developed.

(3) Analysis of variance

Analysis of variance (ANOVA) is employed to test whether the assumption that “main effects A, B, C and interactions AB, BC, AC, and ABC have the most significant influences on the

response while the others are not" can be supported by the experimental data. Results of the ANOVA for seven selected terms A, B, C, AB, AC, BC and ABC are summarized in Table 5.4. In this full hierarchical model, each term has one degree of freedom, and the total error has eight degrees of freedom. It is possible to the hypothesis when $\alpha = 0.05$ by the *F* distribution.

$$H_0: \beta_1 = \beta_2 = \beta_3 = \beta_{12} = \beta_{13} = \beta_{23} = \beta_{123} = 0$$

$$H_1: \text{at least one } \beta \neq 0 \qquad (5.4)$$

Where $\beta_1$, $\beta_2$, $\beta_3$, $\beta_{12}$, $\beta_{13}$, $\beta_{23}$, and $\beta_{123}$ represent A, B , C, AB, BC, BD and ABC, respectively. The critical F ratio with a 95% significance level for 1 and 8 degrees of freedom is $F_{0.05,1,8} = 5.32$. It is seen from Table 5.4 that *F* ratio of interaction effect ABC is higher than the critical F-value and it has *p*-value less than 0.05. Thus, we can conclude that interaction ABC has highly significant effects on maximum temperature during the food-waste composting processes in this design.

Table 5.4. Analysis of variance for maximum temperature in a hierarchal model

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 373.4375 | 7 | 53.348 | 2.36 | 0.1255 |
| **A-Aeration** | 0.0625 | 1 | 0.063 | 0.00 | 0.9593 |
| **B-Moisture** | 0.0625 | 1 | 0.0625 | 0.0028 | 0.9593 |
| **C-BA** | 105.0625 | 1 | 105.0625 | 4.6565 | 0.0630 |
| **AB** | 39.0625 | 1 | 39.0625 | 1.7313 | 0.2247 |
| **AC** | 39.0625 | 1 | 39.0625 | 1.7313 | 0.2247 |
| **BC** | 27.5625 | 1 | 27.5625 | 1.2216 | 0.3012 |
| **ABC** | 162.5625 | 1 | 162.5625 | 7.205 | 0.0277 |
| **Residual** | 180.5 | 8 | 22.5625 | | |
| **Cor Total** | 553.9375 | 15 | | | |

Table 5.5. Analysis of variance for maximum temperature in a non-hierarchal model

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 267.63 | 2.00 | 133.81 | 6.08 | 0.0137 |
| **C-BA** | 105.06 | 1.00 | 105.06 | 4.77 | 0.0479 |
| **ABC** | 162.56 | 1.00 | 162.56 | 7.38 | 0.0176 |
| **Residual** | 286.31 | 13.00 | 22.02 | | |
| **Cor Total** | 553.94 | 15.00 | | | |

The non-hierarchical regression model composed of terms C and ABC was developed to analyze the model variability (Table 5.5). The other insignificant terms, such as A, B, AB, AC, and BC, were neglected and computed as lack of fit error in this non- hierarchical model analysis. In Table 5.5, each term has one degree of freedom, and the total error has thirteen degrees of freedom. The critical F-distribution, $F_{0.05,1,13} = 4.67$, is used to test the hypotheses when $\alpha = 0.05$:

$$H_0: \beta_3 = \beta_{123} = 0$$

$$H_1: \text{at least one } \beta \neq 0 \quad (5.5)$$

Where $\beta_3$, and $\beta_{123}$ represent C and ABC, respectively.

Compared to $F_0$, terms C and ABC are confirmed to have significant effects, as in the results analyzed previously in Table 5.5.

Based on the regression statistics, the proportion of total variability ($R^2 = 0.4831$) and adjusted R-square ($R^2_{adjusted} = 0.4036$) in the non-hierarchical model are smaller than in the hierarchical model ($R^2 = 0.6742$ and $R^2_{adjusted} = 0.3890$). The standard deviation for the non-hierarchical model (S.D. = 4.69) and the hierarchical model (S.D. = 4.75) are almost the same. Although the hierarchical model has a desirable R2 to explain larger data variability, the predicted error sum of squares in the non-hierarchical model (PRESS = 433.7) is considerably smaller than in the

hierarchical model (PRESS = 722), indicating that the non- hierarchical model is likely to be a good predictor with a smaller error when predicting the data. Since the smaller PRESS leads to a larger $R^2_{prediction}$, the non-hierarchical model would explain 21.7% of variability in new data, while the hierarchical model with a smaller $R^2_{prediction}$ would explain only -30.34 % of variability. From these regression statistics, dropping insignificant terms, such as A, B, AC, AC and BC, in the non-hierarchical model are likely to be more effective as a predictor of new data than the hierarchical model.

(4) Fitted and Refined Regression Model

Since the non-hierarchical model is a good predictor, it was chosen as a fitted model to predict the maximum temperature in Equation (5.6):

$$\text{Max Temp.} = +63.56+2.56\ C +3.19ABC \qquad (5.6)$$

Where +63.56 is the grand average of all sixteen observations in response; and 2.56 and 3.19 are half of the corresponding effect estimates of C and ABC, respectively; C and ABC representing factors C (bulking agent), and ABC (the interaction of aeration rate, moisture content and bulking agent), respectively.

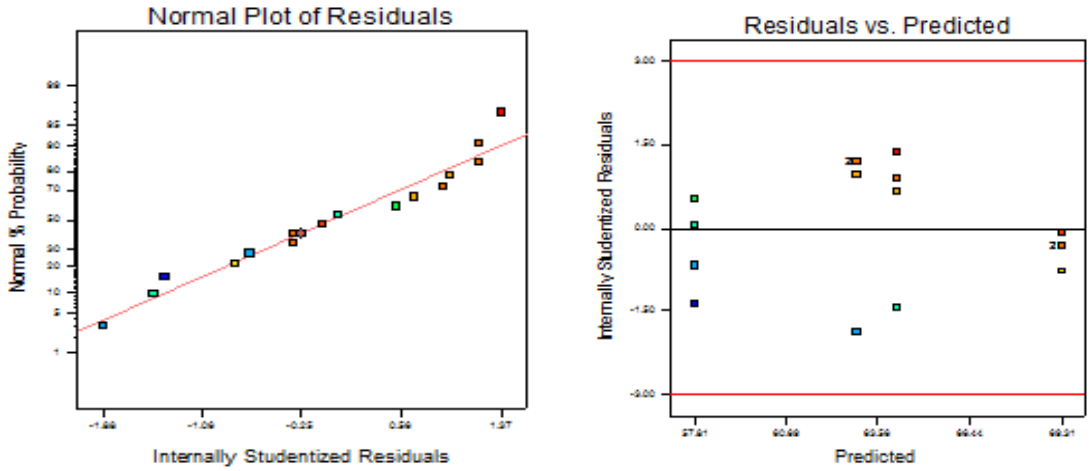
(5) Residuals and Model Adequacy Checking

To validate the adequacy of the developed model the residual analysis is a primary diagnostic tool. The regression model can be used to obtain the predicted or fitted value of y at the points in the design. The residuals are the differences between the observed and fitted values of y.

$$e_i = y_i - \hat{y}_i \qquad (5.7)$$

Where $y_i$ is the experimental response, and $\hat{y}_i$ is the predicted response. If the normality assumption is valid, the residual should be nothing but the experimental errors. These errors can be expected to be in normal distribution, and the standardized residuals should be approximately normal with mean zero and unit variance.

A normal probability plot of residuals for maximum temperature is shown in Figure 5.2(a). The points on this plot lie significantly close to the straight line, demonstrating that C and ABC are significant effects on maximum temperature. Figure 5.2(b) displays plot of residuals versus the fitted values reveals no obvious pattern or unusual structure. Therefore, the model is adequate and the assumption of normality is satisfied.




(a) (b)

Figure 5.2. (a) Normal probability plot of residuals and (b) residual plot of residuals versus fitted values for the response of maximum temperature

(6) Result Interpretations

Figure 5.3 shows the plot of the main effects, C for maximum temperature obtained from the fitted regression model. When peat is the bulking agent, the predicted maximum temperature is 66.1. While for the sawdust it is 61. Higher temperature is expected at the runs with peat.

Figure 5.4(a) and 5.5(a), show response surface plots for the maximum temperature when peat and sawdust are bulking agents, respectively. Response surface plot for both of bulking agent twisted at mid- point of main factors When bulking agent is sawdust, At low aeration rate, high moisture content shows more positive effect on maximum temperature whereas at high aeration rate, low moisture content effect maximum temperature more positively. Figure 5.4b presents contour plot of maximum temperature with sawdust implies that if the bulking agent is sawdust to keep the temperature as high as possible, either low level aeration rate (0.3 l/min·kg), and high level moisture content (70%) or high level aeration rate (0.5 l/min·kg) with low level moisture (55%) would give the desire result. In the case of peat as a bulking agent, the result is completely different than sawdust. For peat, According to the response surface plot (5.5a) and contour plot (5.5b), either high moisture content with high aeration rate or low aeration rate with low moisture content leads to the possible maximum temperature.

