BIODRYING PROCESS: A SUSTAINABLE TECHNOLOGY FOR MUNICIPAL SOLID WASTE MANAGEMENT

A THESIS

Submitted by

ASHA P TOM

for the award of the degree

of

DOCTOR OF PHILOSOPHY

DIVISION OF CIVIL ENGINEERING
SCHOOL OF ENGINEERING
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY, KOCHI

OCTOBER 2018

Dedicated to

The God Almighty

DIVISION OF CIVIL ENGINEERING
SCHOOL OF ENGINEERING
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY

CERTIFICATE

This is to certify that the thesis entitled **“BIODRYING PROCESS: A SUSTAINABLE TECHNOLOGY FOR MUNICIPAL SOLID WASTE MANAGEMENT”** submitted by Asha P Tom to the Cochin University of Science and Technology, Kochi for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by her under my supervision and guidance at the Division of Civil Engineering, School of Engineering, Cochin University of Science and Technology. The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma. All the relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the Doctoral Committee have been incorporated in the thesis.

Place: Kochi
Date: 22-10-2018

Prof. (Dr) Renu Pawels
Research Guide
Professor
Division of Civil Engineering
School of Engineering
Cochin University of Science and
Technology, Kochi 682 022

DECLARATION

I hereby declare that the work presented in the thesis entitled **“BIODRYING PROCESS: A SUSTAINABLE TECHNOLOGY FOR MUNICIPAL SOLID WASTE MANAGEMENT”** is based on the original research work carried out by me under the supervision and guidance of Dr. Renu Pawels, Professor, Division of Civil Engineering, School of Engineering, Cochin University of Science and Technology for the award of the degree of Doctor of Philosophy with Cochin University of Science and Technology. I further declare that the contents of this thesis in full or in parts have not been submitted to any other University or Institute for the award of any degree or diploma.

Place: Kochi **Asha P Tom**

Date: 22-10-2018

ACKNOWLEDGEMENTS

I would like to express my deep sense of gratitude to my research guide Dr. Renu Pawels. She gave me the freedom to choose this project, and the support and care provided throughout the work helped me to complete the work. Her organizing capacity was the inspiring factor without which such a project would not be possible for me. I am very thankful for all the support and care you have provided me throughout the research work, without that this journey would not have been possible.

I would like to express my sincere gratitude to Dr. Ajit Haridas, chief scientist, National Institute of Interdisciplinary Science and Technology, CSIR, Thiruvananthapuram for his valuable guidance and constant inspiration. His sound knowledge in all fields of engineering and technology was the back bone and key factor for the success of this research work. I would like to express my heartfelt thanks to Dr. G. Madhu for the precious suggestions towards improving the research work, and for the kind support throughout the research period. I would like to thank Kerala State Council for Science Technology and Environment (KSCSTE) for the financial support provided for the research. I am very thankful to the former director Dr. Suresh Das and the present director Dr. Ajay Ghosh of National Institute of Interdisciplinary Science and Technology, CSIR, Thiruvananthapuram for providing me the laboratory facilities at NIIST Trivandrum. I would like to express my sincere gratitude to Dr. Sreejith P. S. for the support provided during pre-synopsis presentation. I would like to thank the Principal of School of Engineering, Dr. M.R.Radhakrishna Panicker for the inspiration and support provided.

Also I would like to express my sincere gratitude to Dr. Glory Joseph, Dr. Subha V, Dr. Sobha Cyrus, Dr. K.S. Beena, Dr. Benny Mathews Abraham, Sri. Arun Kumar T, Dr. Deepa G Nair, Dr. Deepa Balakrishnan S, Smt. Seena Skaria, Sri Kunjumon V C for the creative suggestions towards this research work. I would like to thank Dr. J Ansari, Dr. V.B.Manilal, Dr. K.P Prathish, Dr. Krishmakumar B, Smt.Vijayaprasad, Smt.Saharuba P Sri Shajikumar V.K., Dr. Savithri S, Dr. Elizabeth Jacob and Sri. B Abdul Haleeem for the timely support provided towards my research work.

I would like to thank my friends Prasad, Pradeesh, Sayana, Cincy,Sony, Jyothi, Anu, Mareena, Aquilla, Faizal, Paneer Selvam, Sumi, Priya, Anju, Aneesh, Anupama, Godwin, Rahul, Chithran, Dipin, Dayal, Shibin, Jasmine, Siddarth, Swetha, Parvathy, Athira, Remya, Shimi, Ashik, Ajith, Shakthi, Fahdad, Sanju, Anna, Satheesh, Rajesh and Arun for their support towards this research.

I would like to express my love to my family and to all my dear ones without whose support this may not be possible. Finally I remember God almighty for giving me all these wonderful persons in my life to guide me and support me in this research work.

Asha P Tom

ABSTRACT

Key words: Biodrying, moisture content, municipal solid waste, temperature profile, weight reduction, volume reduction.

Municipal solid waste management is a major challenge in developing countries. The world is facing another challenge of fast depleting fossil fuel resources which lead to an extensive search for renewable energy resources. The above two strategies of a proper municipal solid waste management system, as well as the need of renewable energy resources, are highlighting the importance of technologies for municipal solid waste to energy conversion. Municipal solid waste (MSW) is a renewable energy resource since the energy content of MSW source stream is biogenic and also promoting energy production from the MSW will reduce the landfill volume. Municipal solid waste with high moisture content, high specific weight and low calorific value is the typical characteristics observed in developing countries. The high moisture content of the MSW is a critical issue which adversely affects the calorific value and hence the waste to energy prospects of municipal solid waste.

In this scenario, the ‘Biodrying Technology’ is found to be a sustainable method for the conversion of raw MSW substrate with high moisture content into the biodried substrate with low moisture content and increased calorific value. Biodrying is an aerobically controlled convective evaporation process which utilises the self heating nature of municipal solid waste for drying purpose. The primary objective of the current research is to develop a competent and well acclimatised ‘Pilot Scale Biodrying Reactor’ for treating the mixed municipal solid waste of high moisture content. The present research work has been carried out in four stages. In the first stage the characterisation study of the municipal solid waste has been carried out to check the feasibility of the same for biodrying reaction. The ‘Proximate Analysis' of the different components of the mixed municipal solid waste substrate has been used to evaluate the moisture content and volatile solids content. In the second stage, an innovative ‘Pilot Scale Biodrying Reactor' has been structurally developed for treating mixed municipal solid waste substrate of high moisture content. The ‘Biodrying Process Design' has also been carried out to achieve controlled aerobic process inside the mixed municipal solid waste substrate so as to attain optimum self

heating reactions. The instrumentation design has been done by considering the critical process conditions. The third stage of research included six phases of experimental investigations conducted in the innovative pilot scale biodrying reactor system. The mechanism of biodrying reaction has been delineated through the continuous monitoring of weight reduction, temperature profile, moisture reduction, volume reduction and bulk density increase of the reactor matrix through the investigation carried out in six phases. The calorific value of the biodried municipal solid waste has been calculated in the fourth stage of research using the existing empirical modelling equations, so as to assess its suitability for waste to energy applications.

The innovative biodrying reactor developed for mixed municipal solid waste with high moisture content has achieved a significant weight loss of 41 % in 11 days of reaction. Maximum moisture reduction of 39 % and volume reduction of 44 % has been achieved in the designed system in 11 days of process. Self heating temperature of 50 ^{0}C to 60 ^{0}C has been developed in the designed biodrying reactor matrix, which is ensuring hygienisation of the biodried output. The calorific value of municipal solid waste has been increased from the initial value of 10.06 MJ/kg to the final value of 28.35 MJ/kg which is promising towards waste to energy applications of municipal solid waste.

CONTENTS

CURRICULAM VITAE

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

MSW	-	Municipal Solid Waste
V.S.	-	Volatile Solids
R.D.F.	-	Refuse Derived Fuel
S.R.F	-	Solid Recovered Fuel
K.S.U.D.P	-	Kerala State Urban Development Programme
M.C.	-	Moisture Content
DGMFC	-	Digital Flow Mass Flow Controller.
CPCB	-	Central Pollution Control Board
ASTM	-	American Society for Testing Materials

LIST OF NOTATIONS

ϑ_{o2} - Number of molecules of oxygen

ϑ_{co2} - Number of molecules of carbon dioxide

ϑ_{H2O} - Number of molecules of water

ϑ_{NH3} - Number of molecules of ammonia.

TCI - Temperature cumulation Index

T_m - Mean matrix temperature (°C)

T_i - Temperature of air inlet (°C)

Δt - Time interval (day)

W^t_{loss}(kg) - The water losses at time t

WM_0 (kg) - The wet materials at the initial time

WM_t (kg) - Wet materials at time t,

w_0 (%) - Water content at initial time

w_t (%) - Water content at time t

$E_{loss,}$ (kg) - Total net emission loss at time t

LO^t_{loss} - Leachate weight

LHV - Lower heating value (kcal/kg)

W - Moisture content (%)

P_{pl} - Plastics (wt %),

P_{fo} - Food waste (wt %),

P_{pa} - Paper and card board (wt %)

P_{te} - Textiles (wt %)

P_{mi} - Miscellaneous component (wt %)

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The management of municipal solid waste (MSW) is a major challenge throughout the world, and especially in the rapidly growing cities and towns of developing countries (Foo, 1997). The rapid urbanization followed by the industrial development and construction activities is supposed to be the major reason for MSW accumulation (Chattopadhyay et al., 2007). Solid waste management includes the generation, storage, collection, transfer and transport, processing, and disposal in accordance with the best principles of health, economics, engineering, conservation, aesthetics, and other environmental and public considerations (Tchobanoglous et. al.,1993). The developing countries face unique issues in municipal solid waste management like open dumping, burning without air, water pollution control measures and breeding of flies in waste dumping yards which cause major environmental and public health problems (Ogawa, 2000). The management of solid waste at different stages like generation, storage, collection, transfer and transport, processing and disposal stages in developing nations need an environmentally sound technology development which pertains to the best principles of public health (Ramachandra, 2006; Ramachandra and Varghese, 2003; Ramachandra and Bachamanda, 2007). The developing countries sought technical assistance from the developed nations in solid waste treatment technologies with the assumption that solid waste management problem can be solved with mechanisation (Lardinios and Van de Klundert, 1997). The ‘blind technology transfer’ of machinery from developed countries to the developing countries and its subsequent failure has brought attention to the need for appropriate technology (Beukering et al., 1999) to suit the regional conditions like type of waste, composition and treatment. Waste to energy (WTE) technology has the potential to reduce the volume of the original waste by 90%, depending on the composition by recovering the energy (Wang et al., 2009; Kathiravale et al., 2003). The net energy yield from municipal solid waste depends upon the composition, the density, and relative percentage of moisture of the waste (IEA,2003; Fobil et.al., 2005). Technological development is essential for the conversion of raw municipal solid waste into an energy enriched product so that it is suitable for energy producing applications.

1.2. PRESENT SCENARIO OF SOLID WASTE MANAGEMENT TECHNOLOGIES

The solid waste from different sources like residential, industrial, institutional, commercial, construction and demolition, and municipal services constitute municipal solid waste (MSW) in India. The urbanisation trends, constant change in consumption pattern and social behaviour is increasing the generation of municipal solid waste in the country, beyond the assimilative capacity of existing municipal solid waste management system. The pollution of water resources, the proliferation of vectors of communicable diseases, foul odours and the release of toxic metabolites are making waste dumping sites as hazardous regions. Therefore the landfilling of municipal solid waste is not at all a sustainable technological option especially in localities where the land scarcity is a major issue. The amount of municipal solid waste is expected to increase significantly in the near future as the country strives to attain an industrialized nation status by the year 2020 (Sharma and Shah, 2005; CPCB, 2004; Shekdar et al., 1992). The current municipal solid waste management system in the country is capable of collecting 70 % of the total municipal waste generated and out of that only 12.45% is treated. Approximately 17.55 % of the municipal solid waste remains uncollected and 57.55 % of the collected municipal solid waste is disposed in dumping yards without proper treatment (Hoornweg and Bhada-Tata, 2012). All these circumstances points out that need for research and development in the field of MSW management. The world is facing another challenge of fast depleting fossil fuel resources which lead to an extensive search for renewable energy resources. The above two strategies of search for a proper municipal solid waste management system as well as the need of renewable energy resources are emphasizing the importance of technologies for municipal solid waste to energy conversion. Municipal solid waste (MSW) is considered as a renewable energy resource since the energy content of MSW source stream is biogenic. The energy production from MSW will reduce the landfill volume considerably (USEPA, 2006a; EIA, 2007). The present research set the goal to develop a sustainable treatment technology for the municipal solid waste management.

The increasing quantities of plastics and non-biodegradable packaging materials in the municipal solid waste are making the management options more complicated. The previous study results have shown that about 0.1 million tonnes of municipal solid waste has been generated in India every day and it is increasing annually at a rapid rate (CPHEEO, 2000; Sharholy et. al., 2008). The present investigation is carried out in Kerala the consumer oriented state of India which produces large volume of municipal solid waste. Considering an annual increase of 1–1.33% of municipal solid waste (Pappu et al., 2007; Shekdar, 1999; Bhide and Shekdar, 1998) the total municipal solid waste generation in present Kerala state can be estimated as 0.606 kg/capita/day. The database for MSW composition based on direct sampling at four cities of Kerala state as obtained from literature review is summarised in Table. 1.1 (Varma, 2006). It is observed that 55.8% of municipal solid waste of the Kerala state is coming from domestic sources. Next source contributing more to MSW is the hotels and commercial establishments. MSW generation rate from different sources gives an overview of the nature of municipal solid waste of Kerala. The physical composition of typical MSW at the collection point and dumping sites obtained from the previous study have shown that on an average 71.74% of the MSW of Kerala state is putrescible organic matter as shown in Table 1.2 (KSUDP, 2006 ; Varma, 2006).

Table.1.1 Municipal Solid Waste Generation Estimated Based on Direct Sampling

SlNo.	**MSW Generation sources**	**Quantum of MSW Generation (Tonnes/day)**			
		Kollam	**Kochi**	**Thrissur**	**Kozhikkode**
1	Domestic sources	95	134.7	75.75	100.12
2	Commercial establishments	1	32.99	13.02	28.16
3	Marriage & community halls	1	4.75	2.12	1.56
4	Hotel & Restaurants	19	29.9	14.57	24.07
5	Markets	6	20.39	11.01	12.08
6	Institutions/ schools, offices	7	14.75	5.51	10.62
7	Street sweepings	14	31.3	13.87	19.28
8	Hospitals(Non-infectious)	2	4.22	3.6	6.64
9	Slaughterhouse	2	5.26	2.25	-
10	Construction& Demolition	7	17.0	13.6	11.0
	Total	**154**	**295.26**	**155.3**	**213.53**
	Per capita generation (kg/day)	**0.393**	**0.482**	**0.478**	**0.477**

(Varma, 2006)

Table 1.2. Municipal Solid Waste Scenario in Kerala -2006

Composition	**Changanasseri**	**Kottayam**	**Kannur**	**Aluva**	**Trivandrum**	**Average**
Paper	10.2	6.8	8.2	9.72	2.25	7.43
Plastics	4.9	4.25	6.67	6.94	2.79	5.11
Metals	0.2	2.00	1.40	1.38	1.02	1.20
Glass	0.50	2.25	1.60	1.00	1.30	1.33
Rubber& Leather	0.60	2.20	1.67	1.77	2.11	1.67
Compostable organics	76.60	73.45	68.73	70.83	69.09	71.74
Others- Textiles, Inerts &domestic hazardous	7.00	9.05	11.73	8.36	21.44	11.52

The study of the chemical characteristics of typical MSW of the state has revealed that moisture content of MSW is very high with an average value of 69.7% (KSUDP, 2006; Varma, 2006). The heavy moisture laden nature of municipal solid waste and mixed mature of MSW collection were identified as the important factors to be considered in the municipal solid waste management system for the Kerala state. Mixed municipal solid waste in raw state has a heating value in the range of 8-12 MJ/kg of which is one third of the calorific value of coal (25-30 MJ/kg). Municipal solid waste composition comprised of high moisture content, high specific weight and low calorific value is the typical characteristics observed in developing countries (Ramachandra and Bachamanda, 2007). The lower calorific value of municipal solid waste due to high moisture content is an important factor affecting the waste to energy prospects of municipal solid waste (Daskalopoulos et. al., 1997). The moisture content in waste is adding up septic conditions and hence handling problems in municipal solid waste systems. Also, the use of auxiliary fuel is often necessary for the combustion of heavy moisture laden substrate which increases the economics of the energy production processes (Cheng et. al., 2007; Cheng and Hu, 2010; Nie, 2008).

In this scenario the ‘Biodrying Technology' is found to be a sustainable method for the conversion of raw MSW substrate with high moisture content into an energy enriched biodried substrate. Biodrying is an aerobically controlled convective evaporation process which utilises the self heating nature of municipal solid waste for drying purpose (Velis et. al., 2009). The reduction of weight, moisture content and bulk volume together with the bulk density augmentation and self-sanitisation at high temperature is achieved in the biodrying process. The famous waste management hierarchy (Tchobanoglous et. al., 1993) of giving priority to 3R's namely reduce, recycle and reuse is followed in biodrying technology, since it promotes efficient sorting, storage, transportation and end use of waste as a renewable energy source. Biodrying process is different from composting in that composting is a complete stabilisation process, where there is no final energy value of the product (Nellist et. al., 1993). In contrary to that the biodrying reactor partially stabilises the waste at the lowest possible residence time to produce high quality solid recovered fuel (SRF), by increasing the energy content (Adani et. al.,2002). It was reported that biodrying process has increased the potential for thermal recovery of solid waste (Rada et. al., 2007a). Many researchers have demonstrated that the time taken for the biodrying process is very less while compared to that for bio-stabilization (Sugni et. al., 2005). Biodrying is a new technology with only limited research activities (Tambone et. al., 2011) and hence further research and development are necessary to explore the process in detail.

1.3 OBJECTIVES OF THE RESEARCH

- The primary objective of the current research is to develop a competent and well acclimatised ‘Pilot Scale Biodrying Reactor’ for treating the mixed municipal solid waste of high moisture content. The selected secondary objectives to full fill the primary objective were enlisted below.

    - To study the characteristics of the municipal solid waste based on the proximate analysis.

    - The structural and process design of the pilot scale biodrying reactor by considering the practical as well as technical feasibility.

    - To investigate the biodrying process in detail by the continuous monitoring of the process parameters resulting from different phases of experimental investigations and further design modifications to achieve the optimum condition.

    - To study the impact of down flow mode of aeration and its effect on the biodrying process.

    - To assess the potential of the calorific value of biodried output to study its suitability in waste to energy applications.

1.4. THESIS OUTLINE

The present research work has been carried out in four stages.

- The characterisation study of the municipal solid waste has been carried out in the first stage to check the feasibility of the same for biodrying reaction. The ‘Proximate Analysis' of the different components of the mixed municipal solid waste substrate has been used to evaluate the moisture content and volatile solids content.

- In the second stage, an innovative ‘Pilot Scale Biodrying Reactor' has been structurally developed for treating mixed municipal solid waste substrate of high moisture content. The ‘Biodrying Process Design' has also been carried out to achieve controlled aerobic process inside the mixed municipal solid waste substrate so as to attain optimum self heating reactions. The instrumentation design has been done by considering the critical process conditions.

- Six phases of experimental investigations have been conducted in the innovative pilot scale biodrying reactor system in the third stage. The mechanism of biodrying reaction has been delineated through the continuous monitoring of ‘Weight Reduction’, ‘Temperature Profile’, ‘Moisture Profile’, ‘Volume Reduction’ and ‘Bulk density Increase’ of the reactor matrix through the investigation carried out in six phases.

The first five phases of experimental investigation have been conducted in the up flow mode of aeration.

  - In the first phase, the biodrying process in the pilot scale system has been monitored to assess the efficiency of the designed system.
  - The second phase of experimental investigation has been carried out by modifying the design of the biodrying reactor so as to increase the process efficiency.
  - The effect of specific air flow rate variation and reactor matrix height on biodrying reaction has been studied in the third phase.
  - In the fourth phase, the combined effect of packing and reactor matrix height on biodrying process has been investigated.
  - In the fifth phase, the effect of the increase in specific air flow rate on biodrying process efficiency has been investigated.

- The down flow mode of aeration and its impact on biodrying reaction has been investigated in the sixth phase.
- The calorific value of the biodried municipal solid waste has been calculated in the fourth stage of research using the existing empirical modelling equations, so as to assess its suitability for waste to energy applications.

1.5 ORGANIZATION OF THE THESIS

The current thesis has been organised into seven chapters.

Chapter 1 gives an introduction to the research which provides an overview of the present scenario of municipal solid waste management. The main objectives of the research are highlighted and an overview of the thesis outline as well as the organisation of the same has been described.

Chapter 2 describes the detailed literature review of the research.

Chapter 3 illustrates the characterization study of the municipal solid waste by proximate analysis and the suitability of the selected municipal solid waste substrate for active biological reaction.

In ***Chapter 4***, the design and development of the innovative pilot scale biodrying reactor unit have been described.

The ***Chapter 5*** deals with the six phases of experimental investigations to explore the biodrying process in the innovatively developed pilot scale biodrying reactor.

The ***Chapter* 6** of the research included the calorific value assessment of the biodried product using existing empirical modelling equations.

In ***Chapter 7,*** the summary and conclusions derived from the research have been presented. The conclusions highlighted that the biodrying process efficiency achieved in the innovative reactor was successful in converting the raw municipal solid waste into an energy-enriched renewable energy source.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The detailed literature review has been carried out to study the different solid waste management technologies existing in the world. The pros and cones of each one have been studied in detail. The evolution of the research topic ‘Biodrying Technology' as a sustainable solution for treating municipal solid waste with high moisture content has been described.

2.2 WASTE HIERARCHY

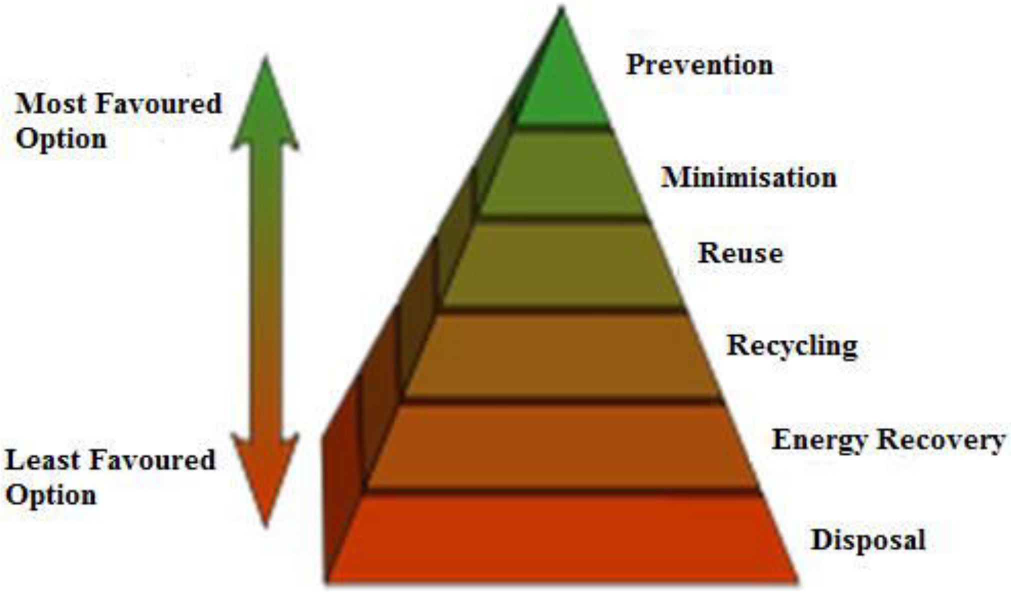


Fig.2.1 Waste Hierarchy Tripod
(Tchnolobanoglous et.al.,1993)

2.2.1 Waste Prevention and Minimisation

The waste hierarchy tripod (Fig.2.1) points out that prevention is the most desirable waste management option, as it eliminates the need for handling, transporting, recycling and disposal of waste. Also, it helps the optimisation of environmental resources. Minimisation is any process or activity that avoids, reduces or eliminates waste at its source or results in other options like reuse, recycling etc. (Tchnolobanoglous et.al.,1993). Two management options namely waste prevention and minimisation can be applied at all stages in the life cycle of a product. A sustainable technology for municipal solid waste treatment should be able to minimise the waste quantity.

2.2.2 Reuse and Recycling

Reuse is preferred over recycling though the purpose is same for both as energy and matter are saved. But the efficiency of the product may reduce in reuse and also certain products become hazardous in the long run. This point out the versatility of waste prevention and minimisation over other methods of waste management. Recycling involves the treatment or reprocessing of discarded waste to make it adequate for reuse. It conserves resources and energy but sometimes tedious, time consuming and result in net energy loss. The recovery of material value in waste has been approached in two significantly different ways: (1) By source separation and separate collection systems; and (2) recovery by mechanical processing and sorting of mixed residual waste at central facilities (Cimpan et.al., 2015). The inherent limitations of the source separation became apparent with increased heterogeneity of the MSW stream. Also, the public willingness to participate in the source separated collection as well as the costs of collecting separately are major factors affecting the MSW management systems. Material mixing followed by sorting has been adopted in recent times as a way to reduce the collection complexity and also to minimise the public participation (USEPA, 2011; WRAP, 2011b).

2.2.3 Energy and Recovery

Biofuel production is increasing at a rapid rate in developed and developing countries. One of the main reason for supporting biofuel production is the need for renewable energy production to substitute the conventional fossil fuels in an attempt to mitigate climate change and reduce dependency on energy imports (Bureau et al.,2010). The developing countries like India are yet to move ahead in the field of biofuel energy production. Presently the municipal solid waste and general industrial and agricultural wastes are the main sources of biomass in India. Therefore energy production and recovery from municipal solid waste is an important factor in the renewable energy production and economic development of the region.

2.2.4 Disposal

The bulk volume of municipal solid waste requires large areas of land for disposing the same. Specially the bulk volume of waste generated in developing nations is very high, which give rise to additional problems of land pollution, water pollution, growth and transmission of disease producing vectors etc. The landfilling of huge quantities of MSW without treatment is not at all a good choice since land scarcity is a serious issue in urban areas (Varma, 2006).

2.3 MUNICIPAL SOLID WASTE VALUE CHAIN

The MSW value chain conventionally consists of three broad aspects, namely, collection & transportation (C&T), processing and finally the disposal of waste. A holistic approach to waste management includes efforts to reduce the quantity of waste generated at all points, which includes waste reduction at the source to the disposal point. The C&T system includes door-to-door collection of segregated waste from households followed by transportation to waste processing plants in covered vehicles. The processing of waste involves the application of appropriate technology, depending upon the quantity and quality of wastes, so as to reduce the overall quantity of waste reaching the landfill sites. Technologies that derive value from the waste to the extent possible should be applied and finally the refuse from the processing plant is collected and disposed of at the scientifically engineered landfills (Tchnolobanoglous et.al.,1993). Every segment of MSW management entails cost, and hence there is a need to manage all the three segments of the MSW value chain(Fig.2.2) in the most efficient manner.

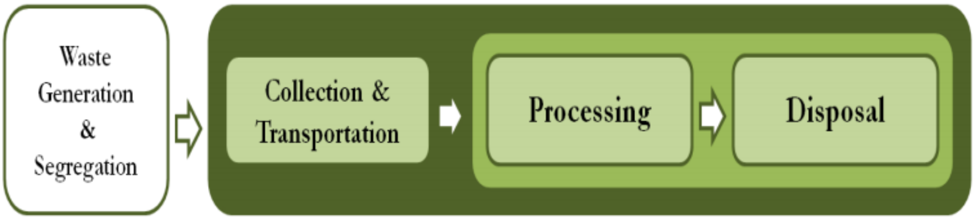


Fig. 2.2 MSW Value Chain
(Tchnolobanoglous et.al.,1993)

The municipal solid waste collection is an important aspect in maintaining public health in cities around the world. The amount of MSW collected varies widely by region and income level; collection within cities can also differ greatly. Collection rates range from a low value of 41% in low-income countries to a high value of 98% in high-income countries (Tchnolobanoglous et.al., 1993). Waste collection is the collection of solid waste from the point of production (residential, industrial commercial, institutional) to the point of treatment or disposal. The municipal solid waste collection is carried out in several ways as given below.

1. House-to-House: Waste collectors visit the individual house to collect garbage. The user pays a fee for this service.
2. Community Bins: Users bring their garbage to community bins that are placed at fixed points in a neighbourhood or locality. MSW is picked up by the municipality, or its designate, according to a set schedule.
3. Kerb side-Pick-up: Users leave their garbage directly outside their homes according to a garbage pick-up schedule set with the local authorities.
4. Self Delivered: MSW generators deliver the waste directly to disposal sites or transfer stations, or hire third-party operators.
5. Contracted Service: Businesses hire firms who arrange collection schedules and charges with customers (Tchnolobanoglous et.al., 1993).

The municipal solid waste collection efficiencies are also seen to be poor, at around 70 % in most Indian cities and continue to be predominantly manual in nature. Transfer stations are rarely used, and the same vehicle that collects refuse from the individual communal bins is also responsible for taking it to the processing or the disposal site. Collection and transportation activities constitute approximately 80–95% of the total budget of municipal solid waste management (MSWM). Hence it forms a critical component in determining the economics of the entire MSWM system. Another important factor to be considered in the design of municipal solid waste treatment technologies for a country like India is the waste segregation and storage of the collected MSW. The source sorted collection is not practically happening in developing countries. The decomposable and non-decomposable wastes are often disposed of at common communal dustbin/disposal centre in developing countries (High Powered Expert Committee Report, GOI 2011) The degree of source separation impacts the total amount of material recycled and the quality of secondary materials that can be supplied. Therefore municipal solid waste collection without segregation is an important practical factor to be considered for the design of municipal treatment systems in the developing countries.. The inefficiency of source separation was observed as a major cause for the failure of the conventional treatment facilities. This points out the need for the development of technologies for managing mixed municipal solid waste.

2.4. SOLID WASTE MANAGEMENT TECHNOLOGIES

The waste remaining after waste minimisation, reuse and recycling should be treated to reduce the negative impacts to the environment. The different solid waste treatment technologies can be categorised mainly into three types namely biological, thermal and landfilling as shown in Fig. 2.3 (Tan et.al., 2014). The thermal treatment methods used for municipal solid waste management are incineration, pyrolysis and gasification. In biological treatment methods or biochemical conversion processes, the micro-organisms (either added or inherently available in the substrate) are used to degrade the waste into various components in the form of solid matter, slurry and gas. Biological technologies are termed the most economical and environmentally safe means of obtaining energy from MSW. Biochemical conversion of waste can be grouped into two namely anaerobic digestion/fermentation and aerobic digestion /composting.

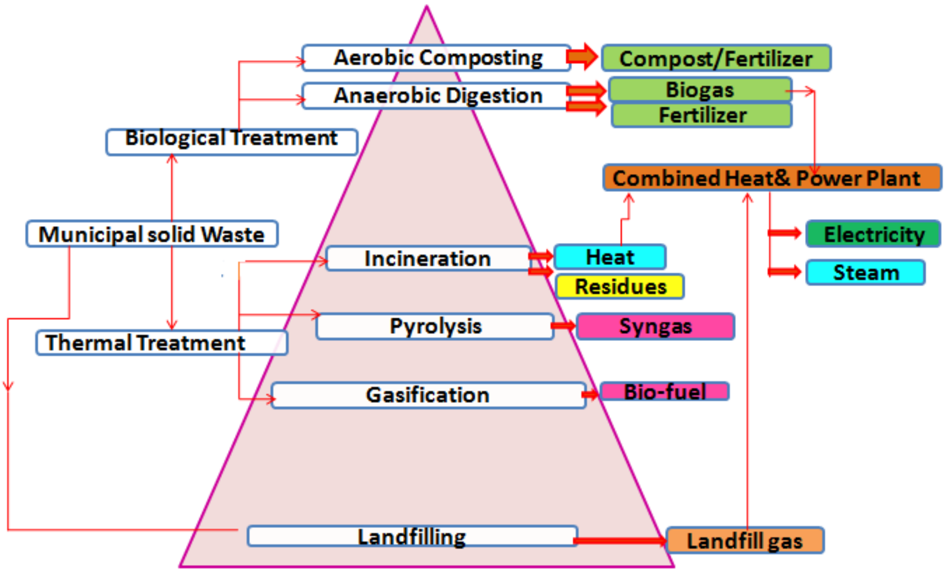


Fig.2.3 Municipal Solid Waste Treatment Technologies
(Tan et.al., 2014)

2.4.1 Anaerobic Digestion

Anaerobic digestion is a biodegradation reaction where the organic compounds are degraded by the microorganisms in the absence of air. This is a complex process that requires specific environmental conditions and particular bacterial populations to decompose the organic waste to the end product. This produces a valuable high energy biogas (CH_4 and CO_2) and a mixture of gases (Lastella et. al., 2002). The process of anaerobic digestion consists of four main biological and chemical stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Demirbas, 2010). In the first step, hydrolysis, the complex chain of organic compounds is broken down into basic structural molecules, such as fatty acids, monosaccharides, amino acids, and related compounds. The process is followed by acidogenesis, where the further breakdown of the remaining components by acidogenic (fermentative) bacteria takes place. At this stage, gases such as CO_2, CH_4, and NH_3 are produced. The third stage of anaerobic digestion is acetogenesis, during which simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen. The last stage of anaerobic digestion is methanogenesis during which the methanogens bacteria convert the intermediate products into CO_2, CH_4, and water (Tchnobanoglous et.al., 1993; Tan et. al., 2015). The amount of methane obtained from the anaerobic digester is about 2–5 times higher than that obtained from landfills. This is due to the uncontrolled operation parameters in landfills which reduce the methane capture efficiency (Otoma et.al., 1997). Biogas can be utilised as energy source for power combustion engines towards electricity generation, space heating, water heating and process heating.

The major limitation of anaerobic digester is that it could only digest particular organic waste, which does not solve the issue of other waste components. Hence it is necessary to segregate biodegradable organic waste before it can be used in the anaerobic process. The different types of organic waste will result in different gas yields. Therefore this technology may not serve as an efficient technology for heterogeneous MSW management and electricity generation because MSW contains different compositions of waste which are not sorted at the source. The problem of sorting of heavy moisture laden waste at the source is also difficult which is a drawback to apply this technology on a large scale.

2.4.2 Composting

Composting is a biological method where the organic component of MSW is aerobically treated to create a product called compost, at relatively low-cost, which is suitable for agricultural purposes (Eriksen et al., 1999; Wolkowski, 2003). During composting, readily degradable substrates are rapidly consumed and the heating process releases significant energy. Depending on the degradability of the organic substrate, the oxygen supply and heat loss, the temperature of the material can rise up to 70 °C or more which eliminate the pathogens from the material (Neklyudov et al., 2006). The development of composting technology has been attributed to the economic as well as environmental factors, such as municipal landfill capacity and cost associated with landfilling and transportation of materials. Also other factors like the adoption of legislation to protect the environment, decreasing the use of commercial fertilizers and increasing the capacity for household waste recycling are leading to development of composting technology (He et al., 1992; Otten, 2001; Hansen et al., 2006; Zhang et al., 2006). Composting of MSW reduces the volume of the waste, kills pathogens, decreases the germination of weeds in agricultural fields, and destroys the malodorous compounds (Jakobsen, 1995). The major disadvantages of composting are that the compost derived from the organic fraction of municipal solid waste can contain metals, persistent organic pollutants, as well as microbial and fungi toxins, whose exposure in certain scenarios impose serious health risks leading to rejection of compost (Domingo and Nadal 2009). A case study on heavy metal distribution in soil and plant in municipal solid waste compost amended plots (Ayari et al., 2010) has revealed that there was an important transfer of metal ions from soils to wheat plants. Thus the composting method of solid waste disposal has to be analysed for detrimental effects, especially if industrial wastes are dumped into municipal landfills. Less market value for the fertiliser output from the composting plants is also a limitation for commercial scale composting plants.

2.4.3 Incineration

Incineration is a thermal treatment method where the controlled burning of waste materials at a temperature of 870°C–1200°C for a sufficient time will oxidise about 99% of the organic matter to produce high pressure steam for power generation. Waste incineration reduces the volume and weight of the waste by 90% and 70% respectively (Murphy and McKeogh, 2006). Incineration is the primary approach of waste treatment technology that converts biomass to electricity. The end product derived from the combustion of waste is hot combusted gas, that composed primarily of nitrogen (N_2), CO_2, water, (H_2O), flue gas, oxygen (O_2) and non-combustible residues (Tchnobanoglous et. al., 1993). The hot flue gases will enter the heat exchanger as a hot stream to generate steam from water. Electricity is generated through the Rankine cycle in the steam turbine.

The single steam cycle normally only produces electricity, while the cogeneration of steam and electricity requires an extracting steam cycle. The biomass requires prior preparation and processing, such as pre-drying to remove the high moisture content of the waste before it enters the combustion chamber to be combusted with air. Controlled incineration systems for electricity and heat productions are similar to most fossil-fuel fired power plants. A typical controlled incineration system for energy production consists of the waste storage chamber, boiler/incinerator, steam turbine/generator, flue gas cleaning system/chimneys and residue treatment system (Weitz et. al., 2002; Johnke, 2002; Korobitsyn, 1999; Tsai and Chou 2006). Waste to energy (WTE) production through incineration can occur in four main stages namely waste pre-treatment, waste combustion, gas scrubbing (including air pollution) and electricity/steam generation. The organic components of the MSW are converted into syngas and other products while the mineral components are converted into slag or vitrified slag or ash which is a byproduct. Steam is fed into a steam turbine where it flows over series of turbine blades which cause the turbine to rotate. The turbine is connected to an electric generator which rotates to produce electricity. The burning of the waste on a grate or to fluidise it with air will achieve complete combustion. The condensing turbines can be used to cool steam so as to increase the power production (Korobitsyn, 1999; Morris,m 1998). The generated heat of combustion is recovered in a waste heat boiler for steam generation. The incineration process produces an effectively sterile ash residue and the pretreatment before combustion will transform this ash into other useful products. MSW incineration system is a stable technology of energy production from wastes which is capable of reducing the amounts of dioxin and other dangerous substances produced. The heating value of the MSW is an important parameter which greatly contributes to the efficiency of the incineration plant. Incineration of MSW operating at uncontrollably high temperature can produce a net energy of about 544 kWh/tone of MSW but environmentally more damaging. Combustion of MSW at uncontrolled temperatures produces chlorinated dibenzo-p-dioxins and corrosive gases that could destroy the steam pipes and cause health related problems. Thus with a controlled temperature in the range of 250-300 °C, the efficiency achieved has been reduced to 15-16% (Johnke, 2002; CoE, CED, 2010). On the other hand, to increase the efficiency of the system, a more heat-resistant material could be used for the steam pipes to withstand these high temperatures. There could also be a dual generating system which involves both gas turbines and waste incineration. Natural gas can be used to power the turbines to produce electricity. The exhaust gas of high temperature between 500°C-600°C from the turbines is then used for further heating of the steam produced by the incinerator to about 400°C. These systems can increase the efficiency to about 20–30% (Tchobanoglous et. al., 1993; Barducci, 1990; Elango et.al., 2007).

The cost of investment and operation of incinerators is often high. The high costs of power generated from this technology can be significantly reduced if concessionary loans that attract low discount rates and grants are sourced to finance such projects. Murphy and McKeogh have reported that in any MSW incineration system, about 15% of the wastes is available as electricity. Again, MSW from 1,000,000 person equivalent could power 12,400 cars; provide electricity for 30,900 houses and heat 15,100 houses Europe and United States (Murphy and McKeogh, 2006).

2.4.4 Pyrolysis

Pyrolysis is the thermal decomposition of waste in the absence of oxygen. The products of pyrolysis include bio-char, bio-oil and gases (methane, hydrogen, carbon monoxide, and carbon dioxide). The processes involved in pyrolysis can be grouped into three categories as slow pyrolysis, fast (or flash) pyrolysis at high temperatures and flash pyrolysis at low temperatures. At low temperatures below 450°C, pyrolysis may produce bio-char while at high temperatures above 800°C, a significant amount of gases may evolve (Mohan et. al., 2006). However, at an intermediate temperature and relatively high heating rates, the main product is bio-oil. Flash pyrolysis is currently the most widely used pyrolysis technology. Slow pyrolysis takes several hours to complete and results in bio-char as the main product (Katyal, 2007). On the other hand, fast pyrolysis yields about 60% bio-oil and takes seconds for complete pyrolysis. Also it gives 20% bio-char and 20% synthetic gas or Syngas (Mohan et. al., 2006; Katyal, 2007). Pyrolysis can produce a net energy of 571 kWh/tonne MSW from either the gas or bio-oil produced (Otoma et. al., 1997; Ruth, 1998). The schematic representation of the production of electricity from fast pyrolysis of MSW is shown in Fig.2.4.

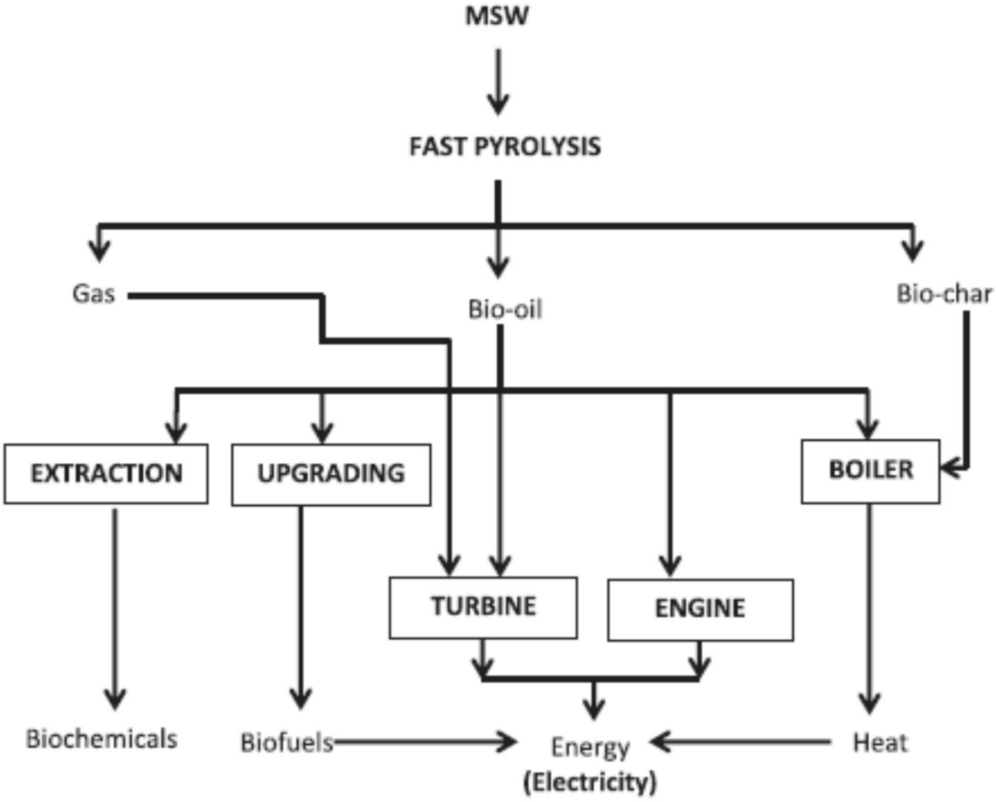


Fig.2.4 Flow Diagram for the Production of Electricity from Fast Pyrolysis of Municipal Solid Waste.

Pyrolysis oil has many advantages over gasification and incineration due to the ease of handling, storage and combustion in an existing power station. The pyrolysis produces lesser byproducts (10–40%), multiple products (liquid, solid and gas) and has the least economic burden and environmental problems compared to incineration

(Mohan et. al., 2006; Katyal, 2007). On the contrary, there are some major drawbacks associated with pyrolysis. The particle size of the feed required for pyrolysis smaller and hence the MSW should be converted into smaller sizes ($\leq$2 mm particle size) before pyrolysis inorder to obtain the best yield and appropriate products after the reaction (Mohan et. al., 2006).

2.4.5 Gasification

Gasification is a thermo-chemical method in which there is partial combustion of the MSW at high temperatures in a controlled environment which virtually converts almost all the MSW into gas and chars (Arena, 2012). During the gasification process, the waste is combusted with a controlled amount of oxygen supply in the operating temperature range of 780°C to 1650°C. The process occurs in two stages. In the first stage, the MSW is partially combusted to get producer gas ($CO_2 + H_2O$) and char. The CO_2 and H_2O are chemically reduced by the char (or charcoal) so that carbon monoxide (CO) and hydrogen gas (H_2) is produced in the second stage. The composition of the resulting gas is 18–20% H_2, 18–21% CO, 2–3% CH_4, 8–10% CO_2, and the rest is nitrogen (Appel et. al., 1971; Williams and Larson, 1992; Belgiorno et. al., 2003). The final products of the process are ash, carbon, hydrogen, nitrogen, sulphur, CH_4 and oxygen. The solid by-products of the gasification reaction are known as char and it mainly consisted of carbon and ash. The by-products are then gasified in the second gasification process using steam and oxygen. The second gasification process also provides the required heat energy for the earlier processes. The syngas is sent to the power generation plant to produce energy, such as steam and electricity. Pre-treatment or initial drying (Rada et.al., 2012) of the waste as well as the quantity of oxidant will increase the heating value of the gas produced. This is achieved due to the reduction of heat demand for the process. The heat demand is high when the waste has high moisture content. When pure oxygen is used as the gasification agent, nitrogen diluent is eliminated thus gas with medium calorific value of 10–20 MJ Nm^{-3} is produced (Belgiorno et. al., 2003; Williams and Larson, 1992). The temperature residence time and the composition of major products formed from the three thermo-chemical conversion technologies were enlisted in Table 2.1.

Table.2.1. Technologies for Thermo-chemical Conversion of MSW for Electricity Production

Technology	**Temperature**	**Residence Time**	**Product Composition (%)**		
			Liquid	**Char**	**gas**
Flash Pyrolysis	Moderate	Short	75	12	13
Incineration	Low	Long	30	35	35
Gasification	High	Long	5	10	85

(Johnke, 2002; Barducci and Neri 1997).

2.4.6 Landfilling

The landfill is a land that is built up from deposits of solid refuse in layers covered by soil. It consists of a random mixture of food scraps and other kitchen waste, paper, plastic, metals, and glass. The organic waste dumped in a landfill site will decompose with time, but the inorganic constituents will be remaining for a long time. Since each landfill has its own particular constituents and the leachate quality of a particular landfill also changes over time; a flexible design is required to treat the varied influent stream. The main environmental problem associated with the landfill is the pollution of ground water. The study by Esmaeili et al.(2010) has revealed that soil column had ample capacity to adsorb metal contaminants and hence the determination of soil potential in landfill site selection is inevitable. The methane gas per mole has a global warming potential 3.7 times that of carbon dioxide (Daniel and Dilip, 1990). The methane emissions were reduced using the clay capping in earlier studies which has been replaced by a new technique 'Phytocapping' nowadays. The study conducted at Rockhampton's Lakes Creek Landfill site in Australia (Venkatraman and Ashwath., 2009) has concluded that phytocaps could reduce the surface methane emissions by a factor 4 to 5 times more than the adjacent site. Also, the thick cap (1400 mm) reduces surface methane emissions 45% more than the thin cap (700 mm). A Comparative study of municipal solid waste treatment technologies using life cycle assessment method (Zaman, 2010) has concluded that landfill with energy recovery facilities is environmentally favourable. However, the large land requirement, difficult emission control system and long time span, are the limitations. Therefore the untreated MSW should not be allowed to reach the landfill.