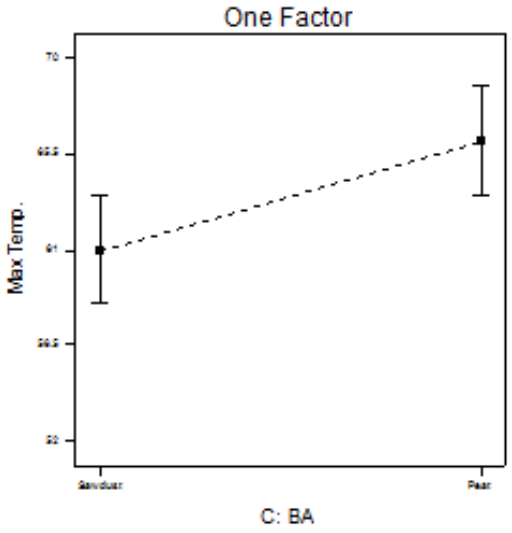
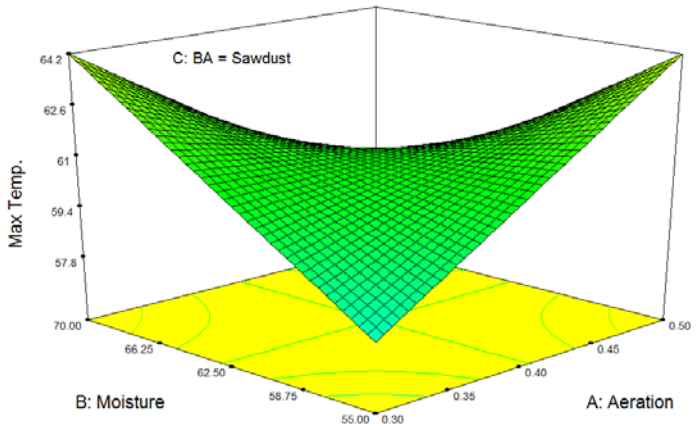



Figure 5.3. Main effect plot of maximum temperature




(a)

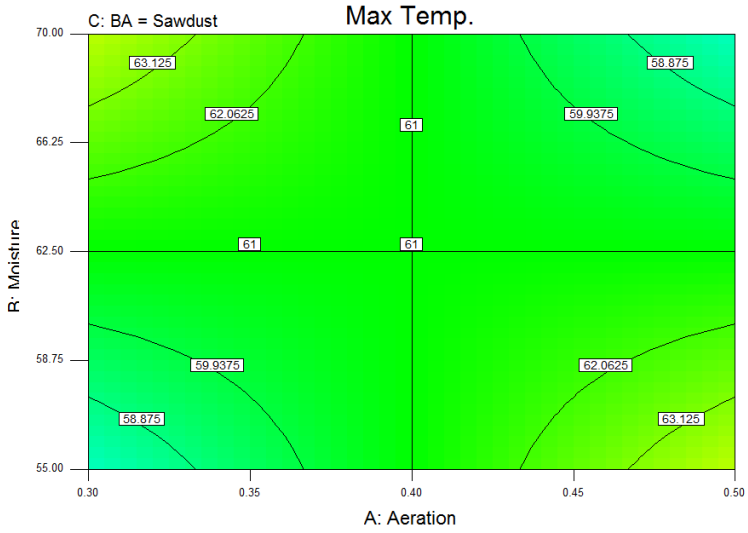
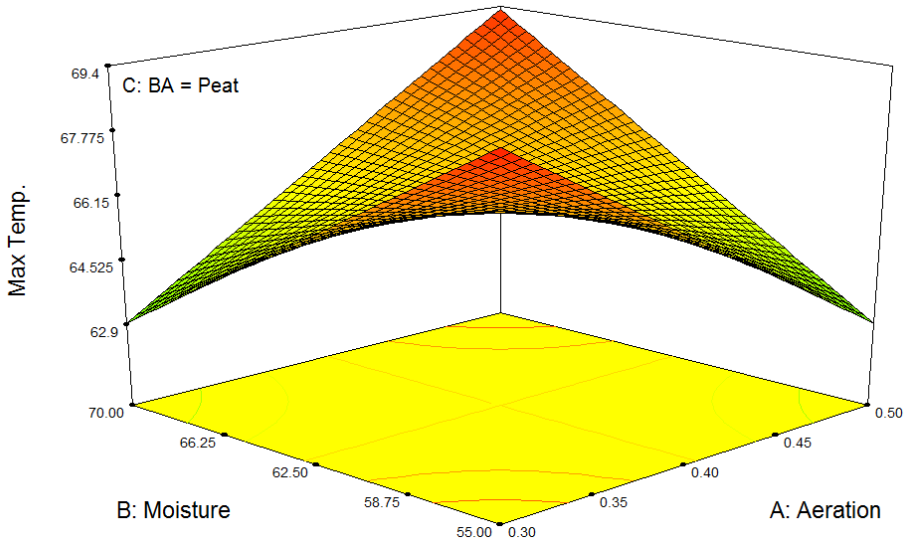



Figure 5.4. (a) Response surface plot and (b) contour plot of maximum temperature when peat is the bulking agent




(a)

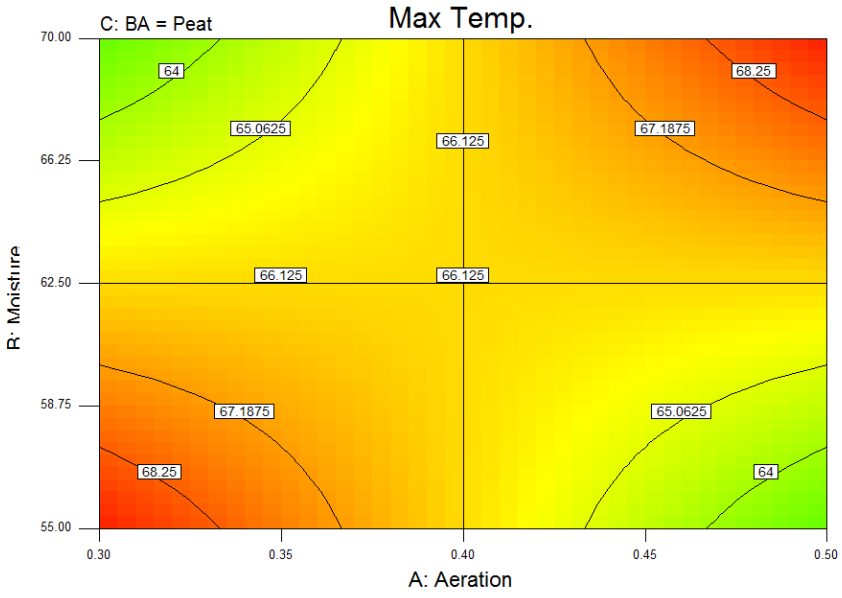



Figure 5.5. (a) Response surface plot and (b) contour plot of maximum temperature when sawdust is the bulking agent

The factorial effects on maximum temperature can be summarized as follows: (1) C/N ratio is not critical in tested range. Aeration rates and moisture content are not critical in terms of their effect but they are involved in interaction which is critical on maximum temperature. Main factor bulking agent and Interaction of aeration rate, moisture content and bulking agent are the most significant factor affecting maximum temperature.

## 5.2 Maximum OUR

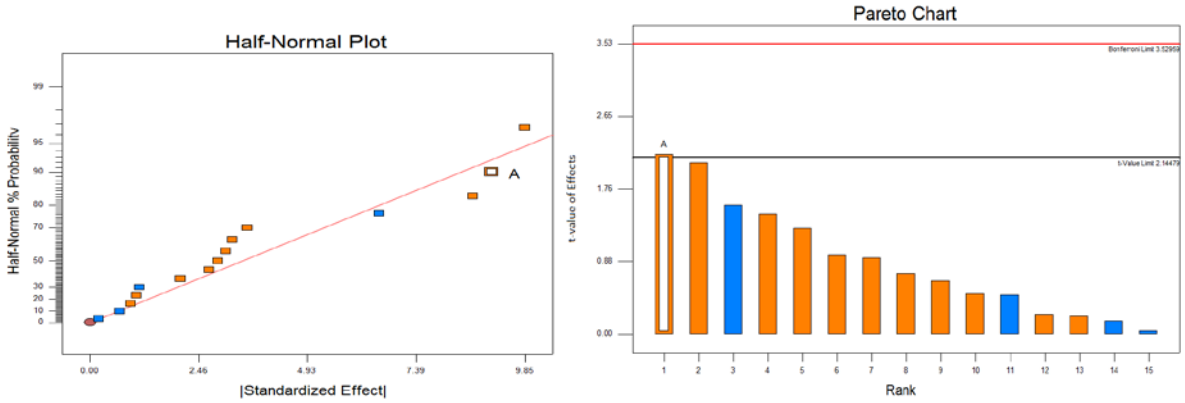
(1) Factor Effect Estimates, Contrasts, and Sums of Squares

The maximum OUR measured from the sixteen runs are 39, 53.5, 52, 38, 42, 49.8, 35.8, 49.5, 62, 48, 30.5, 42, 36, 49, 39, and 26.1, respectively. Using the plus and minus signs method, the factorial effects on maximum OUR can be estimated (Table 5.6). The estimates of the effects and the sums of the squares are shown in table 5.6. A normal probability plot and Pareto chart of effects are shown in Figure 5.6(a) and 5.6 (b). Based on these plots, factors A (aeration rate) is one of the factors far away from the reference line. Since in Pareto chart only factor A is above the t-values limits and it contributes a high percentage of total variability (25.43%). Thus, the effect aeration rate is more significant than the other factors.

Table 5.6. Factor-effect estimates and sums of squares for maximum OUR

| Model term | Effects estimate | Sums of squares (SS) | Percent contribution |
|---|---|---|---|
| **A-Aeration** | 9.1 | 331.240 | 25.43 |
| **B-Moisture** | 1.050399 | 115.563 | 8.87 |
| **C-BA** | 2.891782 | 60.063 | 4.61 |
| **D-C/N** | -6.55 | 171.610 | 13.18 |
| **AB** | -1.11989 | 16.000 | 1.23 |
| **AC** | 3.223 | 4.000 | 0.31 |
| **AD** | 0.925 | 3.423 | 0.26 |
| **BC** | 3.558849 | 64.803 | 4.98 |
| **BD** | -0.2 | 0.160 | 0.01 |
| **CD** | 2.05 | 16.810 | 1.29 |

| | | | |
|---|---|---|---|
| **ABC** | 9.851979 | 148.840 | 11.43 |
| **ABD** | -0.675 | 1.823 | 0.14 |
| **ACD** | 3.075 | 37.823 | 2.90 |
| **BCD** | 2.7 | 29.160 | 2.24 |
| **ABCD** | 8.675 | 301.023 | 23.11 |




(a) (b)

Figure 5.6. (a) Normal probability plot and (b) Pareto chart of the effects for maximum OUR

(2) Analysis of variance

ANOVA analysis for maximum OUR is shown in Table 5.7. Factor A as the only term in this table has 1 degree of freedom and total error has 14 degree of freedom. The F value is less than the critical value and the p-value of factor A is less than 0.05. Therefore it has a significant effect. The main effect plot of factor A on maximum OUR is demonstrated in Figure 5.7. By increasing aeration rate from low level to high level maximum OUR increases.