The land filling can be considered as a waste to energy (WTE) technology when the generated CH_4 (commonly known as biogas) is captured and utilised for energy generation. Landfill gas recovery system (LFGRS) is well suited to a high percentage of biodegradable matter with high moisture content (Tan et.al., 2015). Average gas recovery rates range from 120 to 150 m^3/Tonne of dry MSW, equivalent to a heating value of 2500 MJ/T (The Japan Institute of Energy, 2008). It helps in the mitigation of greenhouse gas (GHG) emissions from waste by converting the CH_4 and crucial factor to successful waste management. Landfill gas comprises 50% methane and 50% carbon dioxide with an energy content of 18–19 MJ/m^3 (Weitz et.al., 1995; Bramryd and Binder, 2001). Methane is a powerful greenhouse gas, with substantial amounts being derived from unutilised methane production from landfill sites. The recovery of methane results in the stabilisation of the landfill site allowing faster reuse of the land, and also it serves to lessen the impacts of biospheric methane emissions on global warming (Bramryd and Binder, 2001; Brorson and Larson, 1999; Wilson, 2007). But the uncontrolled operation parameters reduce the methane capture efficiency of landfills (Otoma et.al., 1997). The CH_4 recovery for electricity production is the least feasible regarding the economics from landfill (Williams and Larson, 1992).

2.5 EXISTING TECHNOLOGICAL GAPS

The technological aspects of various treatment technologies like anaerobic digestion, composting, incineration, gasification, pyrolysis and sanitary landfilling were studied. Considering the different technological options, it was observed that composting is a simple and cost effective technology for treating the organic fraction of MSW. However this method is not very suitable for waste with high moisture content as the problem of fly and odour nuisance prevails. Also the land area requirements for compost plants are very large and longer time is required for the process. If the waste segregation if not properly carried out it will make the compost toxic, which prevents its safe application to agriculture (P.U.Asnani, 2006). The anaerobic digestion of the organic portion of municipal solid waste (MSW) is another cheap method of waste treatment adopted. The biogas from the process is used as a fuel. But the economic development and modernization changed the homogeneity and quantity of the MSW which is leading to the failure of anaerobic digesters using MSW feed. Also the proper maintenance of the anaerobic reactor is a major challenge. The incineration technology with high capital cost and maintenance cost makes it economically nonviable. So it is adopted only for treating hazardous waste like hospital waste, mainly because it requires large investments even for small scale plants. But if the heat energy recovery is possible, the cost can be accommodated. The lower calorific value of raw MSW with high moisture content is the major challenge for heat energy production. Pyrolysis /Gasification for MSW treatment also suffers energy recovery issues for solid waste with high moisture content. The increased moisture content of the waste is also affecting the sorting and storage of raw MSW and also result in increased volume of waste.

Landfilling is the final disposal method of municipal solid waste which is also causing economic barriers due to the scarcity of land. The long distance transportation requirements to the landfill are creating serious health, environmental, social and economic issues. The other methods of municipal solid waste management like recycling and reuse can be done only if the MSW is sorted. The implementation of waste to energy technology (WTE) for the mixed municipal solid waste management needs to be studied.

2.6 WASTE TO ENERGY TECHNOLOGIES

Technologies for the recovery of energy from the waste materials into useable heat, electricity, or fuel are generally called waste to energy technologies (WTE). Waste to energy (WTE) technology has the potential to reduce the volume of the original waste by 90%, depending on the composition by recovering the energy (Wang 2009, Kathiravale, 2003). In the hierarchy of solid waste management, WTE is ranked before the final disposal, indicating the limitations of this option regarding the economic and environmental benefits (Finnveden et. al., 2005). Waste to energy (WTE) processes recover the energy from the waste through either direct combustion (e.g., incineration, pyrolysis and gasification) or production of combustible fuels in the form of methane, hydrogen and other synthetic fuels (e.g., anaerobic digestion, mechanical biological treatment and refuse derived fuel) (Cheng and Hu, 2010). Mechanical Biological Treatment is a combination of mechanical separation techniques and biological treatments (aerobic and/or anaerobic), primarily used to deal with municipal solid waste and reduce the environmental impact of disposing of it in landfill (Defra 2011c, WRAP 2011a). The detailed study of the waste to energy plants in different countries of the world has revealed that refuse-derived fuel production plants as well as incineration plants are the major energy producers in the field of municipal solid waste treatment systems. Incineration and gasification are the two primary WTE technologies that have been used successfully throughout the world. It is estimated that about 130 million tonnes of MSW are combusted annually in more than 600 WTE facilities worldwide, producing electricity and steam for district heating and recovered metals for recycling (Themelis, 2003). Waste to energy plants with incineration has widely accepted as a solid waste management option, complementing landfilling and composting (American Society of Mechanical Engineers, 2008; Denison, 1996: Themelis, 2003; United Nations Environment Programme, 1996; Cheng and Hu, 2010).

Studies on the end use application of refuse derived fuel(RDF) has revealed that the RDF produced in WTE plants can substitute a major portion of fossil fuel in cement manufacturing units, which is successfully implemented in European countries (Kara et. al., 2009; cross ref: Lechtenberg and Partner, 2008). The unique nature of a cement kiln, with flame temperature burning more than 2000°C means that waste materials are destroyed without producing waste ash or harmful emissions. The high temperature in the cement kiln is seemed to be ideal for thermal destruction of residuals without causing adverse environmental impacts (Genon and Brizio, 2008). Also energy is recovered in the burning process; it is an excellent use of the waste material (Lagan Cement, 2008). The use of RDF in cement plants as a substitute for coal promotes the use of renewable energy which is the key strategy for reducing the greenhouse gas (GHG) emissions (Sozen et al., 2007). The scarcity of land and the uncontrolled contamination due to exhaust gas and leachate emissions have made landfill, particularly of organics, no longer a sustainable option (Hartmann and Ahring, 2006). Waste to energy method also faces some technological gaps. Waste availability and the sustainability of the waste resource are important factors to keep the WTE technology operating. The marketability of the produced renewable energy resources is also very important to ensure the economic potential of WTE. It is now accepted that no single solution exists for the management of MSW and with an integrated approach it is most likely to succeed (Earle et al., 1995).

2.7 CHALLENGES OF TREATING MUNICIPAL SOLID WASTE WITH HIGH MOISTURE CONTENT

The composition of the waste varies based on region. The organic components constituting the major proportion of MSW in developing countries, while the paper and plastic content is higher in developed countries. In developed countries the disposable material, magazines and packed food are used in large quantities and this generates the municipal solid waste having higher calorific value, lower specific density and lower moisture content.

In the case of developing countries the use of fresh vegetables is more compared to packed food and this result in a waste composition comprised of high moisture content, high specific weight and low calorific value (Ramachandra and Bachamanda, 2007). The difference in waste composition of high-income, medium-income and low-income nations is listed in Table. 2.2.

Table 2.2 The Relative Composition of Household Waste in Low, Medium and High- Income Countries

Parameters	**Low-income Countries**	**Medium-income countries**	**High- income Countries**
Organic (%)	40-85	20-65	20-30
Paper (%)	1-10	15-30	15-40
Plastics (%)	1-5	2-6	2-10
Metal (%)	1-5	1-5	3-13
Glass (%)	1-10	1-10	4-10
Rubber, leather etc. (%)	1-5	1-5	2-10
Others (%)	15-60	15-50	2-10
Moisture content (%)	40-80	40-60	5-20
Specific weight (kg/m^3)	250-500	170-330	100-170
Calorific value (kcal/kg)	800-1100	1000-1300	1500-2700

(INTOSAI Working Group on Environmental Auditing, 2002).

The incineration of MSW with high moisture content encounters a range of problems, including difficulty in ignition, unsteady and unstable combustion flame, incomplete combustion of the waste, and increased formation of air pollutants. Supplementary fuel, which would significantly increase the operating cost, is often necessary for incineration of waste having high moisture and low energy content (Cheng et al., 2007; Cheng and Hu, 2010; Nie, 2008).

The moisture content of waste greatly affects incinerator operation because the moisture will lower the calorific value of the waste. The increase of waste moisture will decrease the calorific value of waste, resulting in the reduction of energy production (Patumsawad and Cliffe, 2002; Tan et.al., 2014). The correlation of moisture to waste calorific value is shown in Fig. 2.5. In another context, the waste composition also plays an important role in selecting waste to energy technology for MSW treatment. The incinerator could treat a larger variety of waste and to a large extent these waste do not need segregation.

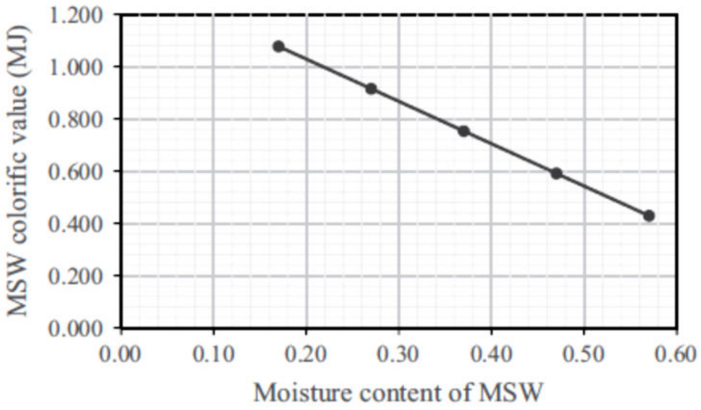


Fig. 2.5 Correlation of Moisture Content and Calorific Value of MSW
(Tan et. al., 2014)

The design and operation of all the energy systems of municipal solid waste are largely influenced by the heating value of MSW. Mixed MSW has a heating value of about one-third of the calorific value of coal (8-12 MJ/kg for MSW and 25-30 for MJ/kg for coal) (International Energy Agency, IEA 2003). The net energy yield from municipal solid waste depends upon the density, composition and relative percentage of moisture of the same (Fobil, 2005). It is essential to develop a technology to make the raw municipal solid waste with high moisture content into a product which is suitable for waste to energy applications. The detailed literature study in this search has lead to the identification of “Biodrying Technology" as a solution to the treatment of municipal solid waste with high moisture content. The present research work is an attempt to achieve the goal of converting raw MSW into an energy value product by biodrying process, which promotes the end use of the municipal solid waste.

2.8 BIODRYING PROCESS

Biodrying is an aerobic convective evaporation process which reduces the moisture content of the waste, with minimum aerobic degradation (Velis et. al., 2009). This process is different from composting in that the output of the composting process is stabilised organic matter, but the output of the biodrying process is only partially stabilised, which is useful for energy production (Rada et. al., 2005). Composting stabilises the organic material of municipal solid waste and no final energy value for the product (Nellist et. al., 1993). When compared with Composting (40-60 days) the biodrying process requires much less time, in the range of 13-18 days (Roca-Perez et al., 2009). The biodrying reactor pre-treats the waste at the lowest possible residence time to produce high quality solid recovered fuel (SRF), by increasing the energy content (Adani et al., 2002). The biodrying process has a good impact on solid waste management since self heating and odour reduction takes place simultaneously (Tambone et. al., 2011). The refuse-derived fuel from the biodrying process has been reported as the best CO_2 free alternative fuel (Flamme, 2006; Mohn et. al., 2008; Staber et. al.2008). Biodrying process increases the potential for thermal recovery of solid waste (Rada et. al., 2002; Sugni et. al., 2005). The biodrying process followed by the Refuse Derived Fuel production (RDF) can replace or reduce the use of fossil fuel consumption in industrial areas, if the pilot plants are placed close to industrial areas.

The incineration of biodried material can be carried out efficiently and heat recovery can be another energy producing option from this technology. The pyrolysis and gasification of auto thermal biodried municipal solid waste was found to be satisfactory as a biofuel (Zawadzka et. al., 2010). Secondary benefits of biodrying include making the output more suitable for short-term storage and transport both by partially bio-stabilising it and by reducing its moisture content (MC) below the necessary threshold for biodegradation. A study on full-scale biodrying reactor using municipal solid waste has reported a moisture reduction of 20% in 14 days period (Debicka and Zygadlo, 2017).

Partial sanitisation of the output is also accomplished for the bulk of the biodried product. The sanitisation to high standards is not necessary, since biodried product is not to be applied on land but to be thermally recovered (Adani et al., 2002; Calcaterra et al., 2000; Rada et al., 2005; Sugni et al., 2005; Wiemer and Kern, 1994). The biodrying of food waste has resulted in higher biodrying performance with low proportion of bulking agent (Mohammed et. al., 2017).

A study of the life cycle analysis of mixed municipal solid waste has concluded that, the most environment friendly integrated system of mixed municipal waste management is mechanical biological treatment (MBT) system with biodrying and refuse derived fuel (RDF) co-incineration (Vladimir and Tatiana 2011). The aeration rate of 0.5 $L.kg^{-1}$ $DM.min^{-1}$ provided on biodrying of MSW has resulted in maximum water loss (Yuvan et.al., 2018). In a biodrying study where exhaust air recirculation was used, it was observed that the end product did not meet the requirement of RDF standard (Somsai et. al.,2017). The homogeneous output from the biodrying process is a challenge which needs further investigations (Rada et. al., 2002; Sugni et. al., 2005).

2.8.1 Mechanism of Biodrying

The principle of biodrying process is that effective utilisation of the heat energy produced during the self heating reaction of municipal solid waste can be used for evaporation of water from the same. The source of energy for the self heating reaction is the easily biodegradable ingredients and the heat released during aerobic degradation of the same can be used for drying. In another view point in the biodrying process the transition of the substrate takes place, when the required heat is generated on the biochemical path (Bartha et. al., 2002). The basic process flow during the biodrying process is shown in Fig. 2.6.

The core process in biodrying is that the heat energy produced in the debris is heated and at the same time, the water from the particle surface evaporates. The desired effect is a decrease in the water content especially at the interfaces of the material, so that it is dried. But the aerobic degradation takes place only in an aqueous environment, which will limit the reaction. The different stages of the biodrying process are shown in Fig. 2.7. There are four phases in the biodrying process that are recognised as follows (Bartha and Brummack, 2007).

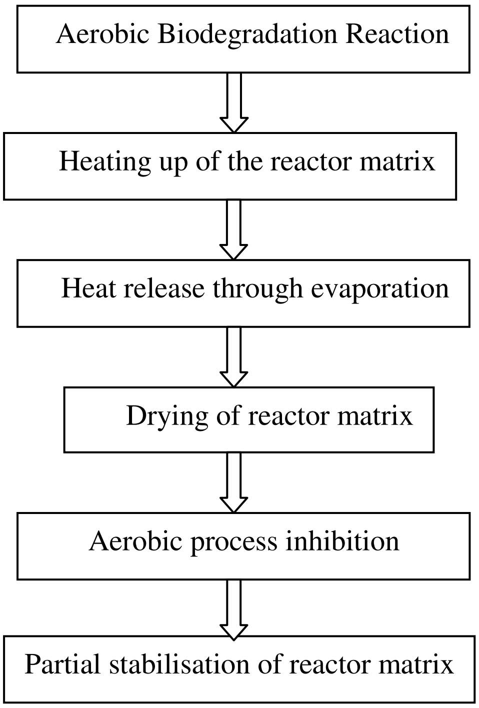


Fig. 2.6 The Process Flow Diagram of Biodrying.

1. Start phase
2. Heating-up Phase
3. The drying Phase and
4. Cool-down Phase

In the *‘start up' and ‘warm-up'* phase the aerobic reactions are most active with a sudden rise in temperature of the reactor matrix. During this initial heating phase, there is essentially no difference in the process targets compared to the conventional degradation process. Here the fast and strong temperature increase is the requirement for the optimised process.

The waste reduction phase is the second one in the biological drying stage, when most of the drying takes place and the largest water removal is achieved, which is designated as a '*drying phase'*. As the drying progresses, water limitation arises and eventually the temperature declines and the drying performance reduces. This is the third phase in the biodrying process that is '*cool-down phase'* which needs to be minimised for the process.

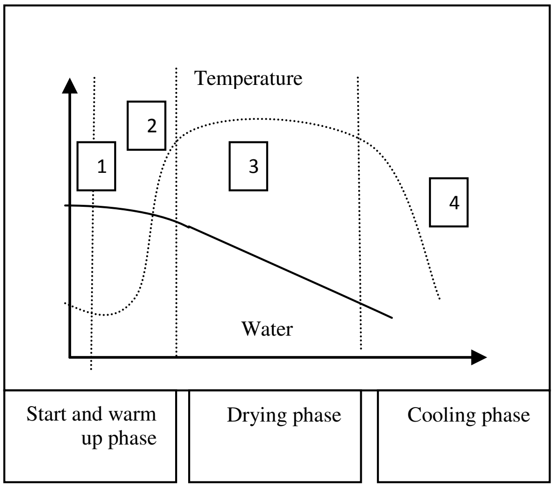


Fig .2.7 Different Phases in the Biodrying Process

2.8.2 Biodrying Process- Design Considerations for Physical Parameters

The mode of ventilation, as well as the rate is crucial in all the biological aerobic decomposition processes. The biodegradation of solid waste takes place at low air flow rates, but at high rates of air flow the moisture loss is more and biodegradation is slower, which is the process favouring biodrying of the waste (Sugni et. al., 2005). The study conducted on auto thermal drying mixture of sewage sludge and organic fraction of MSW in batch bioreactor concluded that the initial moisture content as well as the amount of supplied air are the critical parameters for the biodrying process (Liliana et. al., 2010).

In the biodrying process using a mixture of pulp and paper sludge has reported that air flow direction changes through the perforated pipes distributed throughout the pile increased the dry solids content from 30.5 to 41.6% in 13 days of reaction (Frei et al., 2004b). A full scale biodrying system using a mixture of dairy manure, sawdust and shavings as the substrate has used an intermittent mode of aeration which is controlled based on the pile temperature. The moisture content in the process has reduced from the initial value of 70% to final value of 40% in 21 days of reaction (Wright and Inglis, 2002).

The biological decomposition in the biodrying process generates some quantity of water, but aeration at higher rates removes the moisture faster than the rate of generation, which is favouring the drying process (Richard et. al., 2002). A study on the effect of air flow rate and turning on biodrying of dewatered sludge has shown that under the same mode of turning, higher air flow rate has reduced the temperature of the substrate, while compared to that at lower air flow rate (Zhao et. al., 2010). The higher air flow rate and lower turning frequency had resulted in a similar temperature accumulation, when the lower air flow rate and higher turning frequency was provided. Investigations conducted on the rotary biodrying process, to analyse the effect of duration of air flow rate on drying of household solid waste has revealed that weight loss has no significant effect on air flow rate (Somsai et. al., 2016). But air flow rate is very relevant in the case of static reactors where no turning is provided.

Continuous negative ventilation was reported as a preferable mode of ventilation for biodrying of MSW, but special care is required to prevent aqueous pollution if it is used in municipal solid waste treatment plants (Shao et al., 2012). The daily inversion of airflow in the biodrying process has eliminated the marked temperature differences inside the reactor matrix and leads to a homogeneous final product (Sugni et. al., 2004). An experimental study conducted on auto thermal drying of organic fraction of municipal solid waste has found out that the best drying conditions were achieved for horizontal reactor system with automatic regulation of air flow (Zawadzka et. al., 2009). A limited number of studies exist on aeration levels for the biodrying process especially using mixed municipal solid waste substrate. Hence further investigations are required to study the effect of aeration rate on biodrying process of mixed municipal solid waste.

Temperature is also an important factor affecting the biodrying process. Biodrying reaction is found to increase the potential for thermal recovery of solid waste (Rada et al., 2007a). The self heating reaction and the rising and falling trend of temperature profile considerably influence the rate of evaporation as well as the moisture convection through the matrix. A strategy based on temperature feedback control is recommended to be more promising for biodrying technology (Zang et. al., 2008). Investigations on sludge biodrying have revealed that temperature is the most important indicator of biomass utility. High temperatures (> 55℃) enhance the moisture removal and increase the vapour pressure of the air flow passing through the matrix, which carry more moisture away through the exhaust air (Frei et al., 2004b; Navaee- Ardeh et al., 2006). The bio-generated heat from a slowly biodegradable fraction of bulking agents contributed more to enhance the matrix temperature in sludge biodrying (Zhao et al., 2011). The detailed investigations are required to delineate the temperature profile of biodrying process when municipal solid waste substrate is used. A study on the importance of calorific value of waste as a parameter for determining fuel efficiency has been mentioned that the lower calorific value of municipal solid waste (only 20% of coal) is due to high moisture content which is critical for its use as a fuel (Daskalopoulos et. al., 1997). Also the moisture content in waste is adding up septic conditions due to air voids and hence handling problems. The lower calorific value and handling problems of solid waste can be managed by the biodrying method of solid waste treatment. The biodrying process followed by mechanical treatment applied to remove the fine fraction of municipal solid waste with low calorific content has produced final solid recovered fuel (SRF) with a net heating value (NHV) comparable to that of brown coal (NHV of 16,000–19,000 kJ/Kg) (Adani et al., 2002; cross ref: Wiemer and Kern,1995). The study of energy recovery criteria for MSW management in Romania has shown that the co-combustion of refuse derived fuel (RDF) with other waste is a good solution to the lower heating value (LHV) of RDF (Rada et. al., 2010).

The need for temporary storage or transportation of municipal solid waste before its use as fuel could lead to undesired problems of spontaneous ignition, odour emission, leachate and biogas production, with the consequence of materials damage, environmental contamination and health effects for the workers and inhabitants (Yasuhara et. al., 2010). The microbial activity in the biodegradable organic matter contained in MSW/SRF is responsible for these impacts. But the process of biodrying reduces the moisture content to inhibit microbial activity and hence helps to reduce potential impacts of municipal solid waste when stored or transported (Garg et. al., 2009; Velis et. al., 2009). The biodrying process has resulted in the enhancement of sorting efficiency of municipal solid waste from the initial 34% to final 71% (Zhang et.al., 2009). In the biodrying process, the moisture content of waste is reduced to about 30 to 45% and hence sorting and storage issues can be reduced to a great extent in addition to the reduction of landfill volume (Frei et. al., 2006). A theoretical modelling study has shown that the moisture content of the mixed waste plays a dominant role in the recycling rates of packaging materials such as paper, plastics and glass. The dry basis yields of recycling rate have been increased by 32.8% for paper, 50% for plastics and 44.6% for glass (Magrinho and Semiao 2008).

2.8.3 Biodrying Vs Thermal Drying

There is another concept called thermal drying, where the conventional drying technology of the water withdrawal is implemented for drying waste materials. Here the maximum permissible material temperature is limited by the temperature resistance of the components.

This is done in situations, where it is important to prevent the qualitative change in the mechanical or chemical properties of the substrate. Biodrying is different from thermal drying in that, here the dependence of the biological production of heat from the water content in the material surfaces leads to significant differences in the drying. The basic difference between thermal drying and biological drying is illustrated in Fig. 2.8.