Table 5.7. Analysis of variance for maximum OUR

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 331.24 | 1 | 331.240 | 4.78 | 0.0464 |
| **A-Aeration** | 331.24 | 1 | 331.240 | 4.78 | 0.0464 |

| | | | |
|---|---|---|---|
| **Residual** | 971.0975 | 14 | 69.364 |
| **Cor Total** | 1302.3375 | 15 | |

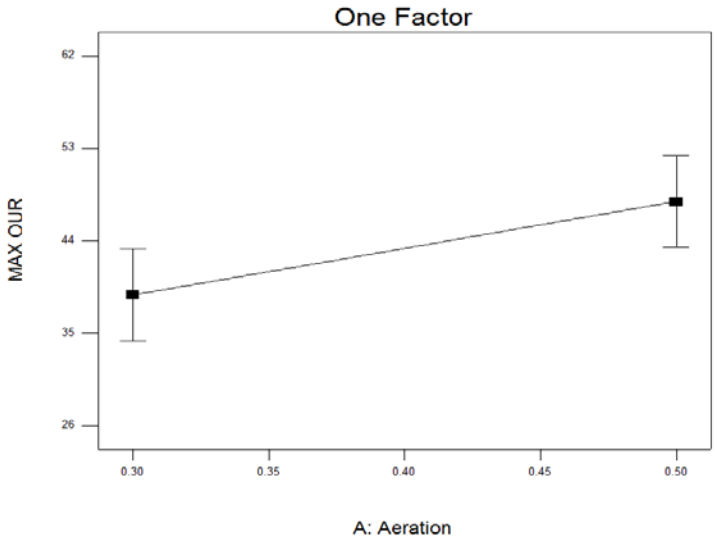



Figure 5.7. Main effect plot for maximum OUR

(3) Fitted Regression Model

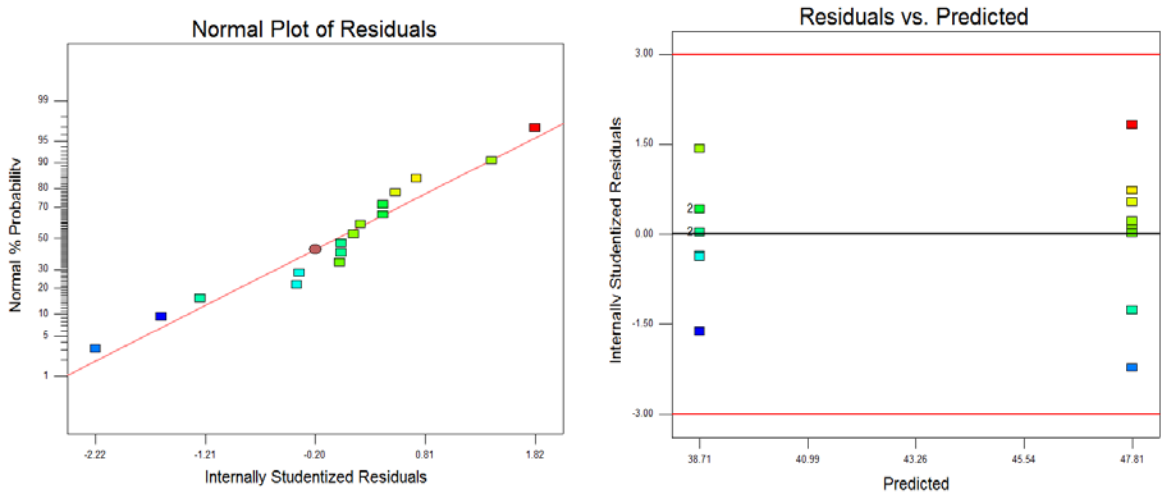
According to the above analysis, main effects A (Aeration rate) is a significant factor and can be used to develop a response surface model. The resulting regression model for predicting maximum OUR is:

$$\text{MAX OUR} = +43.26 + 4.55A \qquad (5.8)$$

Where A represented the main factor, aeration rate.

(4) Residuals and Model Adequacy Checking

To validate the model, normal probability plot of the residual and the residual vs. predicted plot presented in Figure 5.8(a) and 5.8(b). The points on this plot lie significantly close to the straight line; also residual vs. fitted value plot shows a scattered pattern indicating that A is a significant effect and that the fitting regression model is adequate.




(a) (b)

Figure 5.8. (a)Normal probability plot of residuals and (b) residual vs. predicted plot for maximum OUR

Based on the above analyses, aeration has the highest influence on maximum OUR and other factors do not affect maximum OUR significantly.

## 5.3 GI

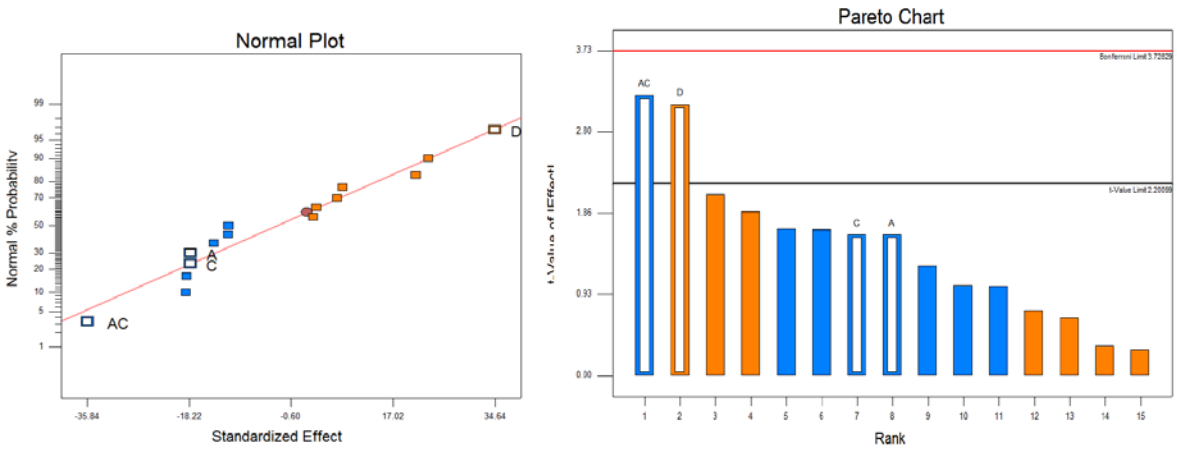
(1) Factor Effect Estimates, Contrasts, and Sums of Squares

According to the plus and minus signs for the contrast constants of the $2^4$ factorial design, the effects on GI can be estimated (Table 5.8). A normal probability plot and Pareto chart of these effects is shown in Figure 5.9(a) and 5.9(b). Based on the plots and effects list, factor D (C/N ratio) and interaction AC have the highest influence on the GI with percent contribution of 26.66% and 28.54%, respectively.

To follow the hierarchy principle, main effect A (aeration rate) and C (bulking agent) are included in the hierarchal model. Therefore, the important factors affecting the GI are aeration rate, bulking agent and C/N ratio. Moreover, the effect from interaction of aeration rate and bulking agent is also significant. For non-hierarchal model the significant factors will be factor D and interaction AC.

Table 5.8. Factor-effect estimates and sums of squares for GI

| Model term | Effects estimate | Sums of squares (SS) | Percent contribution |
|---|---|---|---|
| **A-Aeration** | -2.15 | 1300.20 | 7.22 |
| **B-Moisture** | 99.86 | 555.79 | 3.09 |
| **C-BA** | -76.69 | 1301.13 | 7.23 |
| **D-C/N** | 149.56 | 4799.82 | 26.66 |
| **AB** | -49.66 | 11.58 | 0.06 |
| **AC** | -22.11 | 5138.27 | 28.54 |
| **AD** | 16.32 | 57.14 | 0.32 |
| **BC** | -80.70 | 12.76 | 0.07 |
| **BD** | 90.54 | 1758.99 | 9.77 |
| **CD** | -60.29 | 780.09 | 4.33 |
| **ABC** | 31.98 | 35.44 | 0.20 |
| **ABD** | -49.30 | 521.59 | 2.90 |
| **ACD** | 14.12 | 42.76 | 0.24 |
| **BCD** | -81.12 | 1412.05 | 7.84 |
| **ABCD** | 35.93 | 277.02 | 1.54 |




(a) (b)

Figure 5.9. (a) Normal probability plot and (b) Pareto chart of the effects for GI

(2) ANOVA analysis

The ANOVA table with four selected terms in hierarchal model is shown in Table 5.9, each term has 1 degree of freedom and error has 11 degree of freedom. The F value of factor D and interaction AC are greater that the critical $F_{0.05,1,11} = 4.84$. The p-value of main effect D and interaction AC is less than 0.05 which indicates that these factors are significant.

For non-hierarchal model main factor D and interaction AC are included in the model. The ANOVA analysis in non-hierarchal model presented in Table 5.10 implies that each term has degree of freedom 1 and error has 13 degree of freedom thus the critical F value is $F_{0.05,1,13} = 4.67$. According to the Table 5.10, F value of factor D and interaction AC are higher than the critical value and their p-value is less than 0.05, consequently both of them are significant.

Table 5.9. Analysis of variance for GI in hierarchal model

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 12539.4244 | 4 | 3134.8561 | 6.3096 | 0.0069 |
| **A-** | 1300.1981 | 1 | 1300.1981 | 2.6169 | 0.1340 |

| | | | | | |
|---|---|---|---|---|---|
| **Aeration** | | | | | |
| **C-BA** | 1301.1319 | 1 | 1301.1319 | 2.6188 | 0.1339 |
| **D-C/N** | 4799.8232 | 1 | 4799.8232 | 9.6607 | 0.0100 |
| **AC** | 5138.2712 | 1 | 5138.2712 | 10.3419 | 0.0082 |
| **Residual** | 5465.2158 | 11 | 496.8378 | | |
| **Cor Total** | 18004.6402 | 15 | | | |

Table 5.10. Analysis of variance for GI in non-hierarchal model

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 9938.09 | 2 | 4969.047218 | 8.01 | 0.0054 |
| **D-C/N** | 4799.82 | 1 | 4799.823211 | 7.74 | 0.0156 |
| **AC** | 5138.27 | 1 | 5138.271225 | 8.28 | 0.0130 |
| **Residual** | 8066.55 | 13 | 620.5035206 | | |
| **Cor Total** | 18004.64 | 15 | | | |

Based on the regression statistics, the proportion of total variability ($R^2$ = 0.5520) and adjusted R-square ($R^2_{adjusted}$ = 0.4830) in the non-hierarchical model are smaller than in the hierarchical model ($R^2$ = 0.6965 and $R^2_{adjusted}$ = 0.5861). The standard deviation for the non-hierarchical model (S.D.= 24.91) and the hierarchical model (S.D.= 22.29) are close. The predicted error sum of squares in the non-hierarchical model (PRESS = 11562.73) is smaller than in the hierarchical model (PRESS = 12219.15), indicating that the non- hierarchical model is likely to be a good predictor with a smaller error when predicting the data. From the regression statistics, dropping insignificant terms, such as A and C in the non-hierarchical model is likely to be more effective as a predictor of new data than the hierarchical model.

(3) Response Surface Model

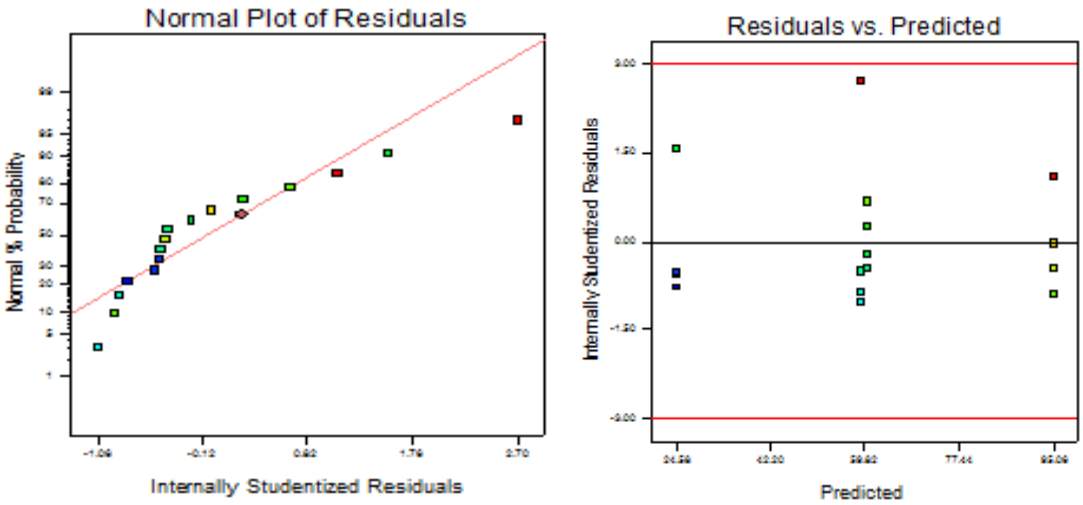
The above analyses indicated that the significant factors that effect on GI are main effect D (C/N ratio) and interaction effect AC. A regression model for predicting GI can be formulated as follows:

$$GI=+132.57+34.64D -17.92 AC \quad (5.9)$$

where D is C/N ratio and AC is interaction of aeration rate and bulking agent.

(4) Residuals and Model Adequacy Checking

Before the conclusions from the ANOVA are adopted, the adequacy of the model should be checked and the diagnostic tool for this purpose is residual analysis. The normal probability plot of the residual and residual vs. predicted plot are presented in Figure 5.10(a) and 5.10 (b), respectively. These plots appear satisfactory, and there is no reason to suspect problems with the validity of the model.

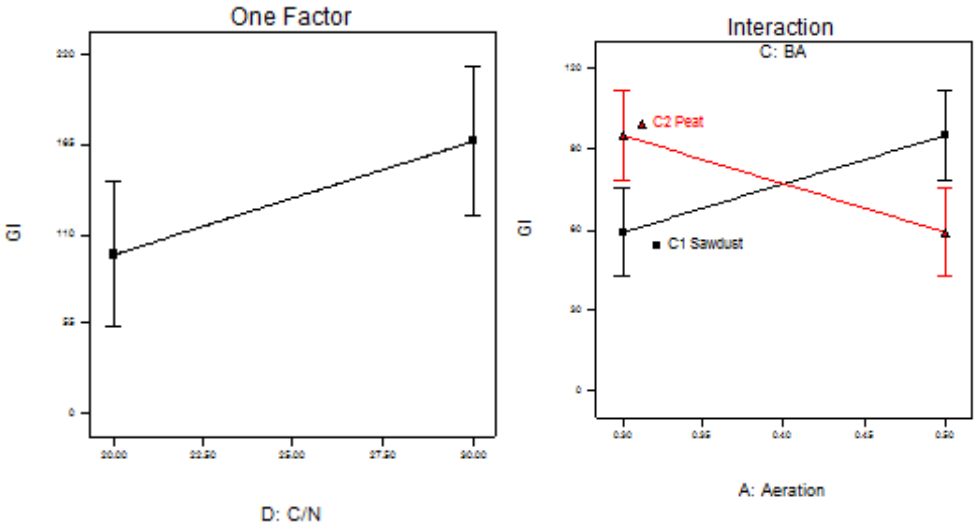



(a) (b)

Figure 5.10. (a) Normal probability plot of residuals and (b) residual vs. predicted for GI

(5) Result Interpretation

Figure 5.11a shows the main effect D plot. The increase of C/N ratio from low level to high level has positive effect on GI, implying that higher C/N ratio can lead to greater GI. As it is seen in Figure 5.11b, GI shows different results with different bulking agent at low and high level of aeration rate. For peat, lower aeration rate shows higher GI and for sawdust as aeration rate increases the GI increases. At higher aeration rate with peat as a bulking agent, GI results low values. The highest GI for peat could be obtained with high C/N ratio and low aeration rate and for sawdust with high C/N ratio and high aeration rate.

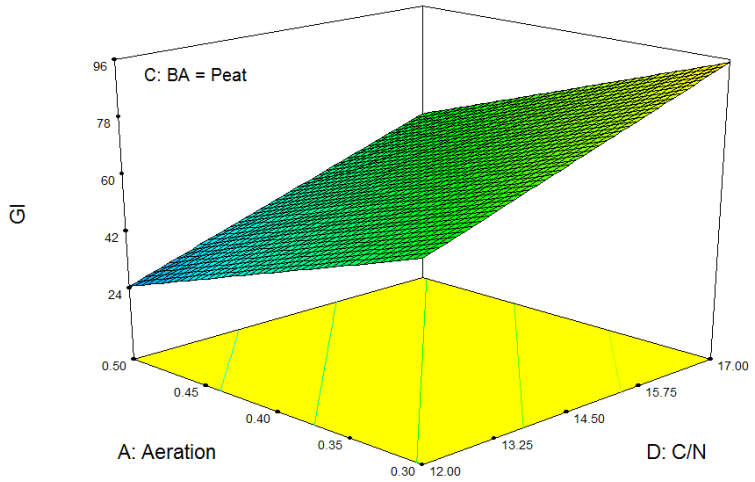



(a) Main effect plot (b) Interaction plot

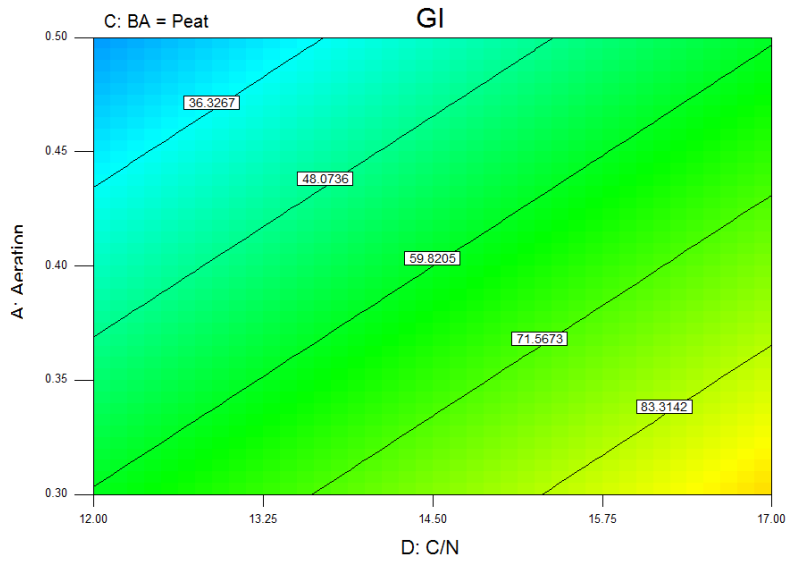
Figure 5.11. (a)Main-effect and (b) interaction plots for GI

A three dimensional plot of surface model and contour plot with peat for GI are shown in Figure 5.12(a) and 5.12(b) When bulking agent is peat high level of C/N ratio and low level of aeration rate improves GI. The increase of C/N ratio at high aeration ratio has negative effect GI. Based on the three dimensional plot of surface model and contour plot of GI with sawdust (Figure

5.13(a) and 5.13(b)), to obtain the highest GI with sawdust as a bulking agent aeration rate should be at high level while C/N ratio is at the high level. When balking agent is sawdust, both increase of C/N ratio and aeration rate influences GI postively.