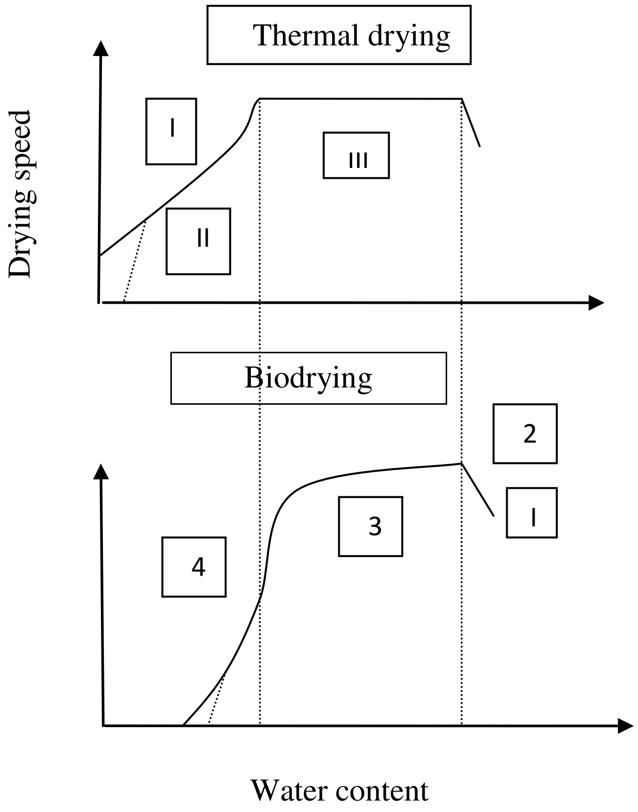


Fig. 2.8 Thermal Drying and Biodrying

The thermal drying process is divided into three sections (Kroll, 1978). In the first drying section (marked I, Fig.2.8, heating the material evaporates the water from the surface with a constant speed. The water content increases linearly, as long as water from pores and capillaries of the material flows outwards to the surface. In the second phase (marked II, Fig.2.8) there is no longer the supply of enough water to the surface, so the evaporation surface is shifted into the material inside. At this point the heat transfer resistance of the material is increased and hence the drying speed drops. This section ends with a non-hygroscopic material with the complete drying. In the case of hygroscopic materials, the last section of closing exists till sorption equilibrium is achieved between the material and the drying air (III: The third drying section).

Biodrying principle is that most of the heat production takes place in the presence of water on the surface, i.e. in the area of the first drying section. The reduction of biological activity due to the increased water limitation of micro-organisms leads to a decline in the drying speed. Once the surfaces are dried, there is practically a standstill of the heat production. The heat stored in the material can be used for drying only from this point onwards. This gives rise to the second drying section (Bartha 2008).

2.9 EVALUATION OF BIODRYING PROCESS AT DIFFERENT LEVELS

Application of process control engineering in biodrying is challenging. The main difficulty is the two-fold role of the waste matrix, being both (1) the mass to be dried, and (2) the substrate supporting the microbial activity, which in turn provides heat for the biodrying. The biodrying reactors use a combination of engineered physical and biochemical processes. Reactor design includes a container coupled with an aeration system; containers can be either enclosed or open tunnel-halls, or rotating drums. The biochemical side of biodrying reaction consisted of aerobic biodegradation of readily decomposable organic matter and on the physical side; convective moisture removal is achieved through controlled excessive aeration.

During biological drying a large number of sub-processes are running at the same time which depend on each other and hence it is a highly complex system. The recognition of fundamental contexts in a reactor waste system is the basis for all further process evaluation and technology development. This needs firstly the systematic study of the existing knowledge of the process and the theoretical development of the missing factors based on the experimental investigations. The aim of the theoretical studies is to evaluate the basic intervention possibilities for the process about the practical use. Five steps of the biodrying process have been identified as shown in (Fig. 2.9) (Bartha et al., 2002).

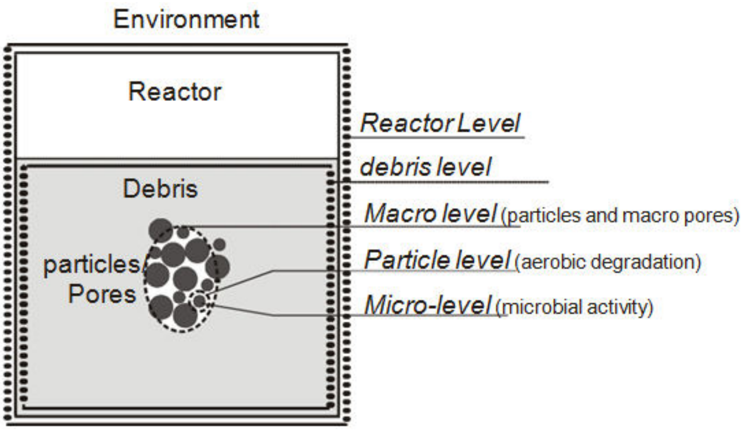


Fig.2.9 Different Levels of the Biodrying Process

It is simply assumed that the underlying sub-processes are of homogeneous behaviour. First of all, the ‘microbial activity’ has been qualitatively studied. The core process, the ‘aerobic biological degradation’, has been described in the second step. In a third step, the ‘decisive process *exchanges* on particle level’ has been studied. In the fourth stage the ‘homogenous debris’ assumption has been described. Finally in the fifth stage the study of considering the single unit of ‘the *reactor* with the entire waste’ has been done.

2.9.1 Micro-Level

The biodrying process is based on the aerobic degradation of native organic substances. Generally all biosynthetic processes are varying widely in nature (Schlegel, 1992). Their degradation speed will be very different for different type of raw materials. Different raw materials can be classified as highly *degradable* (sugar, starch, proteins, fats), *medium biodegradable* (hemicellulose and cellulose) and *poorly biodegradable* (Lignine, resins, tannins). The degradation of organic matter is based on the activity of micro-organisms. The cells of microorganisms can be considered as the smallest continuously working reactors owing to their capability to make material conversion (Wolf, 1991). The term "micro-organism" points to the small size of the individual particle to the average in the µm range. Because of their low weight micro-organisms are slightly worn by air currents. They are therefore present everywhere, only the environment decides their spreading (Schlegel, 1992). The seeding of residual waste is not necessary for biodrying since the optimum population is inherent in the materials.

The growth of microorganisms is only possible in an aqueous environment, where all the reactants, nutrients and oxygen are available to aerobic microorganisms in dissolved form. Therefore a phase change is required for the reduction of fixed or gaseous organic substances and under certain circumstances it is the rate-limiting step in the overall process. The principle of growth of microbes in a discontinuous culture is explained in the literature (Schlegel, 1992) as shown in Fig.2.10. There are four typical growth phases resulting from the mixture of micro-organism substrate and the prevailing environmental conditions. In the first phase called the 'lag-phase' already existing group of microorganisms in the raw substrate will be adapted to a new environment. Many factors such as the type of pre-culture, the composition of media or the age of the cells, have an influence on the time needed for the cells and their transport systems for the conversion of new substrates for the formation of required metabolic enzymes for substrate reduction.

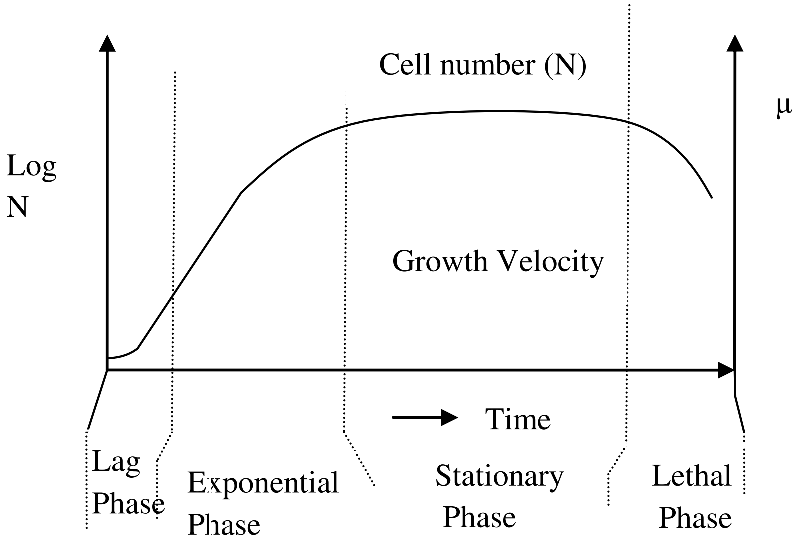


Fig. 2.10 Growth Phases of Micro-organisms

This progress with the changeover and the cells are proliferated. In the second phase of ‘exponential' growth the highest possible growth rate is achieved, and as long as no substrate limitation is present, it remains constant. The third ‘stationary’ phase is reached when the mass of the micro-organisms no longer changes. There is a dynamic equilibrium between the die and the creation of individual cells. In addition to a substrate limitation the high population density, an oxygen limitation or the accumulation of toxic metabolic products (product inhibition) leads to the transition from the exponential phase into the stationary phase (Schlegel, 1992). In the last ‘lethal’ phase, the cell count decreases due to the consumption of toxic substances or conditions.

The energy gain in aerobic degradation is significantly higher since the complete removal of the original substances can be achieved, while the anaerobic degradation is always incomplete in terms of oxidised reaction products. This can be clarified based on the example of the glucose reduction as shown in Table 2.3. Microorganisms can be classified according to different criteria. In relation to the temperature optimisation the microorganisms role in biodrying is divided as (1) *Psychrophile,* micro-organisms reach their maximum growth rates below 20°C; (2) *Mesophilic* microorganisms between 20°C and 42°C and (3) *Thermophilic* organisms above 40 °C with a growth limit at 70 °C (Schlegel, 1992).

Table. 2.3 Glucose Reduction Reaction

Reaction	**Stoichiometric reduction equation**	**Energy Gain**
Aerobic degradation	$C_6H_{12}O_6 + 6O_2 \rightarrow 6\ CO_2 + 6\ H_2O$	+ 2880 kJ
Anaerobic degradation	$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3CH_4$	+ 405 kJ

The thermophilic organisms have the highest absolute growth rate and also the highest reduction performance. The mining performance of populations in the transition area between the mesophilic and thermophilic will be small because of the unfavourable temperature for both groups. The sanitization is of great importance during the treatment of waste with critical pathogenic components. In the case of composting of bio-waste, the most living cells of pathogenic microorganisms were killed off at temperatures above 60°C in a few hours of time (Knoblauch, 2001). One hour heating in the range of 50°C to 55°C temperature will kill most of the common parasites and pathogens (Gottas, 1956).

In the case of biodrying treatment where municipal solid waste with readily degradable biogenic substances is used a similar hygienisation effect can be expected. However partial sanitisation of the output is also reasonable for the bulk of the biodried product since sanitisation to high standards is not necessary as its end use is thermal energy recovery (Adani et al., 2002; Calcaterra et al., 2000).

Regarding the optimum pH value behaviour of the biodrying process, most of the microorganisms are neutrophils (pH-value 7) or may prefer slightly alkaline conditions (pH-value 8). Many micro-organisms produce organic acids as a metabolic product, but they cannot tolerate this. Therefore the compliance of a specific pH value has an important role to play in biodrying reaction. Hence in the case of static biodrying processes, the mixing of materials before treatment and dilution of the acids by addition of water is a technical possibility to reduce such problems.

2.9.2 Particle Level

Aerobic degradation processes for diverse types of substrates with different sizes have various levels of complexity. The biological treatment of mixed municipal waste is assumed to be a highly complex system, where both from the substrate side as well as from the micro-organisms side wide variations exist (Fig.2.11). Therefore a quantitative formal kinetic description of the reduction is impossible.

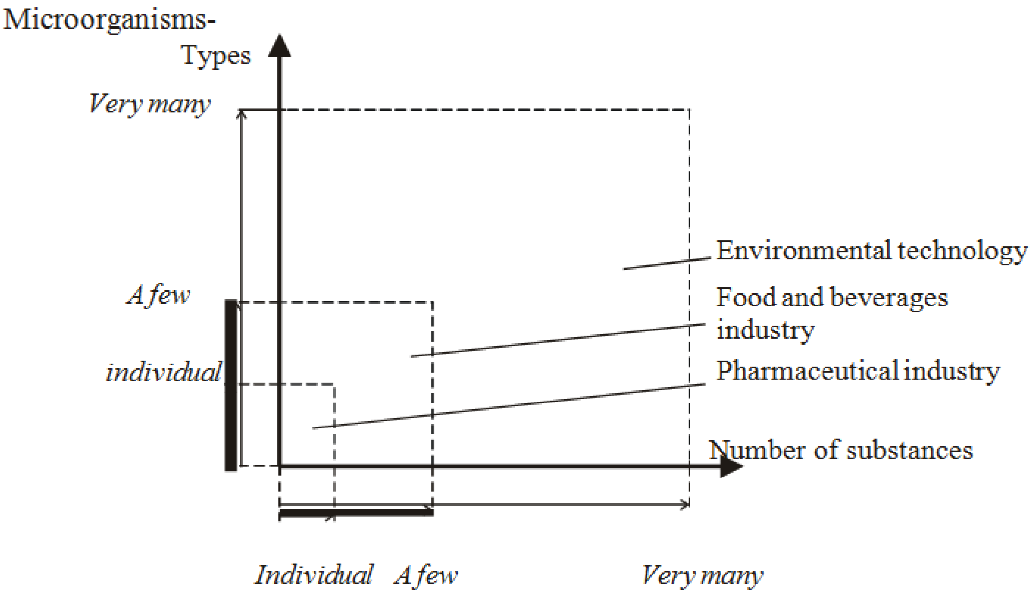


Fig. 2.11 The Schematic Representation of the Complexity of Biotechnological Processes

The scale of the process is a significant factor affecting the results of experiments depending on the material and heat exchange processes. In the literature, there are many mathematical models for the kinetics of the aerobic degradation processes and its technical implementation for a range of substrates. It is a critical fact that there is currently a wide variation between the results from the modelling of biological processes and the implementation of results in practice. The limited suitability for practical use of the models developed has resulted in this situation. The interaction of the entire population of micro-organisms for a given substrate composition denote observable characteristics of the individual process parameters. Temperature is the key factor for the description of the biological processes. It is to be noted that the temperature measured in the medium of a thermodynamic state is a special case of the microbial activity. The value of the temperature can be found by the formal context as given by the equation below.

Reduction of heat production → Heat stored (heat production - heat dissipation - heat losses) →Heat capacity →Temperature explained

The temperature may not be regarded as an objective guide size since it is affected by other process parameters. Also, the gas phase concentration of measured carbon dioxide is unsuitable as a guide size because it depend on the process control and this can be done through the formal context as given below.

Reduction of CO_2 production →Ventilation set current *CO_2 concentration* → CO_2 concentration explained

The weight reduction due to biodegradation and the heat production coupled with carbon dioxide production initially appear as a single independent dimension for the description of the biological activity. For the theoretical and rough accounting of the process, the composition of the material is required. The stoichiometric equation of the complete aerobic degradation can be specified in a general form:

$$C_aH_bO_cN_d + \vartheta_{o2}.O_2 \rightarrow \vartheta_{co2}.CO_2 + \vartheta_{H2O}.H_2O + \vartheta_{NH3}.NH_3\text{-----------}(2.1)$$

Where - a, b,c, d are the stoichiometric number for chemical formula

ϑ_{o2}- Number of molecules of oxygen

ϑ_{co2} - Number of molecules of carbon dioxide

ϑ_{H2O} - Number of molecules of water

ϑ_{NH3} - Number of molecules of ammonia.

The organic material is usually represented with a general formula. In the literature there are different formulae for organic substances with non-specific substances, and also for the mixed municipal solid waste substrate. The validity of the reduction equation 2.1 can be made measurable parameters, especially from the consuming of oxygen and carbon dioxide production, and also by directly measuring the reduction in weight. In the present research, the weight reduction is taken as the monitoring parameter for assessing the biodegradation and the moisture reduction for assessing the drying performance. During the aerobic degradation, the amount of water produced is insignificant. A group of substances included in fats and oils produce more water while considering the mass of the organic matter reduced. But in the biodrying process, the water production is significant which move to the gas phase and thus the efficiency of the overall process is reduced.

The ratio between the water production and the measurable carbon dioxide production is given by the following formula (mol/mol):

$$\tilde{Y}_{\frac{H2O}{CO2}} = \frac{|\vartheta_{H2O}|}{|\vartheta_{CO2}|} \text{ -- } (2.2)$$

$\tilde{Y}_{\frac{H2O}{CO2}}$ - Molar yield of water and measurable CO_2 production

The quantity energy released from the aerobic degradation can be approximately obtained from the calorific value of the specified degraded material. The reference database for waste mixtures reported that the calorific value of mixed municipal solid waste varies between 18,000 - 21,000 kJ/kg OTS (Haug, 1993; Krogmann, 1994; Paar, 2000). The CO_2 related reaction enthalpy can be calculated on this basis, i.e., the heat released during the formation of a unit quantity of CO_2 is determined by:

$$|\Delta h_B| = \frac{H_o}{\tilde{Y}_{CO2/OTS}} \text{ --- } (2.3)$$

Where Δh_B – reaction enthalpy kJ/mol CO_2

H_0- Calorific value (kJ/kg)

OTS- Organic components (kg)

For glucose with a calorific value of 16,000 kJ/kg, this reaction enthalpy is obtained as; $|\Delta h_B| = 480 \text{ kJ/molCO}_2$

By integrating basic knowledge of composting, the optimal start conditions of aerobic degradation are limited as given below (Haug, 1993; Krogmann, 1994).

- Water content - 50-55 %-percent (minimum required in the degradable substance)
- Pore Ratio (Porosity) - 25-30 Vol% (to ensure the flow capability)
- PH-value - 6 to 8
- C/N-ratio - 25 to 35:1.

Since the biodrying also has the same core process, these requirements apply without restriction.

2.9.3 Macro- Level Studies

The principle of the biodrying process is that the dry and usually cold air is passed preferably from bottom to top through the debris. The biodegradation reaction heats the air up and at the same time load it with water vapour (Fig. 2.12). The basic view of the conservation of a bulk pile is a heterogeneous model. In a differential volume of element dV, the solid and liquid phase exists on the one side and on the other side a gas phase. They are separated from each other by the gas phase as shown in Fig.2.12. In the gaseous phase an infinite expansion in x and y direction can be assumed (Bartha, 2008).

The major advantage of biodrying compared to the classic convective drying with warm air is that not only a top layer of particles but all the particles are exposed to dry air theoretically due to self heating reactions.

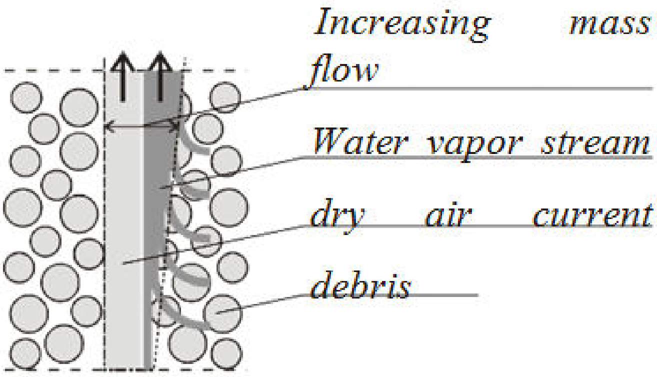


Fig. 2.12. Biodrying Process Flow Diagram
(Peuker and Stahl, 2002).

A thermodynamic equilibrium between the liquid and the gas phase take place locally at the particle level, when sufficiently low flow velocity of the dry air occurs. The drying air for the biodrying process can vary from dry air up to the saturation water vapour. In this sense, the biological drying is perceived as a special case of the flow-through drying. The energy for the evaporation of the water is attained by the biological activity of micro-organisms, i.e. energy will be provided from within the drying material which is the major significance of the process. This is an important difference compared to the conventional drying, in which the energy required for drying is stored at the beginning by a preheated solid-liquid matrix or the drying energy is transported into the debris by the passage of warm air. The effective drying performance can be measured by different means like measuring the water transferred through air, by measuring the weight loss and moisture reduction, or by measuring steam production of exhaust air. In the case of reversal of temperature profile (falling temperature) in the debris, a re-aeration of water vapour is required to prevent the formation of condensation (Peuker and Stahl, 2002). Hence 100% saturation of exhaust air may be avoided to prevent temperature fall at the top layer of the reactor.

2.10 MATERIAL BALANCE IN BIODRYING

The most important material balance for the drying process is the water balance. The balanced water exists either as a liquid on the surfaces of the hard substance or as water vapour in the gas phase. Mass balance for the designed biodrying processes is presented in the flow diagram (Fig.2.13). The corresponding equations used for calculation are

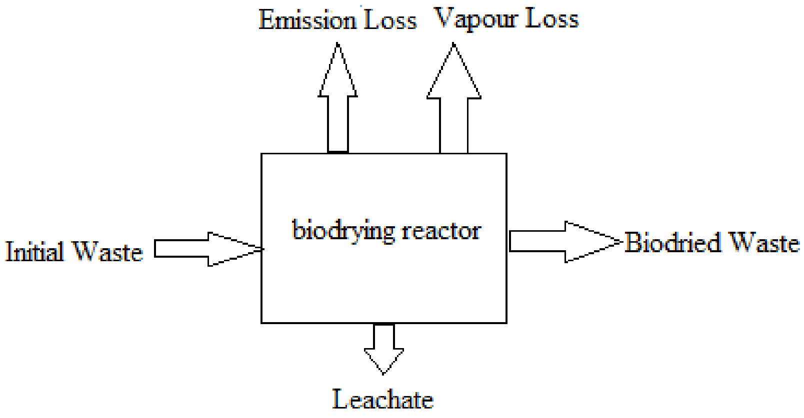


Fig. 2.13 Mass Balance Flow Diagram

The water losses at time t (W^t_{loss}, kg) are calculated by:

$$W^t_{loss} = (WM_0 \times w_0) - (WM_t \times w_t) \text{--} (2.4)$$

Where WM_0 (kg) and WM_t (kg) are the wet materials at the initial time and time t, respectively, w_0 (%) and w_t (%) are water content at initial time and time t, respectively.

Total net emission losses at time t (E_{loss}, kg) are given by

$$E_{loss} = WM_0 - WM_t - W^t_{loss} - LO^t_{loss} \text{--} (2.5)$$

Where LO^{t}_{loss} is leachate weight, that is absent in the up flow biodrying reactor unit

Also the actual emission loss based mass balance analysis can be done (Bartha, 2008; Zhang, 2008) and both the results can be compared to analyse the biodrying process in detail.

2.11 HEAT ENERGY IN BIODRYING

The temperature gradient in the flow direction can be studied through the heat balance calculations, for the same volume of the element as considered in the mass balance. As per previous investigations (Peuker and Stahl, 2002), the specific enthalpy is not linear in biodrying reaction which depends on the temperature; the heat balance equation is a nonlinear inhomogeneous partial differential equation that cannot be solved analytically. Therefore the study of temperature cumulation effect will explore the self heating reaction in biodrying (Zhao et. al., 2010). The temperature cumulation index can be calculated using mean matrix temperature(T_m) and temperature of air inlet (T_i) which is given by:

Temperature cumulation index (TCI) = $\sum(T_m - T_i).\Delta t$ ------------------------ (2.6.)

Where Tm = mean matrix temperature (°C), Ti = temperature of air inlet (°C) and Δt = Time interval (day)

2.12 EXISTING BIODRYING REACTOR CONFIGURATIONS

The biodrying mechanical-biological treatment (MBT) plants are operational named “Biocubi” aerobic drying process and Herof process. But the processes are neither fully understood nor optimised (Adani et.al., 2002). Almost 20 commercial references of biodrying units are operational in MBT plants for different feed materials in Europe, with overall capacity of 2,000,000 Mg/a^{-1} (Herhof GmbH, 2008; Shanks, 2007). Though many biodrying systems exist in the world for treatment of different types of substrates in MBT plants and other waste treatment units, mixed municipal solid waste treatment systems are lacking. There is only one biodrying configuration available in the world for treatment of mixed municipal solid waste that is the patented Wehrle Werk system which is operated on mixed municipal solid waste. It uses mechanical pre-treatment followed by percolation (“Bio-percolat”) and anaerobic digestion, aiming at 32 easily degradable materials (Juniper, 2005). Biodrying configurations existing for commercial MBT plants in Europe are Herof System “Rotte boxes ®” in Germany and Eco-deco “Biocubi®” in Italy. Herof System “Rotte boxes” utilises the costly air recirculation system, since the air is not fully allowed to be efficiently exhausted in the reactor chamber due to the design limitation of the closed chamber (Fig.2.14).