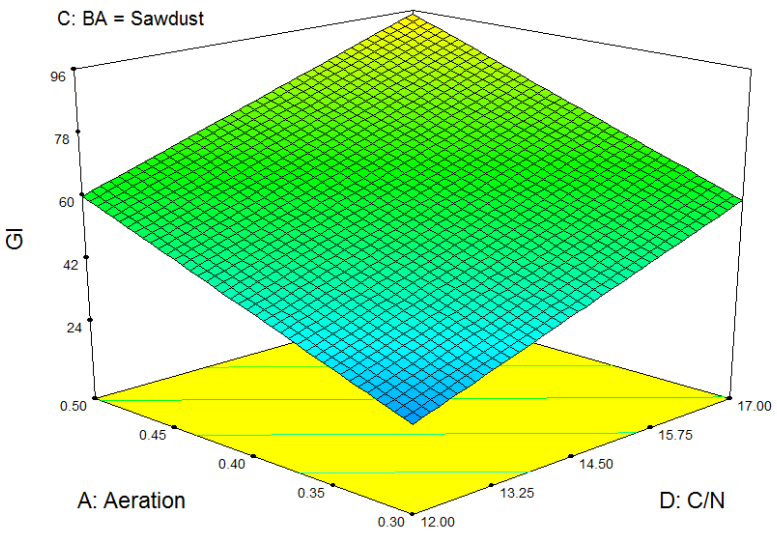



(a)

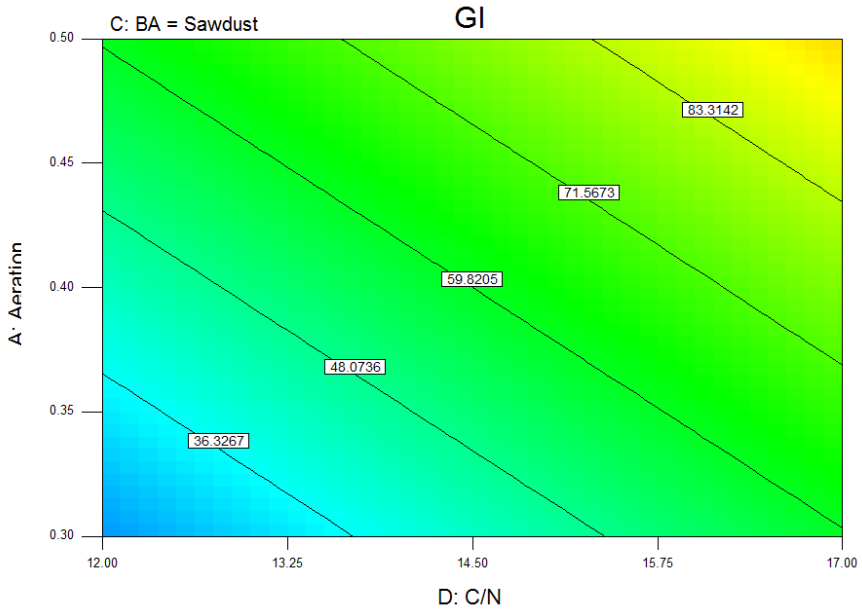



(b)

Figure 5.12. (a) Response surface plot and (b) contour plot of GI when bulking agent is peat




(a)




(b)

Figure 5.14. (a) Response surface plot and (b) contour plot of GI when bulking agent is sawdust

To summarize the factorial effect on GI, it can be concluded that moisture content does not have a significant effect on GI. Also, the individual effect of aeration rate and bulking agent are not critical, but their interaction has significant effect on GI. The only effective main effect on GI is C/N ratio.

## 5.4 Cumulative dehydrogenase activity (DGH)

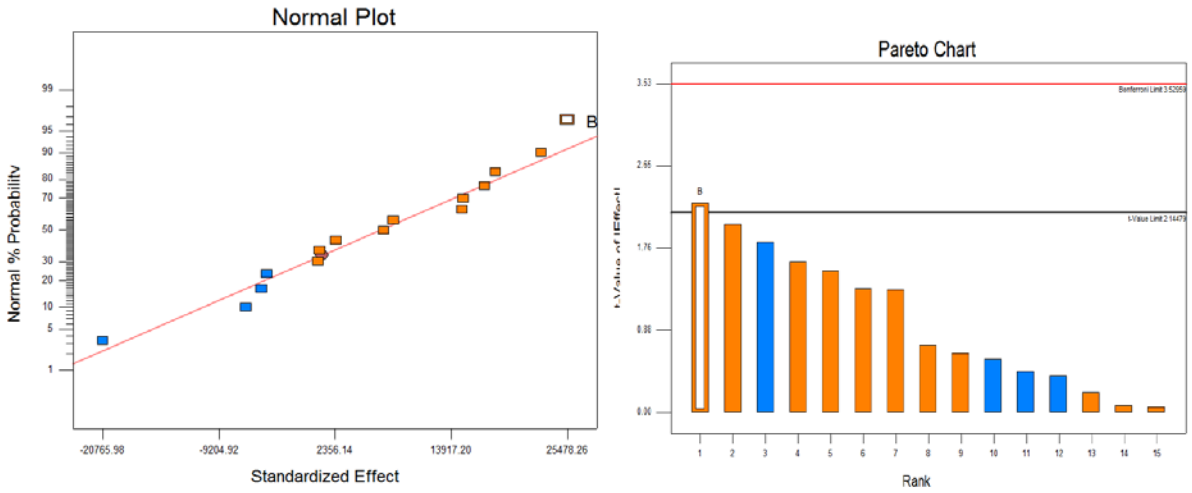
(1) Factor Effect Estimates, Contrasts, and Sums of Squares

The summary of effect estimates, contrasts, sums of squares, coefficients, and percentage contributions for each term are given in Table 5.11 for cumulative dehydrogenase activity. Most terms have positive effect estimates, and the terms B contribute a high percentage of total variability (26.49%) and are likely to have an important effect. However, this must be confirmed by a normal probability plot and a Pareto chart in the next step. The normal probability plot and Pareto chart of the effects are shown in Figures 5.14 (a) and 5.14 (b). Factor B is far from the straight line in normal probability plot when $\alpha = 0.5$ and it also exceed t-value limit in Pareto chart in this graphical analysis. Main factor B (moisture content) is selected as significant factor to continue ANOVA analysis.

Table 5.11. Factor effect estimates, contrasts, and sums of squares for the response of cumulative dehydrogenase activity

| Model term | Effects estimate | Sums of squares (SS) | Percent contribution |
|---|---|---|---|
| **A-Aeration** | 98893.50135 | 412127268.4 | 4.204868897 |
| **B-Moisture** | -61738.85888 | 2596567640 | 26.49236618 |
| **C-BA** | -19143.49383 | 272509271.7 | 2.780368708 |
| **D-C/N** | 3583.857592 | 2756230.738 | 0.028121383 |
| **AB** | 31050.53273 | 43024116.56 | 0.438968211 |
| **AC** | 79087.49826 | 178616506.2 | 1.822395772 |

| | | | |
|---|---|---|---|
| **AD** | 91223.76178 | 1785788565 | 18.22011638 |
| **BC** | 2905.103857 | 214323353.3 | 2.186707047 |
| **BD** | -89655.18624 | 1724903953 | 17.59892038 |
| **CD** | -28163.28765 | 170208320 | 1.736608387 |
| **ABC** | 64710.66623 | 5647780.575 | 0.057623406 |
| **ABD** | 35289.83551 | 267247315.6 | 2.726681807 |
| **ACD** | 74429.13382 | 1188775957 | 12.12889181 |
| **BCD** | 10510.82634 | 23707611.66 | 0.241884987 |
| **ABCD** | 65298.1162 | 914987978.4 | 9.335476651 |




(a) (b)

Figure 5.16. (a) Normal probability plot and (b) Pareto chart of the effects for cumulative dehydrogenase activity

(2) ANOVA analysis

Table 5.12 displays the ANOVA analysis for cumulative dehydrogenase activity. Model term has 1 degree of freedom and error has 14 degree of freedom, thus the critical $F_{0.05,1.14} = 4.60$. F-value of factor B is higher than the critical value and its p-value is less than 0.05. It can be concluded that factor A is a significant factor after model adequacy evaluation.

Table 5.12. Analysis of variance for the response of cumulative dehydrogenase activity

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 2596567640 | 1 | 2596567640 | 5.045640939 | 0.0413 |
| **B-Moisture** | 2596567640 | 1 | 2596567640 | 5.045640939 | 0.0413 |
| **Residual** | 7204624228 | 14 | 514616016.3 | | |
| **Cor Total** | 9801191868 | 15 | | | |

(3) Response surface model

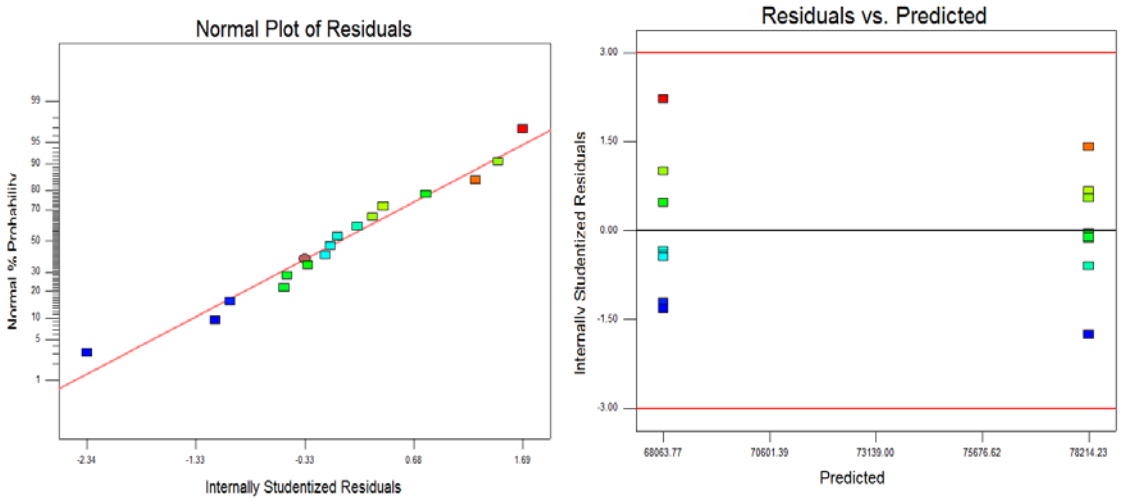
A fitted model to predict the cumulative dehydrogenase activity in food waste composting has been developed and formulated as following:

$$\text{Cumulative DGH} = +73139.00 + 12739.13\ B \qquad (5.10)$$

Where 73139 is the grand average of all sixteen observations in response; and 12739.13 is the half of the corresponding effect estimate B (moisture content).