The simplified reactor design consist of static enclosed chamber with air blowers blowing air through bottom perforated pipes are used (Fig.2.15). The pipe C2 blows and pulls air alternately while the pipes C1 and C2 work conversely. The design lacks the process control since the air blowers are used.

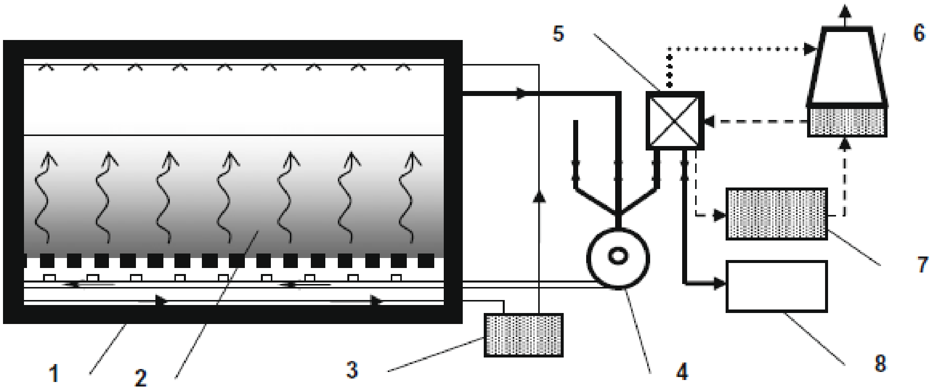


Fig.2.14 Herof System [with enclosed box (1) with air flow (2) exhaust air recirculation (4, 5, 6, 7) leachate collection system (3) and biofilter]

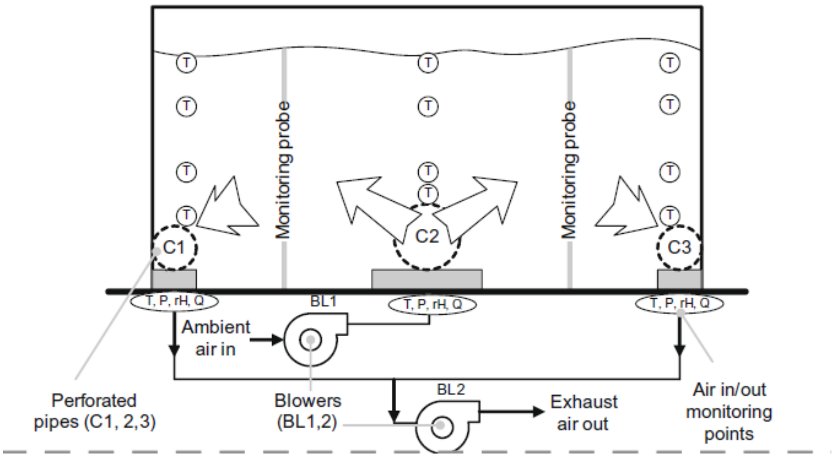


Fig.2.15 Static Enclosed Chamber with Perforated Pipes Blowing and Pulling Air Alternately. (Frei et al., 2004b)

Another rotating biodrying reactor system consists of cylindrical rotating drum with one perforated pipe as shown in Fig. 2.16 (Bartha, 2008).The rotation of the reactor is supposed to give more homogeneous output than static reactor. Considering the energy balance of the process the energy required for rotation will make the process expensive.

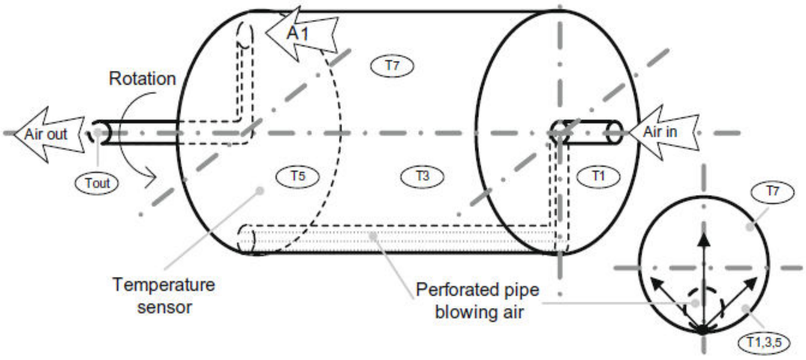


Fig.2.16 Rotating Drum Reactor

The technology transfer for bioconversion technologies could be possible, but wide differences are evident and hence uncritical exploration of the results of reactor designs, scales, substrates and operating regimes may be misleading (Velis et. al., 2009). The blind technology transfer from developed countries to the developing countries and its subsequent failure has brought attention to the need for appropriate technology development to suit the regional conditions like type of waste, composition, treatment, etc.(Beukering et. al., 1999).

2.13 CONDENSATION PREVENTION TECHNIQUES

The prevention of air saturation of the exhaust air is very necessary in biodrying process so that re-wetting of reactor top can be avoided. A number of methods for preventing condensation in reactors have been studied. A detailed study was conducted to select a proper method of heat exchange so as to avoid condensation above the top of the reactor matrix.

2.13.1 Direct-Transfer Type Exchangers

In this type, heat transfers continuously from the hot fluid to the cold fluid through a dividing wall. Although a simultaneous flow of two (or more) fluids is required in the exchanger, there is no direct mixing of the two (or more) fluids because each fluid flows in separate fluid passages. In general, there are no moving parts in such heat exchangers. This type of exchanger is designated as a recuperative heat exchanger or simply as a recuperator.

2.13.2 Direct-Contact Heat Exchangers

In a direct-contact exchanger, two fluid streams come into direct contact, exchange heat, and are then separated. Common applications of a direct-contact exchanger involve mass transfer in addition to heat transfer, such as in evaporative cooling and rectification; applications involving only sensible heat transfer are rare. The enthalpy of phase change in such an exchanger generally represents a significant portion of the total energy transfer. The phase change generally enhances the heat transfer rate. Compared to indirect contact recuperators and regenerators, in direct-contact heat exchangers, (1) very high heat transfer rates are achievable, (2) the exchanger construction is relatively inexpensive, and (3) the fouling problem is generally nonexistent, due to the absence of a heat transfer surface (wall) between the two fluids. However, the applications are limited to those cases where a direct contact of two fluid streams is permissible.

2.13.3 Gas–Liquid Exchangers

In this type of heat exchanger, one fluid is a gas (more commonly, air) and the other a low-pressure liquid (more commonly, water) are readily separable after the energy exchange. In either cooling of liquid (water) or humidification of gas (air) applications, liquid partially evaporates and the vapour is carried away with the gas. In these exchangers, more than 90 % of the energy transfer is by virtue of mass transfer (due to the evaporation of the liquid), and convective heat transfer is a minor mechanism. A ‘‘wet’’ (water) cooling tower with forced- or natural-draft airflow is the most common application. Other applications are the air-conditioning spray chamber, spray drier, spray tower, and spray pond.

2.13.4 Single-Pass Exchangers –Counter flow Exchanger

In a counter flow or counter current exchanger, as shown in Fig. 2.17., the two fluids flow parallel to each other but in opposite directions within the core (Shah, 1981). The temperature variation of the two fluids in such an exchanger may be idealized as one-dimensional, as shown in Fig.2.17.

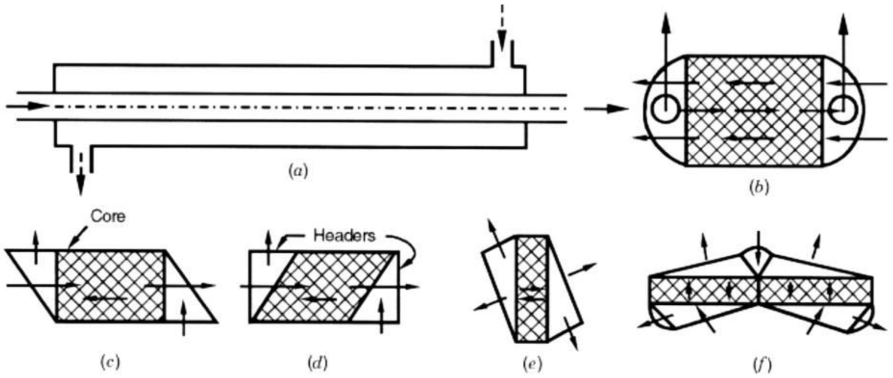


Fig. 2.17 a) -Double-Pipe Heat Exchanger with Pure Counter Flow; (b-f) Plate –Fin Exchangers with Counter Flow Core and Cross Flow Headers. (Shah,1981)

As shown later, the counter flow arrangement is thermodynamically superior to any other flow arrangement. It is the most efficient flow arrangement, producing the highest temperature change in each fluid compared to any other two-fluid flow arrangements for a given overall thermal conductance (UA), fluid flow rates, and fluid inlet temperatures. Moreover, the maximum temperature difference across the exchanger wall thickness (between the wall surfaces exposed on the hot and cold fluid sides) either at the hot or cold-fluid end is the lowest, and produce minimum thermal stresses in the wall for an equivalent performance compared to any other flow arrangements. However, with plate-fin heat exchanger surfaces, there are manufacturing difficulties associated with the true counter flow arrangement. This is because it is necessary to separate the fluids at each end, and the problem of inlet and outlet header design is complex. Some header arrangements are shown in Fig.2.17 (b–f). Also, the overriding importance of other design factors causes most commercial heat exchangers to be designed for flow arrangements different from single-pass counter flow if extremely high exchanger effectiveness is not required.

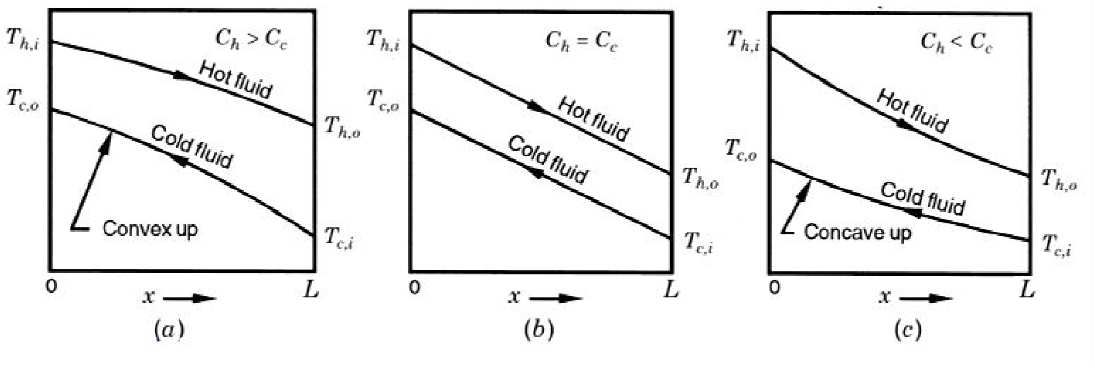
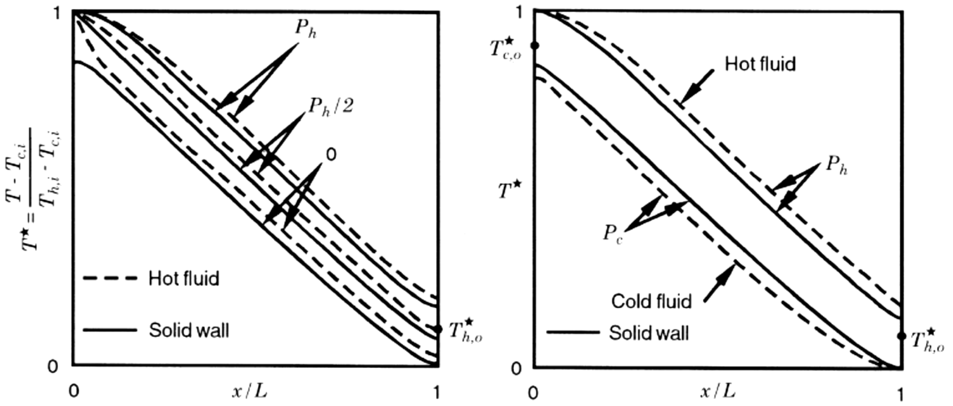


Fig.2.18 Temperature Distributions in a Counter Flow Heat Exchanger of Single-Phase Fluids

Typical temperature distributions for a counter flow regenerator are shown in Fig.2.18. In Fig.2.18 $C_h=(mc_p)_h$ is the heat capacity rate of the hot fluid, C_c is the heat capacity rate of the cold fluid ,and specific heats c_p are treated as constant. The symbol T is used for temperature; the subscripts h and c denote hot and cold fluids, and subscripts i and o represent the inlet and outlet of the exchanger (Shah, 1981).

2.13.5 Cross flow Exchanger

In this type of exchanger, as shown in Fig. 2.19, the two fluids flow in directions normal to each other. Typical fluid temperature variations are idealized as two-dimensional and are shown in Fig. 2.19 for the inlet and outlet sections only. Thermodynamically, the effectiveness for the cross flow exchanger falls in between that for the counter flow and parallel flow arrangements. The largest structural temperature difference exists at the ''corner'' of the entering hot and cold fluids, such



(a) (b)

Fig. 2.19 (a) Hot-side Solid and Fluid Temperature Excursion; (b) Balanced ($C_h=C_c$)Regenerator Temperature Distributions at the Switching Instant

(Shah,1991b)

as point as in Fig. 2.20. This is one of the most common flow arrangements used for extended surface heat exchangers, because it greatly simplifies the header design at the entrance and exit of each fluid. If the desired heat exchanger effectiveness is high (such as greater than 80 %), the size penalty for the cross flow exchanger may become excessive. In such a case, a counter flow unit is preferred.

In a cross flow arrangement, mixing of either fluid stream may or may not occur, depending on the design. A fluid stream is considered unmixed when it passes through individual flow channels or tubes with no fluid mixing between adjacent flow channels. In this case within the exchanger, temperature gradients in the fluid exist in at least one direction (in the transverse plane) normal to the main fluid flow direction.

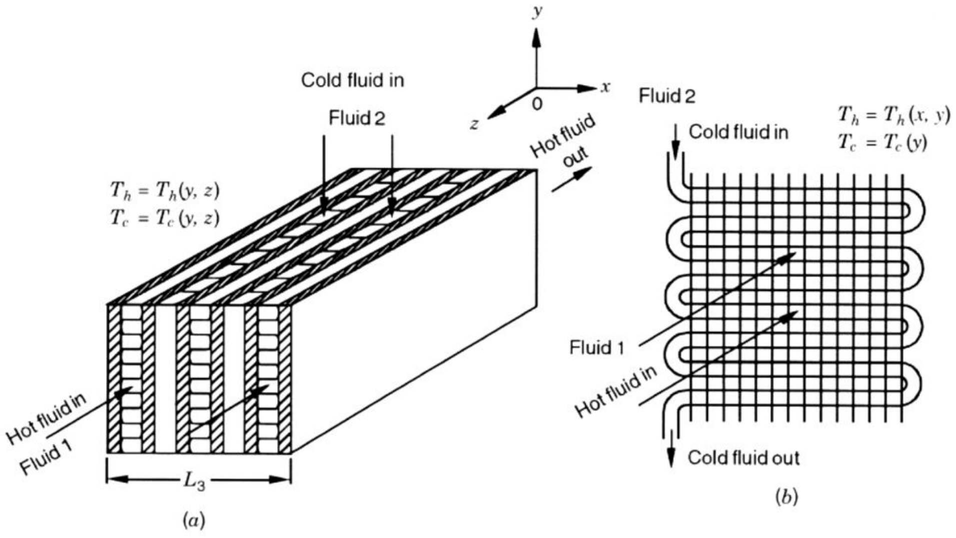


Fig. 2.20 (a) Plate-fin Unmixed Cross Flow Heat Exchanger; (b) Serpentine (one tube row) Tube-Fin Unmixed Cross Flow Heat Exchanger. (shah,1981).

A fluid stream is considered completely mixed when no temperature gradient exists in the transverse plane, either within one tube or within the transverse tube row within the exchanger. Ideally, the fluid thermal conductivity transverse to the flow is treated as zero for the unmixed-fluid case and infinity for the mixed-fluid case.

Fluids 1 and 2 in Fig. 2.20(a) are unmixed. Fluid 1 in Fig.2.20 (b) is unmixed, while fluid 2 is considered mixed because there is only one flow channel. The temperature of an unmixed fluid, such as fluid 1 in Fig.2.20, is a function of two coordinates z and y within the exchanger, and it cannot be treated as constant across a cross section (in the y direction) perpendicular to the main flow direction x. Typical temperature distributions of the unmixed fluids at exchanger outlet sections are shown in Fig.2.21. The outlet temperature from the exchanger on the unmixed side is defined as a mixed mean temperature that would be obtained after complete mixing of the fluid stream at the exit. For the cases of Fig. 2.19, it is idealized that there is no variation of the temperature of either fluid in the x direction. The temperature of a mixed fluid (fluid 2 in Fig. 19 (b) is mainly dependent on the coordinate y. The temperature change per pass (in the x direction) of fluid 2 in Fig. 2.17 is small compared to the total. In a multiple-tube-row tubular cross flow exchanger, the tube fluid in any one tube is considered mixed at any cross section.

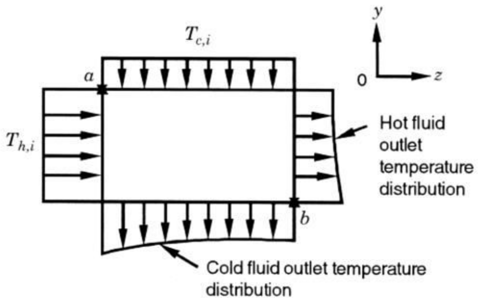
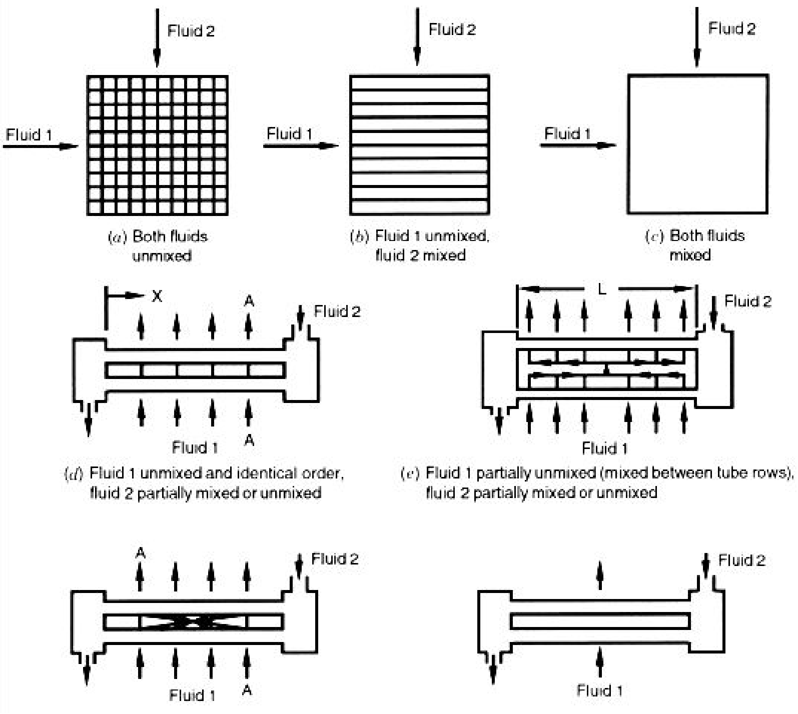


Fig.2.21 Temperature Distributions at Inlets and Outlets of an Unmixed Cross Flow heat exchanger *(Shah 1981)*

However, when split and distributed in different tube rows, the incoming tube fluid is considered unmixed between the tube rows. Theoretically, it would require an infinite number of tube rows to have a truly unmixed fluid on the tube side. In reality, if the number of tube rows is greater than about four, it will practically be an unmixed side. For the heat exchanger system with fewer than about four or five tube rows, the tube side is considered partially unmixed or partially mixed. Note that when the number of tube rows is reduced to one, the tube fluid is considered mixed.

Mixing thus implies that a thermal averaging process takes place at each cross section across the full width of the flow passage. Even though the truly unmixed and truly mixed cases are the extreme idealized conditions of a real situation in which some mixing exists, the unmixed condition is nearly satisfied in many plate-fin and tube-fin (with flat fins) exchanger applications.



(*a*) Both fluids unmixed

(*b*) Fluid 1 unmixed, fluid 2 mixed

(*c*) Both fluids mixed

(*d*) Fluid 1 unmixed and identical order, fluid 2 partially mixed or unmixed

(*e*) Fluid 1 partially unmixed (mixed between tube rows), fluid 2 partially mixed or unmixed

Fig. 2.22 Symbolic Representation of Various Degrees of Mixing in a sSngle-Phase Cross flow exchanger. *(Shah 1981)*

It was observed that for the same surface area and fluid flow rates, (1) the exchanger effectiveness generally decreases with increasing mixing on any fluid side, although counter examples can be found in the multi-pass case; and (2) if the fluid with maximum specific heat capacity is placed on the unmixed fluid side, the exchanger effectiveness and performance will be higher than that for placing the same on the mixed fluid side. Seven idealized combinations of flow arrangements for a single-pass cross flow exchanger are shown symbolically in Fig.2.22. The flow arrangements are: (a) Both fluids unmixed. A cross flow plate-fin exchanger with plain fins on both sides represents the ‘‘both fluids unmixed’’ case. (b) One fluid unmixed, the other mixed. A cross flow plate-fin exchanger with fins on one side and a plain gap on the other side would be treated as the unmixed–mixed case: (c) Both fluids mixed. This case is practically less important, and represents a limiting case of some multi pass shell-and-tube exchangers (d) one fluid unmixed and coupled in identical order, the other partially mixed. Here identical order refers to the fact that a fluid coupled in such order leaves the first row at the point where the other fluid enters (leaves) the first row, and enters the other row where the second fluid enters (leaves) that row (see the stream AA in Fig. 2.22(d).

A tube-fin exchanger with flat fins represents the case of tube fluid partially mixed, the fin fluid unmixed. When the number of tube rows is reduced to one, this exchanger reduces to the case of out-of-tube (fin) fluid unmixed the tube fluid mixed (case b). When the number of tube rows approaches infinity (in reality greater than four), the exchanger reduces to the case of both fluids unmixed (case a). (e) One fluid partially unmixed, the other partially mixed. The case of one fluid (fluid 1) partially unmixed (i.e., mixed only between tube rows) and the other (fluid 2) partially mixed

(Fig.2.22.e) is of less practical importance for single-pass cross flow exchangers. When the number of tube rows is reduced to one, this exchanger is reduced to the case of out-of-tube fluid unmixed, the tube fluid mixed.

2.14. LITERATURE REVIEW-SUMMARY

The technological options for different municipal solid waste treatment methods have been studied in detail. It was observed that waste to energy technologies for municipal solid waste treatment are the need of time to prevent the accumulation of the same in landfills and dumping yards. Mixed municipal solid waste treatment technologies are better for situations where the segregated collection of municipal solid waste at source is lacking. Another advantage of mixed municipal solid waste treatment systems is that high calorific value of components like plastics and textiles which will increase the total energy value of the solid waste. Also the inherent bulking agents like paper, textiles and plastic can be utilised for the biodrying process with the use of mixed municipal solid waste as substrate. Thermal methods are most suitable for treating municipal solid waste in mixed condition. Raw municipal solid waste with high moisture content and low calorific value is challenging while considering the feasibility of thermal treatment methods. In this scenario, the "Biodrying Technology" is a sustainable option for converting raw municipal solid waste with high moisture content into a product with low moisture content and high calorific value, which can be used for waste to energy applications. The biodried municipal solid waste facilitates the energy recover from incinerators and also it avoids the need of auxiliary fuel for starting combustion. The production of refuse derived fuel (RDF) from biodried output has the potential to partially substitute the fossil fuels in industrial applications which will help to substantially reduce the amount of the waste going to landfill. The major application of RDF produced from MSW is in thermal power plants, cement kilns and industrial processes. The detailed evaluation of the mechanism of biodrying process has revealed that it is a complex reaction that has different levels. The aerobic degradation of organic substances by microbes is a deciding factor in biodrying reaction. The cells of microorganisms can be considered as the smallest continuously working reactors and the growth of microorganisms require an optimum physico-chemical environment. Four phases of microbial growth namely lag phase, exponential phase, stationary phase and lethal phase decides the process control strategy in biodrying. The thermophilic organisms have the highest absolute growth rate and also the highest moisture reduction performance and also the mesophilic organisms actively participate in biodrying reaction. One hour heating of the substrate in the range of 50 °C to 55 °C temperature will kill most of the common parasites and pathogens which is the suitable temperature range for effective sanitization of biodried output. However partial sanitisation of the output is also reasonable for the bulk of the biodried product. This is due to the fact that sanitisation to high standards is not necessary as the end use of biodried material is in thermal energy recovery. The pH of the substrate is an important factor affecting the microbial reaction, and hence in the case of static biodrying processes, the mixing of materials before treatment will ensure maintaining optimum pH range. The pilot scale reactor system can be used in the present study so that it can simulate the actual conditions in commercial scale units. The process temperature profile and weight loss profile studies in the innovatively designed pilot scale biodrying reactor are very valuable for further research activities in this field.

The volume reduction, bulk density enhancement and the moisture reduction of municipal solid waste with high moisture content is a matter of high importance in solid waste management practices, which is making the biodrying process versatile.

CHAPTER 3

MUNICIPAL SOLID WASTE CHARACTERISATION STUDY

3.1 MUNICIPAL SOLID WASTE DATABASE

The municipal solid waste components in this study were categorised into different types based on the data base of municipal solid waste (MSW) for Kerala state (KSUDP, 2006; Varma, 2006). The database has revealed that on an average about 71.74 % of municipal solid waste of the region is organic in nature. The major portion of organic waste is constituted by the food waste and the remaining part is the garden waste, which is contributing to the high moisture content of MSW of the region. The characterisation relevant to the biodrying process mainly consisted of the study of physical parameters, which determines the energy potential of MSW. The individual components of municipal solid waste have been analysed to find out the moisture content (%) and the volatile solids content.

3.2. MATERIALS AND METHODS

The components of mixed municipal solid waste have been categorised as organic, paper and cardboard, plastics and textiles. The metals and inert components were not considered in this study since the energy value is negligible for the same. The proximate analysis has been carried out for individual components of mixed municipal solid waste.

3.2.1 Proximate Analysis

Proximate analysis includes the measurement of moisture content and volatile matter content of the mixed municipal solid waste. The measurement has been carried out for individual components of municipal solid waste. The individual results have been applied by weighted average method so that the results for mixed municipal solid waste can be obtained.

Moisture Content

Moisture content is determined for triplicate numbers of samples on a particular day of collection. The dishes used for the analysis were preheated at 105^0 C for 24 hrs. The percentage moisture content of the individual component of MSW has been determined by taking 1kg of the thoroughly mixed samples in a pre-weighed dish. The samples were dried in a hot air oven at 105^0C till a constant weight is achieved (ASTM- D 3173-87,1996).The percentage moisture content is calculated as the percentage loss in weight before and after drying. The equation for calculation is given as

$$\% \text{ Moisture content} = [(\text{Wet weight- Dry weight})/\text{Wet weight}] \times 100$$

Volatile Matter Content

The triplicate samples of individual components of MSW used in the moisture determination were weighed and placed in a muffle furnace for 7 minutes at 950°C (ASTMD-3175-89).The samples are weighed after the combustion to determine the dry ash content. The volatile solids content can be calculated as given below.

$$\% \text{ Volatile Solids} = [(\text{Dry sample weight-Ash weight})/ \text{ Dry sample weight}] \times 100$$

3.2.2 Weighted Average Method for Moisture Content

Weighted average method includes applying the weightage to the experimental results based on the composition of the municipal solid waste. The composition of municipal solid waste has been taken from the existing database. In the present study previous results has been taken from the available database (Varma, 2006; KSUDP, 2006).

The results of moisture analysis have shown the wide differences in the organic component of MSW which is most contributing to the moisture content. The moisture content of mixture of the specified components of MSW is calculated as given below.

Moisture content of typical mixture of different components of municipal solid waste is calculated as= Σ (Ai × Ci)

Where, Ai - average moisture content of a particular component

Ci- average composition of a particular component of msw*

*(*KSUDP, 2006)*

3.2.3 Volatile Solids Content of Mixed Municipal Solid Waste by Weighted Average Method

Volatile solids content of typical mixture of different components of municipal solid waste is calculated as= Σ (Bi × Ci)

Where, Bi - average volatile solids content of a particular component

Ci - average composition of a particular component of msw* (*KSUDP, 2006)

3.3. RESULTS AND DISCUSSIONS

The experiments were conducted on different days and for different combinations of waste as available on that particular day. This method is selected to understand the varying nature of the waste characteristics and to obtain a statistical range for the analysing parameters. The graphical representation of the proximate analysis results for organic portion of the municipal solid waste is shown in Fig.3.1.

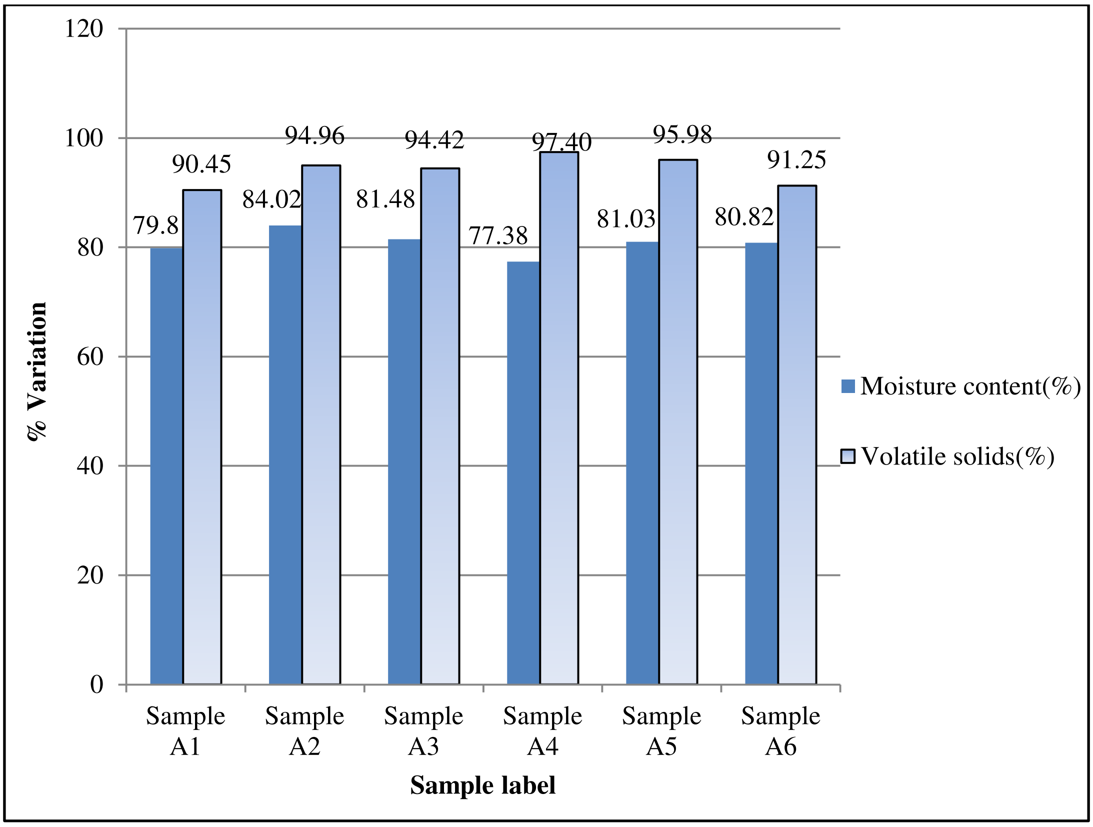


Fig.3.1 Moisture Content (%) and Volatile Solids Content (%) of the Organic Component of Municipal Solid Waste

The daily average value of moisture content of organic portion varies from 77.38 % to 84.02 %. The organic component of municipal solid waste is having high variation in moisture characteristics. The average value of moisture content of organic component (average of samples A1 to A6) is calculated as 80.76 %. The daily average value of volatile solids content of organic portion varied from 90.45 % to 97.4 %. The average value of volatile matter of organic samples (A1 to A6) has been obtained as 94.07 %. The higher percentage of volatile matter indicates the energy value of the component, and hence it is beneficial. These experimental results confirmed that high moisture content of the organic portion of municipal solid waste is the main reason for the reduced calorific value of the MSW since its volatile content is high.

The results of proximate analysis carried out for paper and cardboard component of MSW is shown in Fig. 3.2.

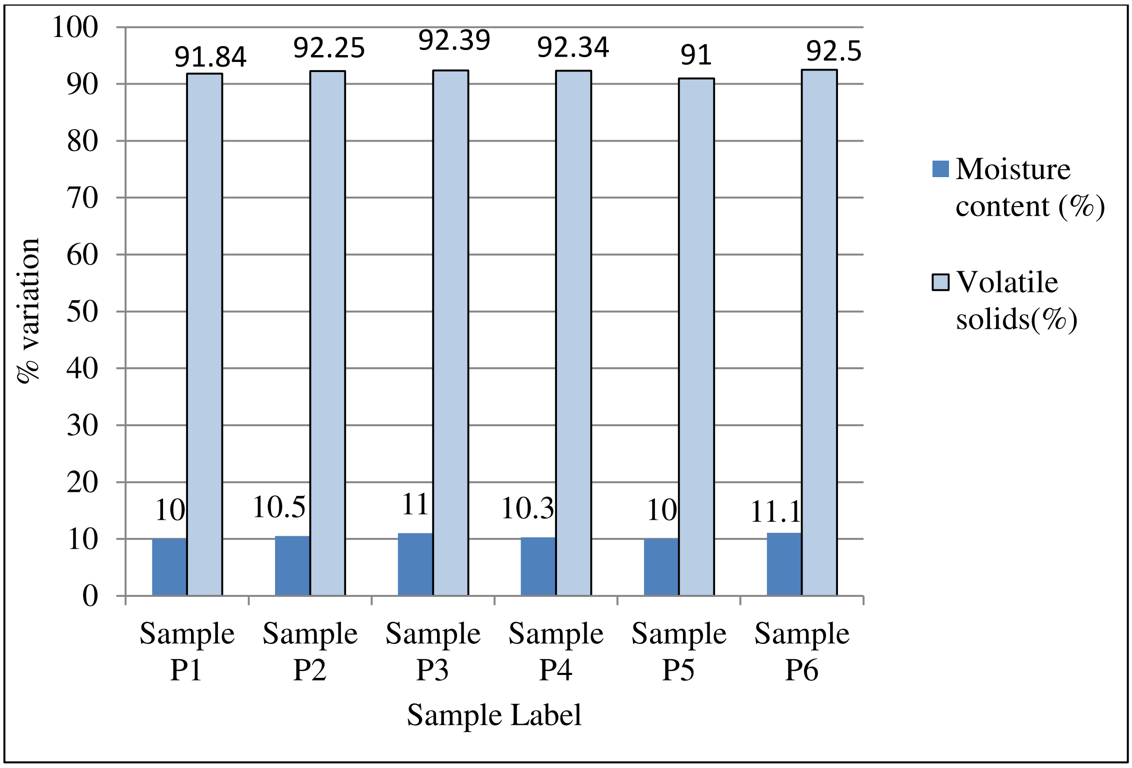


Fig. 3.2 Moisture Content (%) and Volatile Solids Content (%) of Paper and Cardboard Component of Municipal Solid Waste.

It was observed that the variation observed in moisture content of different paper samples is negligible. The average moisture content of 10.48 % has been obtained for six numbers of samples (P1 to P6). The volatile solids (V.S.) content of the samples of paper and card board obtained vary from 91 % to 92.39 %. There was no much variation in volatile solids content of paper and cardboard which resulted in an average value of 92.05 %. The major portion of moisture content of the plastics is contributed by milk covers in the present study. The moisture variation of different samples of plastics has shown in Fig.3.3.

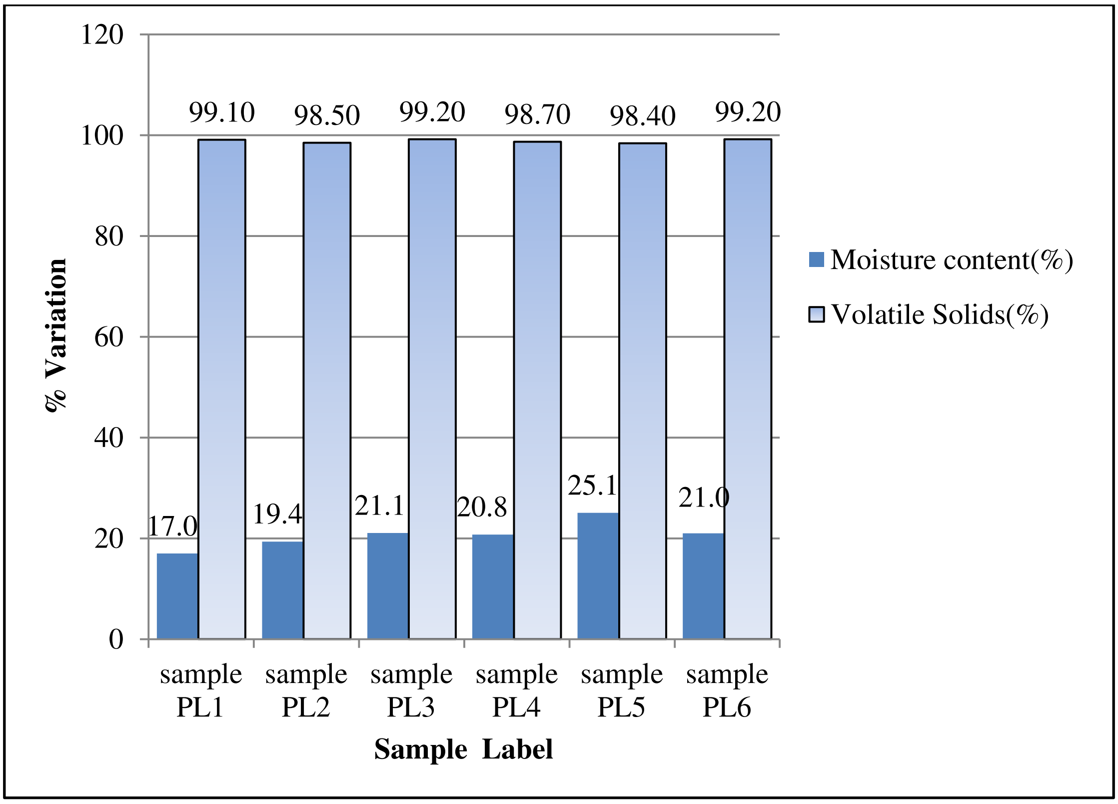


Fig.3.3 Moisture Content (%) and Volatile Solids Content (%) of Plastics Component of Municipal Solid Waste

The moisture content of plastics varies in the range 17-25 %. The average value of moisture content of six samples (PL1-PL6) was obtained as 20.7 %. The volatile solids contents of plastics were observed in the highest range of 98.4 - 99.2 %. The average value of volatile matter of six samples (PL1-PL6) was obtained as 98.85 %. The higher percentage of volatile solids indicates the high energy value of plastics.

The results obtained for proximate analysis for textiles were shown in Fig. 3.4. The moisture variation has been observed in the range 10.1 % to 11.79 %. The average value of moisture content of samples (T1 - T6) was obtained as 11.16 %. The volatile solids content of textiles were obtained in the range 94.36 % to 95.1 %. The average value of volatile solids of textiles was 94.76%, which is advantageous for energy production.

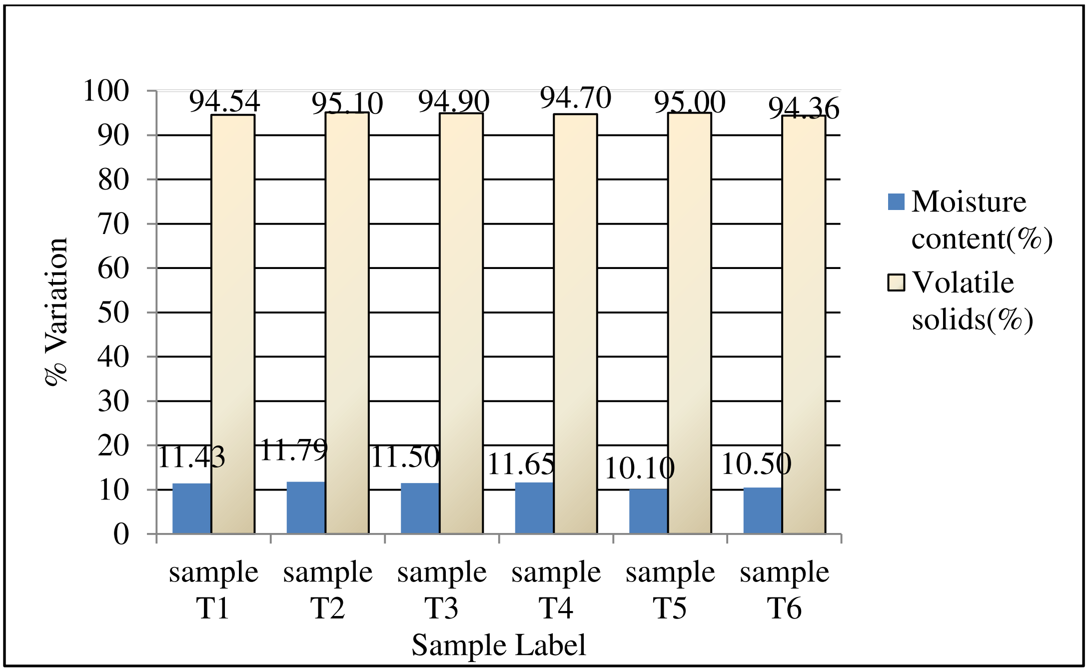


Fig.3.4 Moisture content (%) and Volatile Solids Content (%) of the Textiles Component of Municipal Solid Waste

The components of MSW like metals, rubber, glass, leather, inert particles, etc. are about 10.73% of total MSW (KSUDP, 2006) and their moisture contribution is considered as negligible when compared to other components. Hence their moisture content is assumed as zero for the present study.

The weighted average value of moisture content of typical mixed municipal solid waste is obtained as

$$\Sigma\,(Ai \times Ci) = 61\ \%$$

The weighted average value of volatile solids content of typical mixed municipal solid waste is obtained as

$$\Sigma\,(Bi \times Ci) = 90.2\ \%$$

3.4. SUMMARY

The proximate analysis of different components of mixed municipal solid waste has revealed that it has an average moisture content of 61 %. This is the optimum range required to start the biodrying reaction. Also, the high volatile matter content of 90.2 % has been obtained for the mixed municipal solid waste, which is indicating the suitability of the biodried output in energy producing applications.

CHAPTER 4

BIODRYING REACTOR DEVELOPMENT

4.1 GENERAL

An innovative pilot scale reactor has been developed by considering the feasibility of the structural strength aspect, as well as the selected process conditions. The developed biodrying reactor unit mainly consisted of four parts called reactor chamber, insulation chamber, top chamber and bottom chamber (Fig.4.3). The structural dimensions of the pilot scale reactor chamber have been selected based on the critical bulk density of the municipal solid waste substrate.The study of bulk density distribution in composting piles has reported that bulk density and porosity are influenced by the combined effects of subsidence, loss of organic matter due to biological degradation process, and change of water content due to transport processes (Ginkel et al., 1999).

4.2 STRUCTURAL DESIGN OF PILOT SCALE BIODRYING REACTOR

4.2.1 Dimensions of the Biodrying Reactor

The design details of the biodrying reactor chamber were enlisted in Table.4.1. The volume of the reactor chamber has to accommodate the critical conditions of the substrate. Therefore critical bulk density of 200 kg/m^3 has been taken for the present study which is taken from the available municipal solid waste database (Varma, 2006). The volume required to hold 100 kg waste under critical conditions of bulk density has been obtained as 0.50 m^3. The additional volume has been considered to hold the exhaust gases and including that the total volume of biodrying reactor has been obtained as 0.565 m^3. The cylindrical shaped reactor has been selected since the circular shape is good for uniformity of the reactor matrix as the corners can be avoided. The height of the reactor was limited to 2.0 m at the selected diameter of 0.60 m. Also the practical feasibility of working as well as the moulding and strength aspect of the reactor material has been considered.

Table 4.1 The Structural Dimensions of the Reactor.

Particulars	Quantity	Unit
* Total Density of municipal solid waste (minimum)	207.06	kg/m^3
Critical total density of municipal solid waste taken for design	200	kg/m^3
Weight of MSW	100	kg
Volume required to accommodate 100 kg	0.50	m^3
An extra volume of 10-15 % is required to hold the exhaust gases, Considering an average of 13 % additional Volume	0.565	m^3
Selecting a cylindrical shaped reactor with diameter of 0.60 m, the height required	2.0	m

(*Varma, 2006)

4.2.2 Material Selection for the Reactor Unit

The material used to fabricate the reactor was selected based on the strength aspect, corrosion possibilities, economic considerations, and the fabrication possibilities. The fibre coated mild steel was found to be suitable for insulation chamber, bottom chamber and top cap. The fibre coating is provided so that the corrosion of the insulation chamber can be prevented. The material selected for the moisture analysis chamber of reactor is acrylic, it has high strength, non-corrosive and the visibility of the process inside the reactor is an added advantage.

Fig.4.1 Pilot Scale Biodrying Reactor

4.2.3 Reactor Chamber

The moisture reduction during the biodrying process is taking place in the reactor chamber (Fig.4.1). The structural details of the pilot scale reactor unit have been plotted in Fig.4.2. The different images during the operating stages of the reactor are shown in Fig. 4.3, Fig.4.4 and Fig 4.5.

Design Thickness for Acrylic chamber

The acrylic material was available only in sheets of various thicknesses. So the sheets were to be fabricated into the tubular shape of the moisture analysis chamber. For thepresent design, 2 mm thick acrylic sheets were selected and circular tube of 60 cm diameter and 20 cm height was fabricated, after checking the strength against hoop stress exerted by 100 kg of municipal solid waste.