(4) Model Adequacy Checking

To check the adequacy of the model residual analysis was done as a diagnostic check, the normal probability plot of residual (Figure 5.15(a)) is almost a straight line, indicating no abnormalities. The plot of residuals versus the fitted values (Figure 5.15(b)) reveals a scattered pattern. Therefore, the model is adequate and the assumptions of normality are satisfied.




(a) (b)

Figure 5.17. (a) Normal probability plot of residuals and (b) residual vs. predicted for cumulative dehydrogenase activity

(4) Result Interpretation

Figure 5.16 shows the plot of main factor B. When moisture content increases from low level, 55% to high level, 70% the cumulative dehydrogenase activity increases.

Figures 5.17(a) 5.17(b) show response surface plots and contour plots for cumulative dehydrogenase activity when aeration is at the middle point and bulking agent is peat. According to the plot, when moisture content increases the plane of the response surface is ascended and it has a constant increasing slope by moisture content. The contour lines of cumulative dehydrogenase activity are straight lines and shows direct relationship with moisture content.

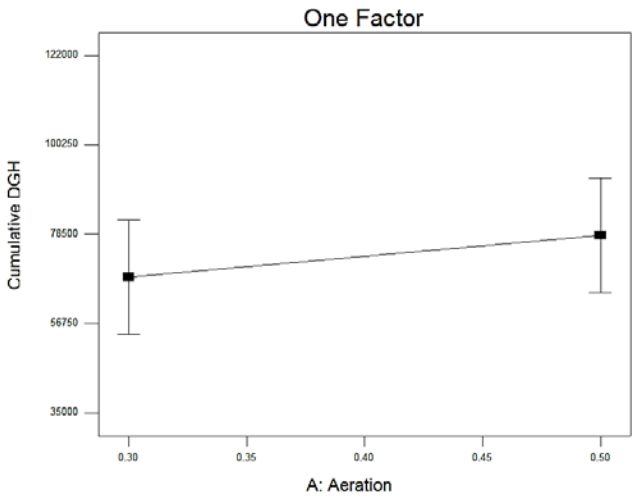
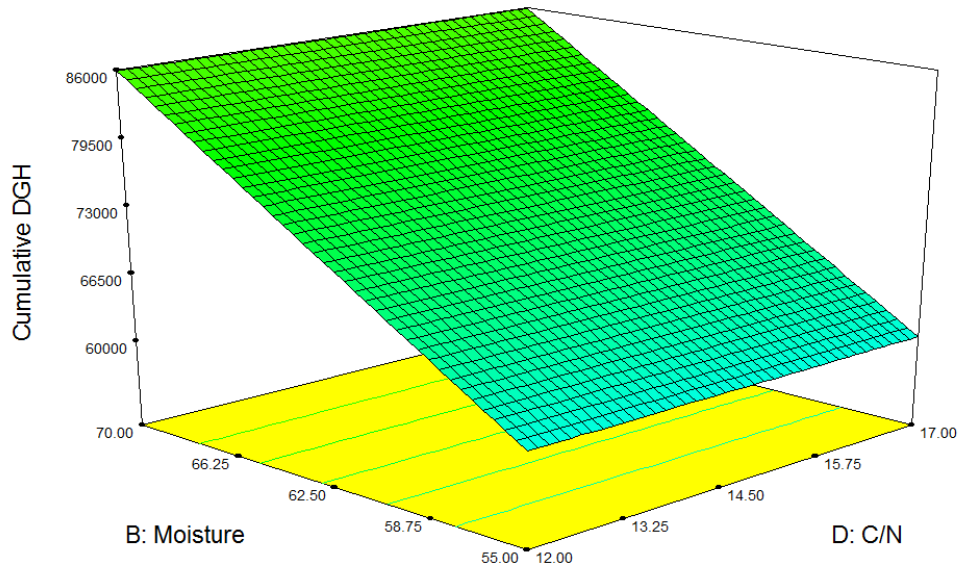



Figure 5.18. Main effect plot of cumulative dehydrogenase activity in moisture content




(a)

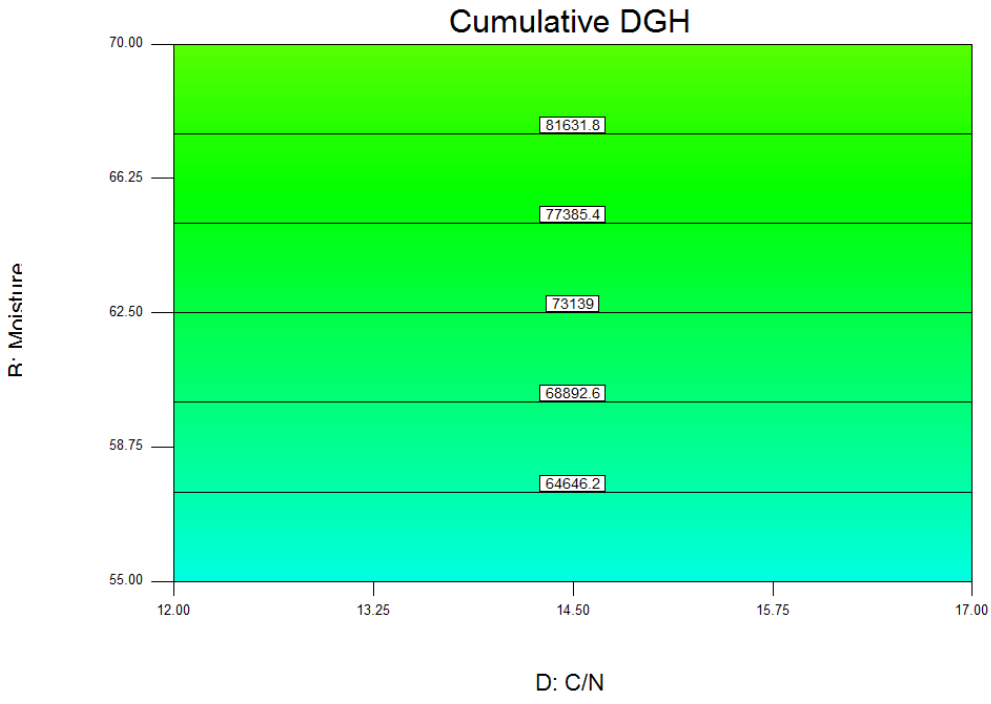



Figure 5.19. (a) Response surface plot and (b) contour plot of cumulative dehydrogenase activity when aeration rate is 0.4 l/min·kg and bulking agent is peat

## 5.5 Cumulative β-Glucosidase activity (BGH)

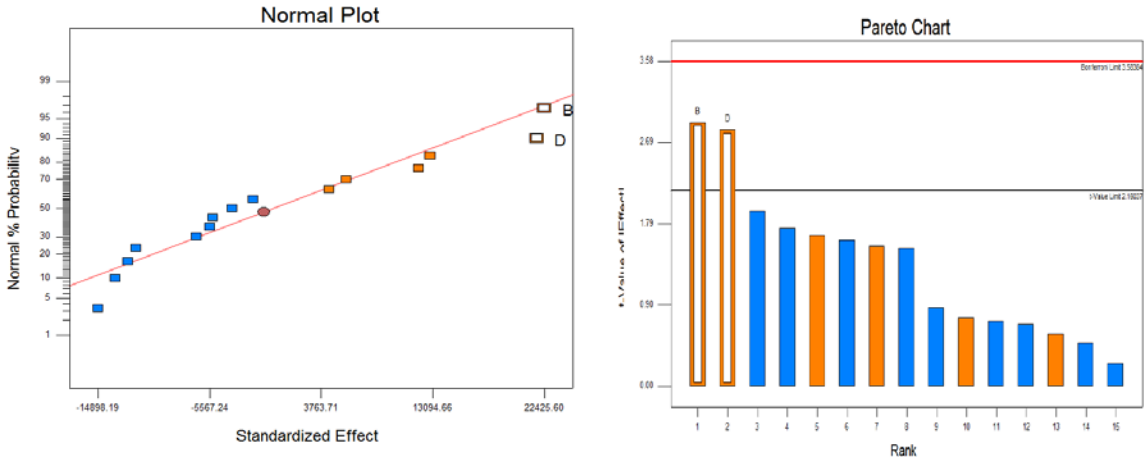
(1) Factor Effect Estimates, Contrasts, and Sums of Squares

The summary of effect estimates, contrasts, sums of squares, coefficients, and percentage contributions of Cumulative β-Glucosidase activity for each term are given in Table 5.13. Terms A and B contribute a high percentage of total variability (28.72% and 27.12%, respectively) and are likely to have an important effect. To confirm this, a normal probability plot and a Pareto chart should be checked. A normal probability plot and Pareto chart of effects are shown in Figure 5.18(a) and 5.18(b). In normal probability plot factor D is far from the straight line but factor B is close to straight line, but in Pareto chart both factor B and D exceed the t-value limit line. Therefore, factor B and D are considered as significant factor to continue the ANOVA analysis.