Youngs Modulus of Elasticity, E= 3.2×10^9 N/m^2

Poissons ratio μ= 0.30

Hoop stress, $\sigma1= (P \times r) \div t$

Longitudinal stress, $\sigma2 = (P\times r) \div 2t$

Pressure, P = Load/Area= $1000/(\pi/4\times0.6\times0.6)$

= 3538.57 N/m^2

t - The thickness of acrylic provided =2 mm.

r- Radius of reactor = 0.3 m

$\sigma1 = P\times r \div t$

$= 3538.57\times0.3 \div (.002)$

$= 5.307\times10^6$ N/m^2

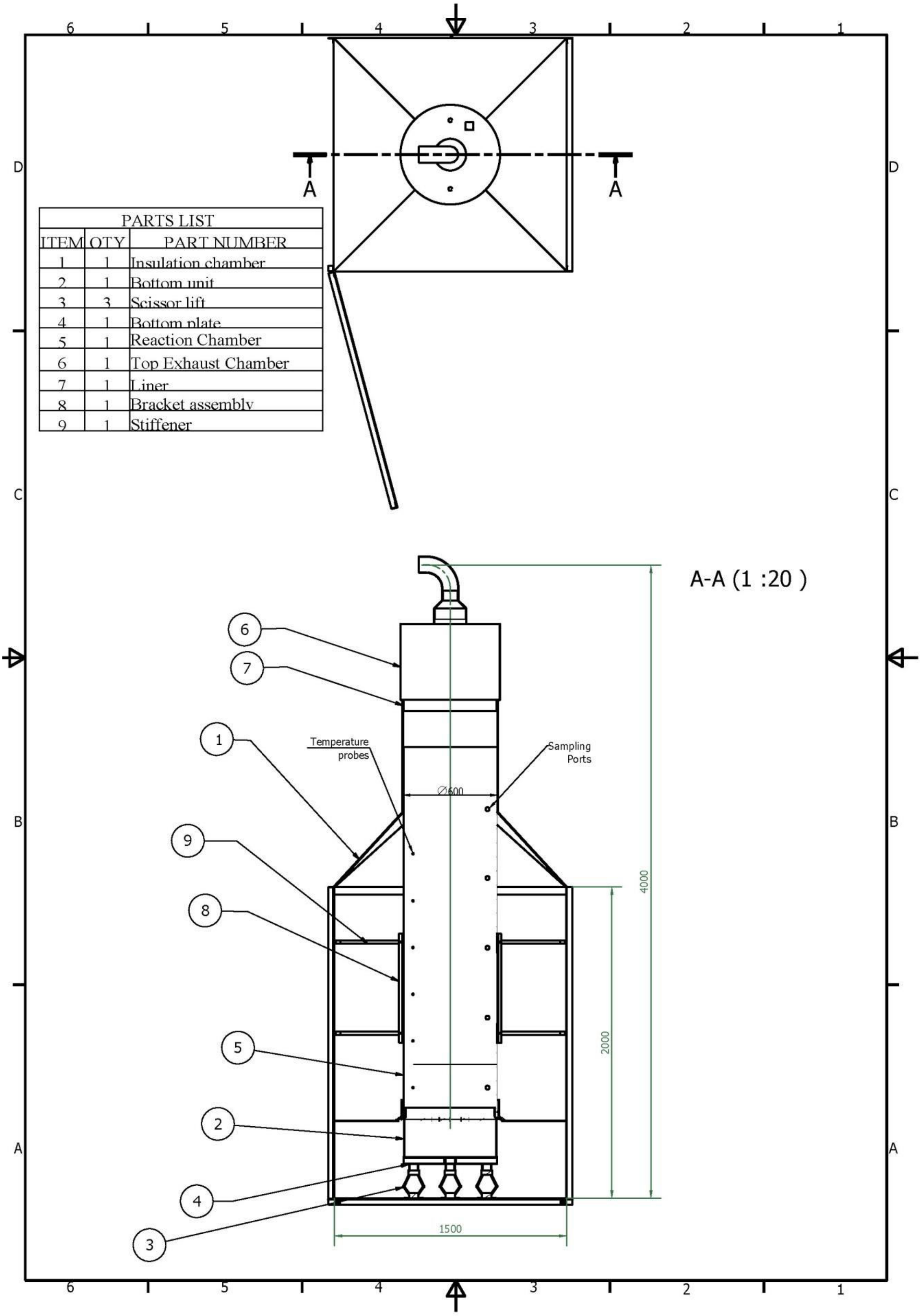
$\sigma 2 = P\times r\div 2t$

$= 3538.57\times0.3\div (2\times.002)$

$= 2.6535\times10^6$ N/m^2

Ultimate tensile strength of the acrylic = 70×10^6 N/m^2

Hence the thickness provided is sufficient. . The acrylic material of 2mm thick was found to be strong enough to resist the hoop stress due to MSW.



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Insulation chamber
2	1	Bottom unit
3	3	Scissor lift
4	1	Bottom plate
5	1	Reaction Chamber
6	1	Top Exhaust Chamber
7	1	Liner
8	1	Bracket assembly
9	1	Stiffener

Fig.4.2 Structural Design of Pilot Scale Biodrying Reactor

Fig.4.3 Empty Reactor Chamber

4.2.4 Insulation Chamber

The insulation chamber of dimension 1.5 m ×1.5 m × 2.0 m has been designed for the biodrying reactor configuration as shown in Fig. 4.2. This chamber was designed in such a way that the insulation property of air is utilised to insulate the reactor chamber from ambient environment (Fig.4.4). The insulation of the reactor chamber is necessary to prevent the energy loss taking place through the walls of the reactor.

This will simulate the process taking place in bigger scale plants. In commercial scale plants the ratio of surface area of reactor exposed to atmosphere and volume of the substrate will be less compared to the lab scale one. Hence inorder to simulate the actual process conditions taking place in bigger scale plants the design of insulation chamber is very essential. The dimensions are fixed by considering the safety during reactor feeding and emptying.

4.2.5 Inlet Design- Top Chamber

The inlet design for the top chamber of the reactor was challenging. A number of alternative designs have been considered for the design of inlet of biodrying reactor like single chamber model (Rada et.al., 2005a) multi-chamber model (Frei et. al., 2004b), rotary chamber model(Bartha ,2008) etc. Finally the most suited innovative top chamber reactor was designed as inlet for this study. The reactor feeding from the top was found to be effective for safety and easiness in operation. The designed inlets consist of airtight removable top chamber fabricated of the fibre coated mild steel (Fig.4.4).

Fig.4.4. Closed View of Reactor

Fig.4.5. Filled Reactor

4.2.6 Outlet Design – Bottom Chamber

The outlet of the reactor was another important configuration which affects the smooth working of the reactor. The reactor outlet was designed effectively to serve the double purpose of provision for mechanical aeration was well as the provision for emptying the reactor after the process. The outlet consisted of a bottom chamber with a perforated top plate for supplying the required quantity of air for the reaction(Fig.4.1). The bottom chamber has been supported on a hydraulic scissor lift which is provided for slow emptying of the reactor (Fig.4.4, Fig.4.5). The reactor was designed with side supports so that it will remain static throughout the operation.

4.3 BIODRYING PROCESS DESIGN

The major assumptions considered in the psychrometric design of the biodrying reactor in the present investigation is

1. The reactor matrix is homogeneous and adiabatic in terms of physical properties on a macroscopic scale.
2. Temperature and moisture concentration gradients exist along the height of the reactor matrix only. These parameters were considered uniform along the diameter of the reactor matrix. This assumption makes it possible the use of one dimensional analysis of parameters (i.e., along the height of reactor).
3. Self heating inside the reactor matrix was assumed to be at a uniform rate and hence the temperature development inside the entire reactor feed is assumed to be in the range of 50°C to 60°C.
4. The psychrometric design for the present study had neglected the condensation reactions inside the biodrying reactor.
5. The effects of shrinkage other than changes in the density and thermal properties of the reactor matrix were neglected. The mass diffusivity of the reactor matrix was considered as a function of biodrying conditions only and hence it was held constant for a particular biodrying zone in reactor. Also the particle dimension of the reactor feed was limited to 20 cm and particle thickness limit was taken as 5 mm in the present investigation.

4.3.1 Air Flow Design

The drying of the MSW is affected by the rate of air flow and the resulting self heating biodegradation reactions (Annexure-1). The inlet air flow conditions of 25 ºC and 90 % relative humidity (RH) was selected as the critical conditions. The design of air flow is done by considering the critical moisture content of MSW as 70%. Tanner diagram (Fig.4.6) is used to assess the limit of moisture content required for combustion of an organic material without adding auxiliary fuels (Babcock and Wilcox, 1992). In the present study the moisture content of 45% was fixed as the target for design purpose which is within the maximum limit of 50% as shown in tanner diagram. The moisture content of biodried output has been considered as 45 % for design which is the requirement for energy producing applications of a material. The proper air flow control is critical for the biodrying process. Psychrometric chart developed by Carrier (1911) has been used in the present study to analyse the process involving moist air and determine the air flow requirements of process (Fig.4.7). The biodrying process design calculations were shown in Table.4.2.The thermodynamic table has also been referred for air density calculations which are also considered for the design purpose. The psychrometric chart for high temperature range has been referred as the temperature rise in the range 50^0C – 60^0C is expected from the designed reactor unit (Fig.4.7).In the proposed design of reactor, the maximum air flow rates required for achieving the desired biodried output within 10, 11, and 15 days were obtained as 40 L/m,37 L/m and 27 L/m respectively.

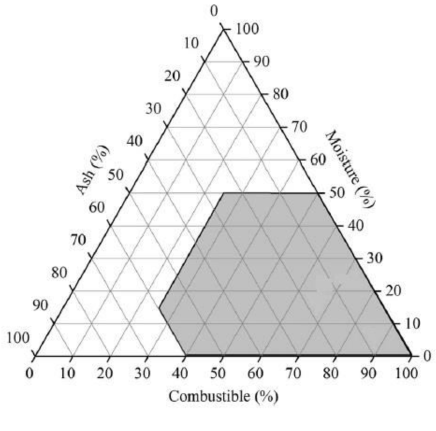


Fig.4.6. Tanner Diagram (Babcock and Wilcox, 1992)

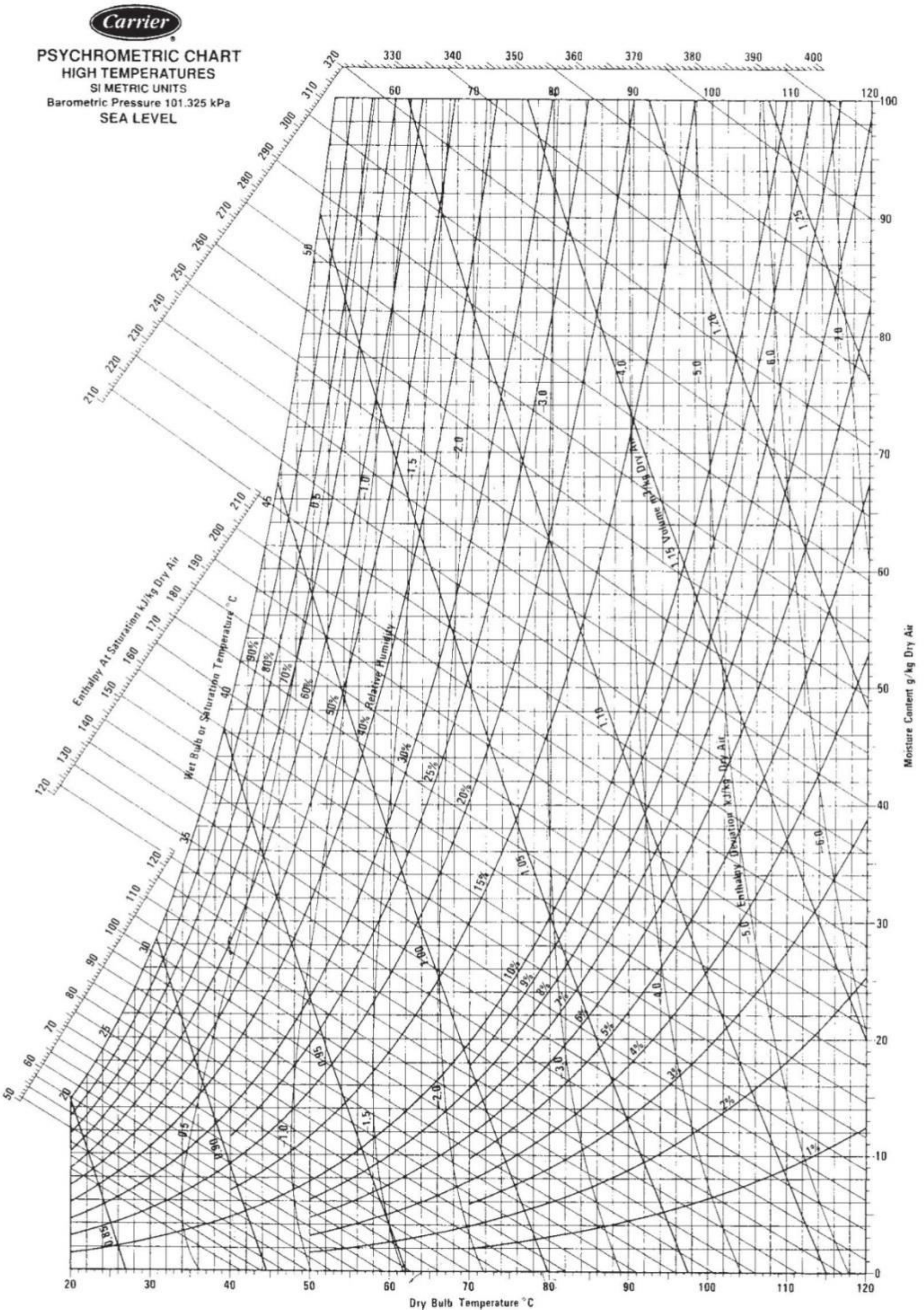


Fig.4.7. Psychrometric Chart

(Carrier,1911)

Table 4.2 Process Design Calculations

Process critical conditions considered		
Temperature of inlet air to reactor	25	˚C
RH of inlet air	90	%
Self heating Temperature rise	50	˚C
Moisture content of MSW	70	%
Quantity of MSW	100	kg
Quantity of water removal required, for 45% moisture of biodried product	45.45	kg
Using the Psychrometric Chart (Fig.4.2)		
Input air 25˚C, 90 % RH		
Humidity of drying air	0.018	kg/kg of air
Specific volume of air	0.87	m^3/kg
Humidity of self-heated air at 50˚C, at RH 100%	0.086	kg/kg of air
Therefore water removed	0.068	kg/kg of air
i.e., 0.87 m^3 air remove 0.068 kg water		
therefore, the amount of air to remove 45 kg water	581.49	kg air
From thermodynamic table, density of inlet air at 25˚ C	1	kg/m^3
Air flow for ten days	58.15	kg per day
	2.42	kg per hour
	0.04008	kg/minute
	0.040081434	m^3/minute
Air flow for10 days	**40**	**litre/minute**
Air flow for 11 days	**37**	**litre/minute**
Air flow for 15 days	**27**	**litre/minute**

4.4 HEAT ENERGY REQUIREMENT IN BIODRYING

The heat energy required to raise the temperature of a material by ϴ ºC is given by the equation (Bach et al., 1987; Silusar and Armisheva, 2013).

Heat Energy Equation is given by

$$Q = mc\Theta \text{--} (4.1)$$

Where c -specific heat capacity of material (kJ/kg ˚C)

m- mass (kg),

Θ - Change in temperature (ºC)

Table 4.3 Heat Requirements of Biodrying Process

Particulars	Quantity	Unit
Initial moisture content of MSW	70	%
Expected moisture content of biodried output	45	%
Weight of MSW	100	kg
Water content in 100 kg	70	kg
The total quantity of Water to be removed	45.45	kg
Water removal required from 1 kg of MSW	0.4545	kg
Initial temperature of MSW matrix	25	˚C
Temperature rise expected in biodrying process	50	˚C
specific heat capacity of water, C_w	4.186	kJ/kg ˚C
specific heat capacity of MSW, C_s	1.25	kJ/kg ˚C
Θ- change in temperature	25	˚C
Heat energy required by 1 kg of MSW (Heat energy required to raise the temperature of MSW by 50˚C+ heat energy required to raise the temperature of water by 50˚C)	82.63	kJ
Total heat energy Required to raise the temperature of 100 kg MSW to 50˚C	8263	kJ

The initial moisture content of the municipal solid waste has been considered as 70 % and the expected moisture content of the biodried output has been taken as 45 % for design of the heating regime. The initial temperature of the reactor feed has been considered as 25ºC. The specific heat capacity of water is taken as the standard value and the specific heat capacity of municipal solid waste has been calculated based on the proportion of different components of MSW.

4.5 SELF HEATING PROCESS IN BIODRYING

The heat energy released during the complete decomposition of the organic matter is given by the equation

$$(C_6H_{10}O_4)_x + 6.5O_2 \rightarrow (C_6H_{10}O_4)_{x-1} + 6CO_2 + 5\ H_2O + 2578.6\ \text{kJ----- } \quad (4.2)$$

The reaction kinetics for the organic matter degradation can be represented by first-order equation (4.3)

$$\mathrm{C_t} = 1 - e^{-[0.00632 \times 1.066^{(T-20)}] \times t} \text{ -- } (4.3\ )$$

(Keener et. al., 1998)

Where C_t represents the mass of oxidised organic material, in relation to total amount of organic matter provided (kg/kg) at any time t (day)

T (ºC) is the process temperature.

Other constants in kinetic equation were taken as per Di Maria et. al., 2008.

The components other than organic materials in the waste can be assumed as the inherent bulking agents inside organic waste.

The functional unit considered for the present study is 100-200 kg per day of mixed municipal waste undergoing biodrying process. The components other than organic materials in the waste can be assumed as the inherent bulking agents inside organic waste. The average organic matter concentration is 70 % and maximum temperature rise is assumed to take place in initial five days of reaction. It is assumed that the maximum heating takes place in 5 days of reaction.

As per kinetic equations, 19.3% degradation of readily degradable organic matter occurs in 5 days, when averageself heating temperature is 50°C,

The maximum heat energy generated in biodrying= 25317.50 kJ........... (4.4)

As per kinetic equations, 10.4% degradation of readily degradable organic matter occurs in 5 days when averageself heating temperature is 40°C,

The maximum heat energy generated in biodrying= 14036.12 kJ..................(4.5)

4.6 PROCESS INSTRUMENTATION DESIGN AND REACTOR OPERATION

The process instrumentation design has been carried out based on the results obtained from critical conditions in process design. The schematic diagram of the process flow along with instrumentation is shown in Fig. 4.10. The process air flow was provided through the bottom air inlet chamber to the top of the reactor. The air supply unit consists of an air compressor followed by a digital gas mass flow controller (DGMFC) *[Sierra, USA],* which assisted in maintaining the required rate of air flow throughout the process (Fig. 4.8). The monitoring of temperature development in the process was carried out by using temperature sensing probes of PT-100 (*SAKS, India)* at eight different locations along the height of the reactor unit.The insertion lengths of probes were 10 cm inside into the reactor. The integration of temperature data for 10cm insertion length of sensor is possible using the designed data acquisition software, and also the data storage was carried out. Six numbers of temperature probes were provided at 20-30 cm intervals along the height of the reactor matrix.

The remaining two probes were used to measure the air temperature, one for measuring inlet air temperature and the other one for outlet air temperature. The order of insertion of temperature probes has been in such a manner that probe numbers 1 to 8 were inserted in order from bottom to top of biodrying reactor unit.

The humidity transmitter (Kimo, France) was used to measure the relative humidity of the inlet air as well as the exhaust air at specific intervals of time. The CO_2analyser (*Testo, India*) was provided to continuously monitor the carbon dioxide production(Fig.4.8). The load cell of capacity 1000 kg (SAKS, India) was provided to continuously monitor the weight loss from the reactor which can be used to assess the moisture loss from the reactor.

The entire reactor unit along with the insulation chamber has been placed over the load cell. The electronic measurement devices were connected to the data acquisition system (DAQ), which records data at every second of time and hence the process monitoring was effective. Also, the manual analysis of moisture content was carried out at intervals during the working stage of the reactor. In addition to that, the volume reduction in the innovative biodrying reactor was monitored on a daily basis, by measuring the reduction of height along the reactor matrix.

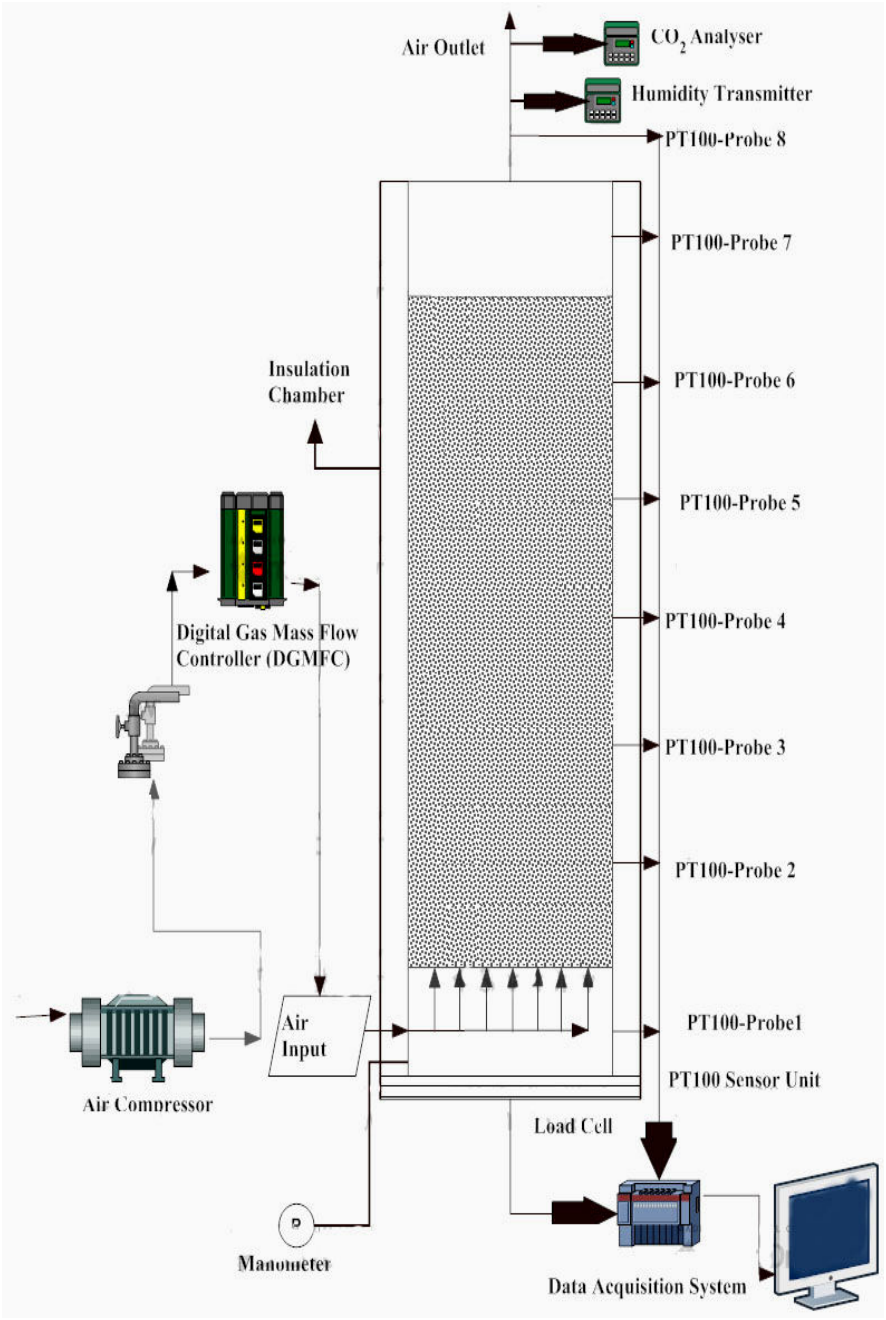


Fig. 4.8 Schematic Diagram of Biodrying Process

The working of the designed biodrying reactor can be explained with the help of the schematic diagram as shown in Fig. 4.8. The reactor chamber was fixed above the bottom chamber in air tight manner, which is placed inside the insulation chamber. The reactor feeding was carried out from the top chamber of the reactor into the reactor chamber after thoroughly mixing the substrate (Annexure-II). All the instrument probes are fitted into the reactor at the corresponding locations. The airflow at the required rate is supplied through the perforated top plate of the bottom chamber. Continuous process monitoring has been done using the data acquisition system. When the required process is result is achieved, the bottom chamber has to be dismantled from the moisture analysis chamber by removing the flanged connection and by operating the scissor lift below the bottom chamber .This leads to removal of biodried substrate from the reactor chamber. The removed substrate can be stored inside the lower platform of the insulation chamber.

CHAPTER 5

SIX PHASES OF EXPERIMENTAL INVESTIGATIONS ON THE INNOVATIVE PILOT SCALE BIODRYING REACTOR

5.1 INTRODUCTION

Six phases of experimental investigations have been conducted in the innovative pilot scale biodrying reactor system. The mechanism of biodrying reaction has been delineated through six phases of experiments. The continuous monitoring of weight reduction, temperature profile, moisture content, volume reduction and bulk density increase of the reactor matrix has been carried out.