Table 5.13. Factor effect estimates, contrasts, and sums of squares for the response of Cumulative β-Glucosidase activity

| Model term | Effects estimate | Sums of squares (SS) | Percent contribution |
|---|---|---|---|
| **A-Aeration** | 5858.385102 | 180627551.2 | 2.579476784 |
| **B-Moisture** | 22425.60182 | 2011630468 | 28.72736777 |
| **C-BA** | -3685.08094 | 238216742.9 | 3.40188722 |
| **D-C/N** | 21792.05105 | 1899573956 | 27.12712921 |
| **AB** | -14898.18527 | 237648194.2 | 3.393767982 |
| **AC** | -12406.3866 | 71954133.59 | 1.02755098 |
| **AD** | 4422.17695 | 78222595.91 | 1.117068625 |
| **BC** | 12870.31432 | 120554130.3 | 1.721589971 |
| **BD** | -6673.476503 | 178141154.6 | 2.543969453 |
| **CD** | -1950.680245 | 15220613.67 | 0.217360084 |
| **ABC** | -5548.178691 | 10760354.05 | 0.153664728 |
| **ABD** | -13479.42921 | 726780047.6 | 10.37888322 |

| | | | |
|---|---|---|---|
| **ACD** | -11743.36348 | 551626343.2 | 7.877576465 |
| **BCD** | 11922.9817 | 568629970.3 | 8.120399119 |
| **ABCD** | -5312.760602 | 112901700.9 | 1.61230839 |




(a) (b)

Figure 5.20. (a) Normal probability plot and (b) Pareto chart of the effects for cumulative β-Glucosidase activity

(2) ANOVA analysis

ANOVA analysis for cumulative β-Glucosidase activity is displayed in Table 5.14. The degree of freedom of each term is 1 and the degree of freedom of error is 13 so critical $F_{0.05,1,13}$ is 4.67. F-values of main effects B and D is greater than the critical F-value, also their p-values are less than 0.05, and therefore both of the factors are significant. The fitting model can be developed based on the significant factors. The normality assumption for the model should be checked to use the model to predict the cumulative β-Glucosidase activity in food waste composting.

(3)Response Surface Model

According to the above analysis, main effects B (moisture content) and D (C/N ratio) can be used to develop a response surface model. The resulting regression model for predicting cumulative β-Glucosidase activity is:

$$\text{Cumulative BGH} = +92979.42 + 11212.80\ B + 21792.05\ D \qquad (5.11)$$

where B and D are main effects, moisture content and C/N ratio respectively.

(4) Model Adequacy Checking

To be trustworthy, the adequacy of the developed model must be validated. A normal probability plot of these residuals is shown in Figure 5.19(a). This plot does not reveal any significant deviation. The residual vs. predicted values (Figure 5.19(b)) does not follow any patter so the normality assumption is not violated. Thus, the fitting regression model is adequate.

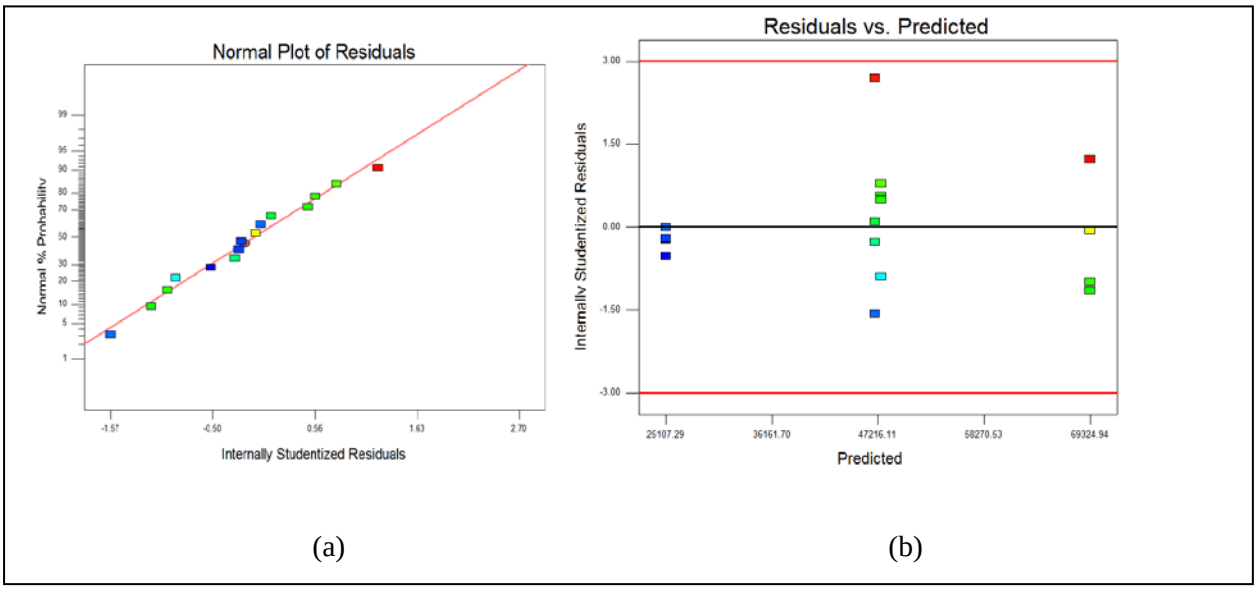


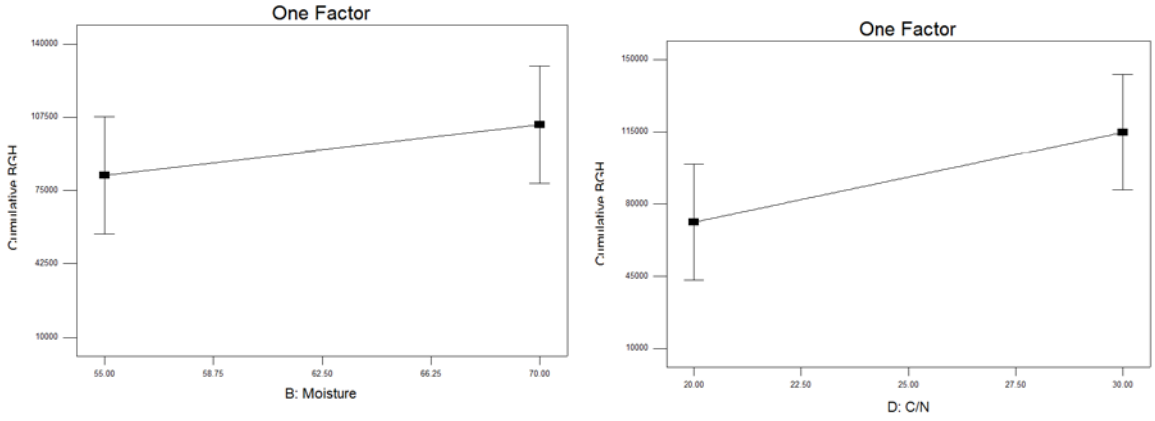

Figure 5.21. (a) Normal probability plot of residuals and (b) residual vs. predicted for cumulative β-Glucosidase activity

(4) Results Interpretation

The main effect plots of factor B and D presented in Figure 5.20(a) and 5.20(b), respectively. Increase of factor B and C have positive effect on the cumulative β-Glucosidase activity. When moisture content and C/N ratio increase from low level to high level, the cumulative β-Glucosidase activity increases as well. A three dimensional plot of the response surface and contour plot of cumulative β-Glucosidase activity are displayed in Figure 5.21(a) and 5.21(b) respectively. The highest cumulative β-Glucosidase activity happens when moisture content is at high level (70%) and C/N ratio is also at the high level(17), the lowest activity has been observed when both moisture content and C/N ratio are at the low level (55% and 12, respectively).

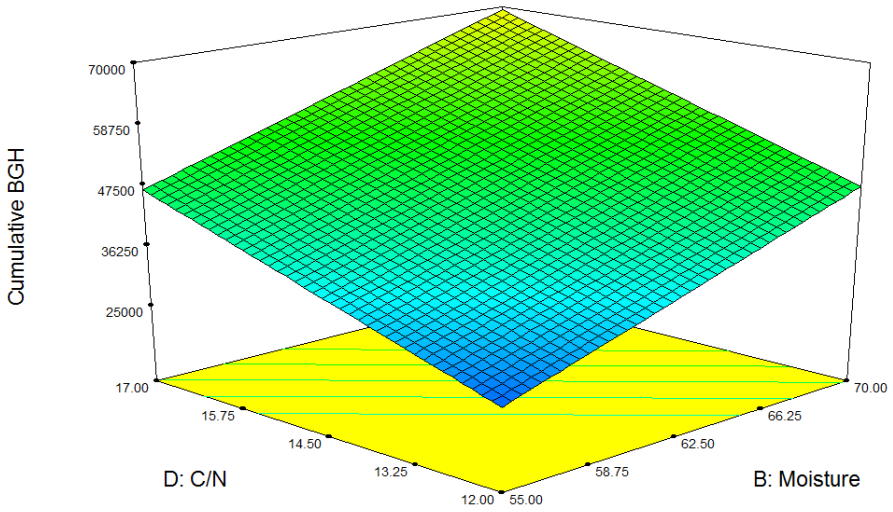
Table 5.14. Analysis of variance for the response of cumulative β-Glucosidase activity

| Source | Sum of Squares | df | Mean Square | F Value | p-value Prob > F |
|---|---|---|---|---|---|
| **Model** | 3911204424 | 2 | 1955602212 | 8.224036549 | 0.0049 |
| **B-Moisture** | 2011630468 | 1 | 2011630468 | 8.459656259 | 0.0122 |
| **D-C/N** | 1899573956 | 1 | 1899573956 | 7.98841684 | 0.0143 |
| **Residual** | 3091283532 | 13 | 237791040.9 | | |
| **Cor Total** | 7002487956 | 15 | | | |




(a) (b)

Figure 5.22. .Main effect plots of cumulative β-Glucosidase activity (a) Moisture content (b) C/N ratio




(a)

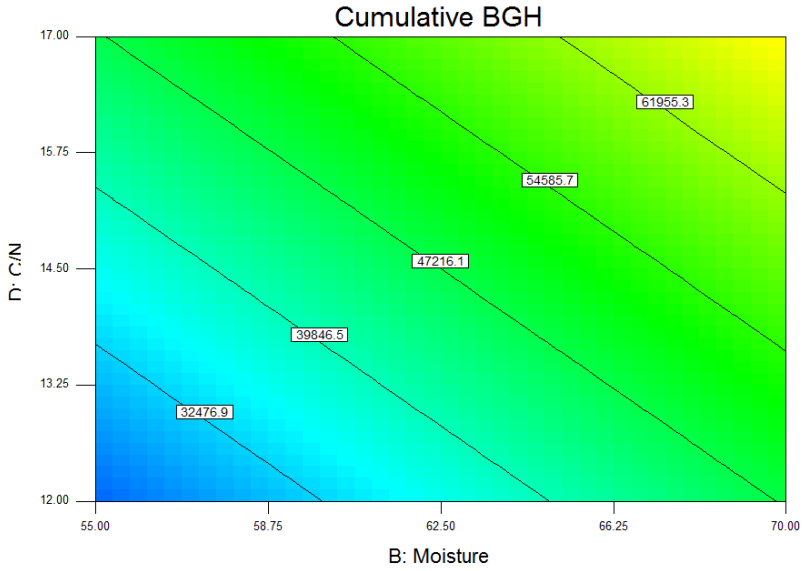



Figure 5.23. (a) Response surface plot and (b) contour plot of cumulative β-Glucosidase activity when aeration rate is 0.4 l/min.kg and bulking agent is peat

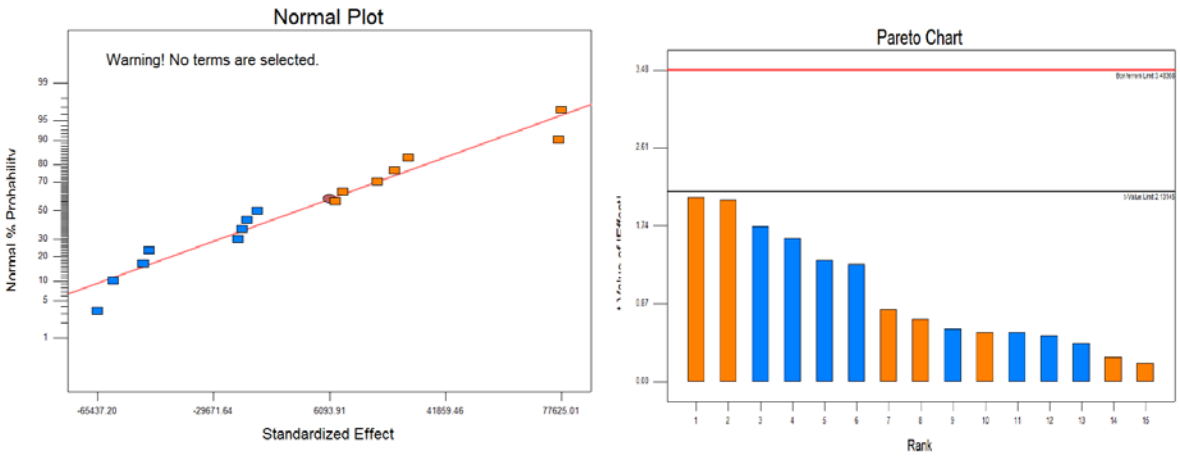
## 5.6 Cumulative phosphomonoesterase activity (PHM)

(1) Factor Effect Estimates, Contrasts, and Sums of Squares

The summary of effect estimates, contrasts, sums of squares, coefficients, and percentage contributions for each term of cumulative phosphomonoesterase activity are given in Table 5.15. The interactions BD and BCD appears to contribute the greatest percentage total variability (20.12% and 27.69%, respectively) and are likely to have an important effect. From the normal probability plot and Pareto chart of effects in Figures 5.22 (a) and 4.22 (b), no significant effects emerge at $\alpha = 0.5$. All effects tend to lie along the line in the normal probability plot and no effects exceed t-value limit in the Pareto chart. None of the main or interactions has significant effects on cumulative phosphomonoesterase activity. Therefore, no further ANOVA and statistical analysis will be done.

Table 5.15. Factor effect estimates, contrasts, and sums of squares for the response of cumulative phosphomonoesterase activity

| Model term | Effects estimate | Sums of squares (SS) | Percent contribution |
|---|---|---|---|
| **A-Aeration** | -11453.62474 | 351478421.2 | 7.699699 |
| **B-Moisture** | 12380.16604 | 613074044.5 | 13.43037 |
| **C-BA** | 7050.872309 | 97322280.92 | 2.132001 |
| **D-C/N** | 4839.517996 | 93683737.72 | 2.052293 |
| **AB** | -5117.283545 | 13931274.06 | 0.305187 |
| **AC** | -4482.147795 | 55512083.55 | 1.216081 |
| **AD** | -14005.67482 | 784635708.7 | 17.18871 |
| **BC** | 17979.54591 | 34889943.53 | 0.76432 |
| **BD** | -15156.59805 | 918889857.3 | 20.12976 |
| **CD** | 6073.542872 | 147551692.1 | 3.232357 |
| **ABC** | 1810.288572 | 18763715.15 | 0.411049 |
| **ABD** | -4815.991143 | 92775082.75 | 2.032387 |
| **ACD** | -3720.460243 | 55367297.68 | 1.21291 |
| **BCD** | 17778.95839 | 1264365445 | 27.69796 |
| **ABCD** | 2376.573116 | 22592399.11 | 0.494923 |




(a) (b)

Figure 5.24. (a) Normal probability plot and (b) Pareto chart of the effects for Cumulative phosphomonoesterase activity

# 6 Conclusions and Recommendations

## 6.1 Conclusions

A small-scale composting system was designed and manufactured. Various factorial effects on food-waste composting were investigated via a factorial design approach through measuring temperature, OUR, GI, moisture and ash content, enzyme activity assay, and C/N ratio. Full $2^4$ factorial designs were employed with four factors (two levels for each factor) examined through sixteen runs of composting experiments. The factors tracked include aeration rate, moisture content, bulking agent (peat and sawdust), and C/N ratio. Based on the factorial analysis, response surface models were developed to reflect interrelationships between the operation and evaluation parameters during composting. A summary of the findings now follows:

(1) Experiment results validated the enzyme activities as proper indexes during the course of composting. The maximum enzyme activities occurred in the first and third weeks, which is the active phase of decomposition. To utilize enzymes for compost characterization, single point determinations are inadequate and it is necessary to study enzyme activity dynamics because composting material contains widely different organic substrates. Since some of these enzymes are substrate-inducible enzymes such as β-Glucosidase and Phosphomonoestrase, they can be used as a good index of qualitative and quantitative fluctuation of the amount of substrate during composting. Dehydrogenase activity assay is one of the simplest and quickest methods to monitor the stability of MSW compost. Despite the necessity to perform several measurements over time, measurement of enzyme activity is the easy, rapid, and inexpensive way to understand the biodegradation processes and evaluate compost stability.

(2) The seed germination using root growth seemed to be an effective and simple means of assessing the maturation of MSW compost. Evolution of phytotoxicity during composting

appeared to be associated with the stage of decomposition. The GI was low at the end of composting time, which indicates that longer time is required to have mature compost. Also, due to the positive effect of high C/N ratio on GI, more studies are needed to confirm that higher C/N ratio can improve GI of the produced compost, whereas the level of C/N ratio in this study was much lower that the optimum value for C/N ratio (20-30).

(3) C/N ratio has a significant effect on most of the parameters measured to monitor the composting process, although the rage that we considered for C/N ratio was small and of the levels were under 20. C/N ratio significantly affected the GI. Based on the GI results, compost with high C/N ratio showed less toxicity after composting. C/N ratio also showed dramatic effect on pH and EC. In the runs with high C/N ratio the number of days that compost was in the acidic phase was more than the other runs. The final EC, max and min EC were higher in the runs with lower C/N ratio. C/N ratio did not influence the dehydrogenase and phosphomonoesterase activity but influenced the β-Glucosidase activity.

(4) The aeration rate positively affect the maximum OUR and negatively affected the maximum EC. Its interaction with moisture content and bulking agent made its effect significant on maximum temperature. Also, its interaction with bulking agent has influence on GI. Its effect on enzyme activity was not significant.

(5) Moisture content impacted EC and dehydrogenase activity. Runs with high moisture content experienced more acidic days than the runs with low moisture content. The cumulative dehydrogenase activity was higher at high moisture content. It did not affect temperature and other enzymes profile significantly.

(6) Bulking agents (peat and sawdust) affected the pH profile. Its interaction with aeration ratio impacted GI value.

## 6.2 Recommendation for Future Research

Because composting is a complex and dynamic process, it can be affected by multiple factors, where understanding of biochemical changes of compost is still incomplete. This study considered only four different factors at two levels. Investigating additional factors (e.g., different ratio of bulking agents, fixed temperatures, pH level of raw materials) at two levels or higher in statistical factorial designs is recommended.

This study used the OUR and GI to evaluate maturity and stability of compost. Conducting other tests such as respiration rate, water soluble carbon and nitrogen, $CO_2$ evaluation are recommended to assess process performance and evaluate the maturity and stability of the produced compost.

The single replication of response data used in this study may be insufficient to reflect the actual effects of the factors on composting process because the variance in response data due to the experimental error, SSerror, is forced to be zero. Thus, replicating more response data for future studies is advised to achieve the more precise effect estimates required to screen factor(s), and to collect more accurate data for regression models. Moreover, a more refined model will be useful if the prediction of response data is validated.

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