The first five phases of experimental investigation have been conducted in the up flow mode of aeration. In the first phase, the biodrying process in the pilot scale system has been monitored to assess the efficiency of the designed system. The second phase of experimental investigation has been carried out by modifying the biodrying reactor design so as to increase the process efficiency. The effect of specific air flow rate variation and reactor matrix height on the biodrying reaction has been studied in the third phase. In the fourth phase, the combined effect of packing and reactor matrix height on biodrying process has been investigated. The effect of the increase in specific air flow rate on biodrying process efficiency has been studied in the fifth phase. The down flow mode of aeration and its impact on biodrying reaction has been investigated in the sixth phase.

5.2 EXPERIMENTAL INVESTIGATION- PHASE I - MONITORING OF THE BIODRYING PROCESS IN THE INNOVATIVE PILOT SCALE REACTOR

5.2.1 Objectives

First experiment was conducted with the major objective of identifying the feasible operating conditions of the reactor, as well as to analyse the critical process parameters affecting the biodrying process. In order to achieve the major objective of the research the continuous monitoring and analysis of the different process parameters for the designed biodrying reactor unit has been carried out in the first phase.

5.2.2 Introduction

Pilot scale investigations are necessary to study the science and engineering aspect of biodrying process. Though a number of pilot scale plants exist for biodrying process reactors for mixed municipal solid waste treatment are very scarce (Velis et. al., 2009). The detailed technological study is essential to understand the applications of biodrying reaction for mixed municipal solid waste management.

5.2.3 Materials and Methods

The study area selected for the present investigation is Kerala state. The compositions of municipal solid waste for this study was selected referring the typical municipal solid waste composition data base of Kerala state (Varma 2006). The mixed municipal solid waste for the reactor has been collected in a systematic manner (Fig.5.2.1). The organic materials were collected from the National Institute of

Interdisciplinary Science and Technology (NIIST) campus, Thiruvananthapuram where the reactor was installed. It included the raw as well as cooked food waste, green leaves, dried leaves etc. These materials were separately stored in bins.

Paper Plastics Textiles

Raw food waste Cooked food waste Cardboard waste

Fig.5.2.1 The Different Components of Collected MSW.

The weight of the organic materials in these bins has been measured in the electronic balance. The bigger sized components were chopped into smaller size so that proper packing and mixing can be carried out. The paper and cardboard waste has been also collected from the NIIST campus and cut into smaller size. The paper waste includes news paper, print paper, magazine covers, card board etc. They are separately weighted and stored in bins. The plastic waste mainly includes the milk covers and packing covers of different types. They are also separately collected and weighted. The textile waste has been collected from the nearby stitching centers and stored in separate bins

Table. 5.2.1 Composition of the Synthetic Municipal Solid Waste Substrate in Phase-1

Component	Particulars	Weight (kg)	Subtotal (kg)	Grand Total (kg)
Organic components	Raw food waste	15	78.4	112
	Cooked food waste	45.4		
	Fibers	10		
	Dried leaves	4		
	Fresh leaves	4		
Paper and Cardboard	News paper	8.44	13.44	
	Print Paper	2		
	Cardboard	3		
Paper and Cardboard	Crushed bottles	3	10.1	
	Milk Covers	4.1		
	Plastic Covers	3		
Textiles	Cotton	7.1	10.1	
	Polyester, Nylon	3		

The sampling has been carried out for individual components of MSW. Firstly the organic components were mixed thoroughly and samples were taken for moisture analysis. Similarly the sampling is carried out for the other components also. After sampling the mixing of the different components like organic materials, paper and cardboard, plastics and textiles has been carried out in the required proportion. The synthetic municipal solid waste substrate of 112 kg was prepared in the laboratory as per the composition shown in Table 5.2.1.

Mixed municipal solid waste of 109 kg has been used as the reactor feed in the first phase of study. The particle size of waste components was limited to a maximum value of 20 cm and the maximum thickness was 5 mm. The proportion of different components in the mixed municipal solid waste consisted of 70 % organic components, 12 % paper and cardboard, 9 % plastics and 9 % textile materials. These components were thoroughly mixed, so that relatively homogeneous moisture content is maintained. The initial moisture content of the mixed municipal solid waste substrate in the present study has been calculated as 61.25 %. The moisture content of metals and inert materials were assumed to be negligible and hence not considered in this study. The samples of mixed municipal substrate were ground and sieved through 2 mm mesh sieve (Garcia et al., 1991) for measuring the water soluble carbon. Then 5 gm of individual samples were digested using potassium dichromate method (Walkley and Black, 1934) in the reflux apparatus and the titration was carried out using ferrous ammonium sulphate in order to get the water soluble carbon in the sample. The total nitrogen content was analyzed in the biodried output by using Kjeldahl method as per IS 5194-2002.

5.2.4. Biodrying Reactor-Process and Working

The reactor design consist of an inner circular acrylic reaction chamber of 0.60 m diameter and 2.0 m height, with a capacity of treating 0.565 m^3 of waste in one batch The proportionally mixed synthetic municipal solid waste of 109 kg with bulk density of 173 kg/m^3 and initial moisture content of 61.25 % was fed through the top chamber of the reactor. The temperature probes were inserted at 30 cm intervals along the height of the reactor. Temperature measuring probe numbers 2,3,4,5 and 6 were inserted in to the reactor feed at heights of 30 cm, 60 cm, 90 cm, 120 cm and 150 cm respectively from the reactor bottom (Fig 5.2.2). Temperature of the inlet air was measured by probe 1. The probes 7 and 8 were inserted at the top chamber and air outlet respectively to monitor the exhaust air temperature. The air flow was provided at the required rate through the digital mass flow controller into the bottom chamber

Fig. 5.2.2 Temperature Probes Inserted into the Biodrying Reactor.

of the reactor. After filling the reactor the top chamber was fixed air tight and the CO_2 analyser and humidity probes were inserted on the top chamber. The volumetric air flow through the controller was designed as 40 liter per minute (L/m) for the first phase of experiment as per the psychrometric design. This accounts for a specific air flow rate of 0.528 m^3/kg.day supplied into the biodrying reactor. The continuous observations and monitoring of the instrument readings as well as the reactor process conditions were carried out for a perid of 33 days. The biodrying reaction reduced and almost stopped by 21 days. Inorder to assess the further process the reaction continued for further 12 days. Then it is stopped as no further drying reaction exist.

After filling the reactor with synthetic sample of municipal solid waste weighing 109 kg, it was observed that the temperature probe- 5 at 150 cm height from bottom of reactor chamber was above the reactor matrix. The reactor was equipped with standard control and measurement devices. The height of the reactor matrix was observed as 1.38 meters.

5.2.5. Results

The biodrying reactor before and after 33 days of biodrying process is shown in Fig. 5.2.3.

a) Filled Reactor Before Biodrying b) Biodrying Reactor After Process

Fig. 5.2.3 Biodrying Reactor Before and After 33 days of Biodrying Reaction-Phase 1.

It can be seen that the volume of mixed municipal solid waste (MSW) substrate has been considerably reduced. There exist visible demarcated zones of dry and wet region of substrate inside the reactor matrix. The top portion of the reactor matrix was wet, while the bottom portion was dried.

5.2.5.1. Temperature Profile

Self heating nature of the municipal solid waste is effectively utilised in biodrying process, which help to prevent the septic nature of waste as well as to preserve the waste for long time without odour production. Temperatures profile in biodrying process has been recorded in every second through the data acquisition system. The variation of temperature in every ten minute has been monitored and studied in detail. The temperature variation at every ten minute interval of time has been plotted at various heights from the air inlet (30 cm, 60 cm, 90 cm, 120 cm, 150 cm and 240 cm) along with inlet air and outlet air temperature variations (Fig. 5.2.4).

Three different approaches were considered for the analysis of temperature profile. Firstly the initial six hour variation of temperature along the height of reactor was plotted against time as shown in Fig.5.2.4. The graph clearly indicates that the initial six hour period is very critical for biodrying process. The probes at 60 cm and 90 cm distance from the air inlet have showed a sudden temperature rise of 10ºC in the initial six hour period.

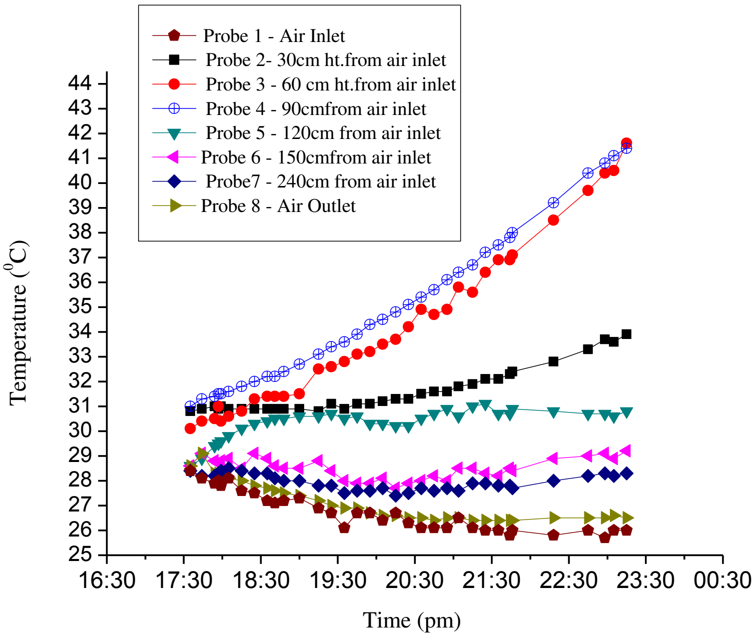


Fig. 5.2.4 Temperature Profile Inside the Biodrying Reactor in the Initial Six Hours of Reaction- Phase 1.

The second consideration in temperature analysis was to study the profile formations in the first ten day period of biodrying reaction (Fig.5.2.5). The temperature probes above 90 cm, have recorded temperature fall, since the condensed water was dripping downwards in to the reactor feed through the side walls. This is the main visible reason for lower temperature in this zone. Also the relative humidity has reached saturation value in the substrate top region. The rising trend of temperature continued for first three days in probes 3 and 4 placed at distances of 60 cm and 90 cm respectively from the air inlet (Fig.5.2.5). Then it started a decreasing trend, while the temperature in probe at distance of 30 cm form air inlet maintained the increasing trend up to six days and the maximum temperature observed was 48ºC in this probe. The observed values of temperature by the end of 10 days of reaction were 42.9°C, 43°C and 33°C at heights of 30 cm, 60 cm and 90 cm respectively from the air inlet.

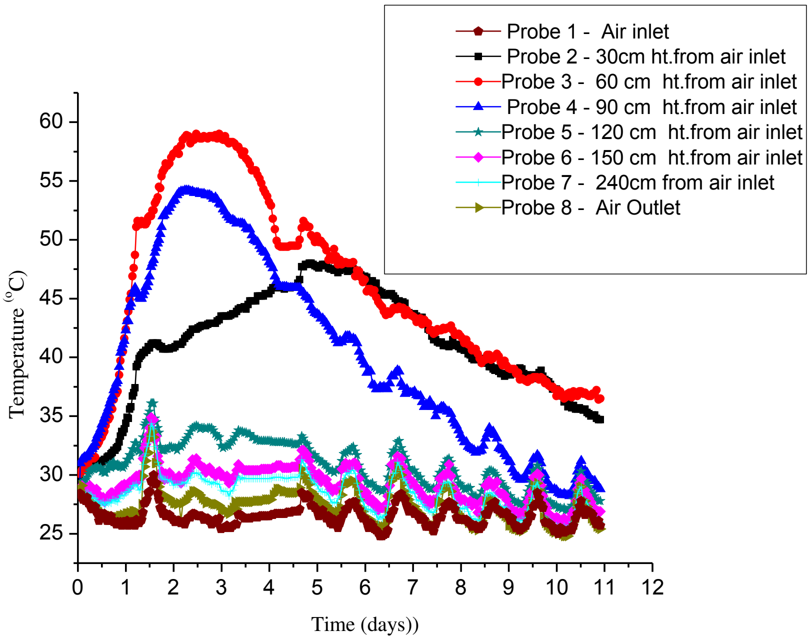


Fig. 5.2.5 Temperature Profile Inside the Biodrying Reactor in First 10 Days of Reaction –Phase 1.

Finally the temperature profile for a period of 33 days has been plotted along the reactor height. Two well defined peaks of temperature rise were observed in thirty three days of observation (Fig.5.2.6). The first cycle of temperature rise lasted till the third day on the probes 3 and 4. The probe 2 has recorded temperature rise till the sixth day and after that a falling trend of temperature has been observed till the 15th day of the process. The falling trend of temperature has resulted due to active biodrying process and the resulting evaporative cooling. The second cycle of temperature profile has started on the probes 2 and 3 after 16th day of process at a rate of 5ºC to10ºC rise per day. The rising trend continued only for a short duration of one day, and after that the temperature profile has shown falling trend (at a less rate 1 ºC to 2 ºC per day). The third cycle of temperature started after 16 days of biodrying reaction. In this cycle temperature rise and fall occurred on the probes 2 and 3. The rise and fall of temperature within the narrow range of 1ºC to 2ºC rise recorded on all the probes in this cycle and continued till the end of monitoring period of thirty three days of biodrying process.

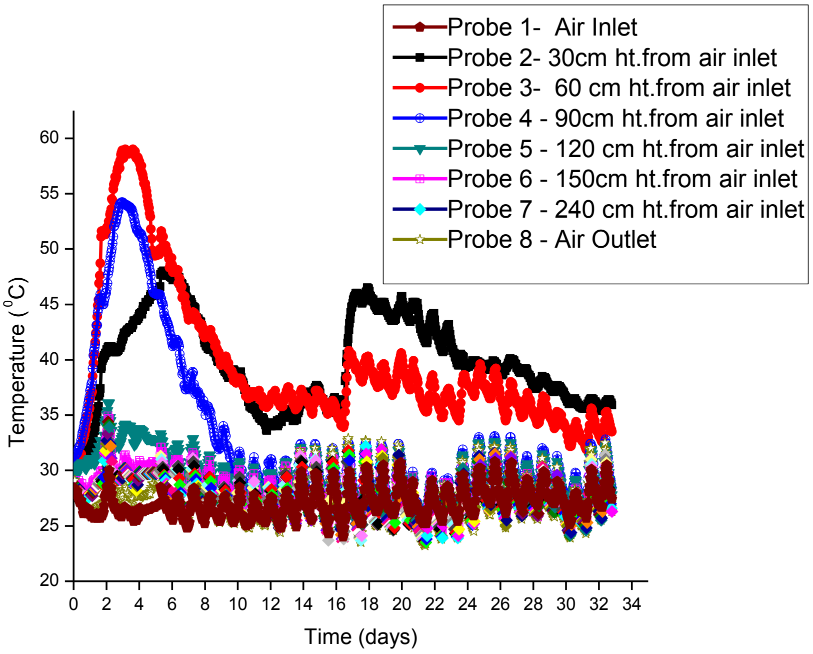


Fig. 5.2.6 Temperature Profile Along the Height of Biodrying reactor During 33 Days of Reaction - Phase1.

In the third temperature cycle fungus growth was prominent throughout the reactor feed top. The fungus growth was in a cyclic manner with fungus rising up when temperature falls and when the temperature rises fungus falls.

The temperature contour for entire biodrying process monitoring has been plotted in Origin Pro-8 software as shown in Fig. 5.2.7. It is clearly evident from the temperature contour that maximum self heating at a peak temperature of 59ºC has existed in the core region of reactor matrix at 50 cm to 80 cm height from air inlet. Also this peak temperature self heating has been sustained for a duration of four days (i.e., from the second day till the sixth day of process). This clearly indicated that the initial period is critical for the biodrying process, during which the maximum self heating process has to be explored.

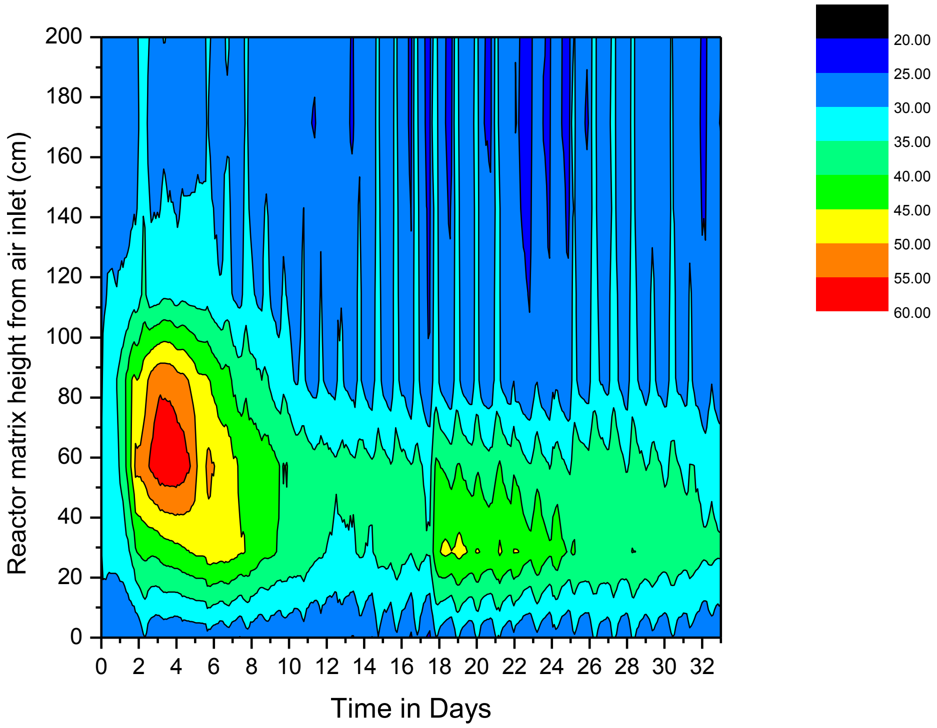


Fig.5.2.7 Temperature Contour Plot- Phase 1.

Such a detailed temperature profile analysis is innovative in the field of biodrying process which is very useful for the design of commercial scale biodrying reactors.

5.2.5.2 Biological Profile

The growth of fungus has been observed on the inner side wall of the transparent cylindrical reactor from fourth day of reaction onwards. Growth of fungus species were observed on the reactor feed top. The species included 80 % *Agaricus bisporous* and other species were of minor quantity. The population of fungi increased in size and number as the biodrying reaction proceeded and finally the species *Agaricus bisporus* started growing above the reactor matrix top, by the seventeenth day of reaction. In addition to that rotifer worms were also observed in large numbers, during the short cycle of temperature rise that occurred from sixteenth day of reaction onwards. From seventeenth day of reaction onwards a microbial competition was observed between fungi and rotifer worms for survival. The rotifer worms were observed in large numbers during the period of temperature rise, but during the same period the *Agaricus bisporus* species started falling down on the reactor matrix top. The exact reverse of this situation was observed during the period of temperature fall, when large numbers of fungi species *Agaricus bisporus* standing erect on the top of reactor matrix and the number of rotifer worms decreased. This competition of microbial organisms continued throughout the short cycles of temperature rise and fall till the end of monitoring period of 33 days. It was observed that most of the paper inside the reactor matrix at the top most 20 cm height has been degraded by the fungi while below that biodried and preserved paper was visible where the fungus was unavailable for degradation.

5.2.5.3 Weight Reduction

The biodrying reactor is placed over the load cell and the weight reduction has been continuously monitored. The weight loss is calculated in every second of time and the data has been transferred through the data acquisition system and reading taken on the monitor of computer. The results of weight reduction were plotted against time (Fig.5.2.8). The weight of the reactor matrix was reduced by 37 kg in the initial 20 days of biodrying process, i.e., an average weight reduction of 1.85 kg/day was obtained in this period.

The cumulative weight loss achieved in the biodrying process was 33.94 %, which is less than the actual evaporation loss because of the high rate of condensation of evaporated water back in to the reactor. It was observed that the weight reduction was significant only till the 20th day of experiment and after that weight loss was negligible.

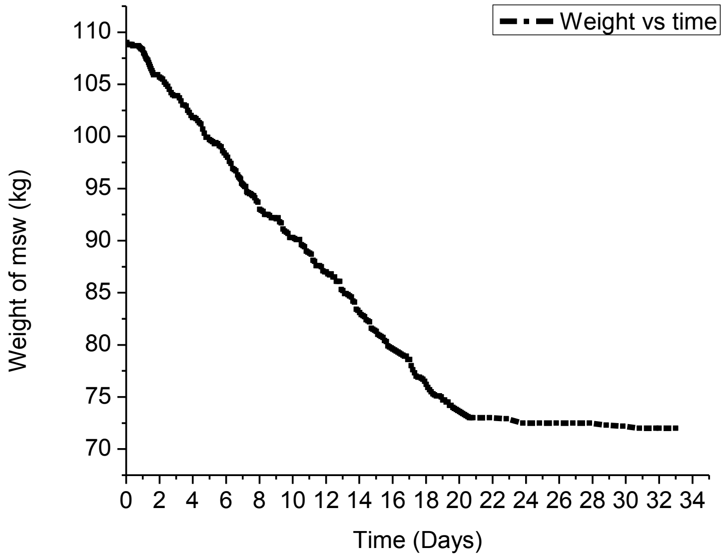


Fig. 5.2.8 Weight Reduction Profile in the Biodrying Reactor- Phase1.

5.2.5.4 Moisture Profile

Six numbers of representative samples were collected from the reactor matrix on selected days that included samples from the two sampling ports (40cm and 80 cm from the air inlet) and also from the reactor feed top. The average value of moisture analysis results of the six samples were plotted against time, along with standard deviation error bars (Fig. 5.2.9).

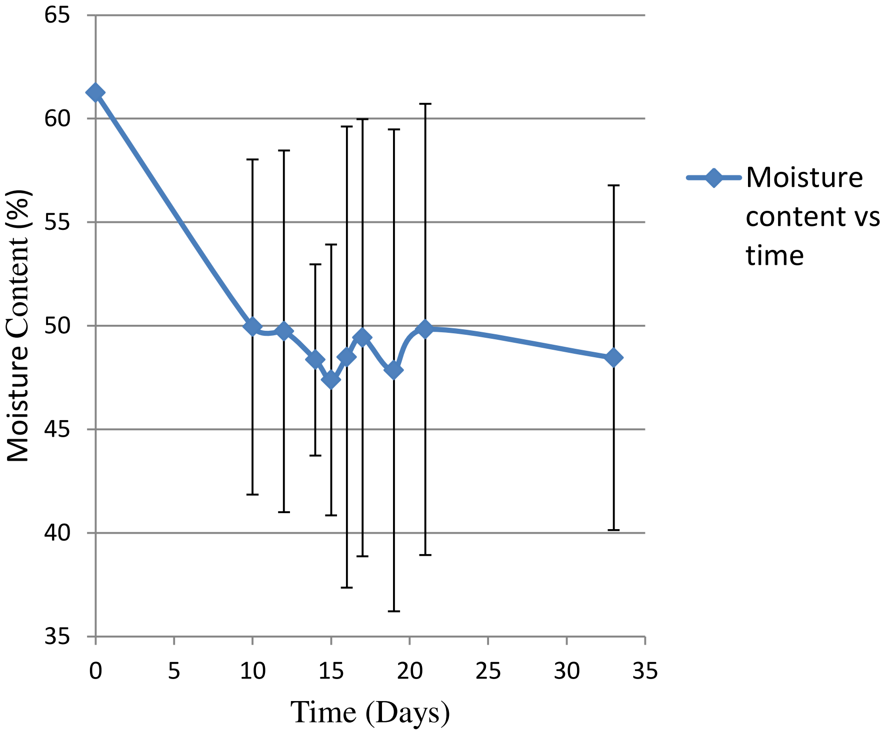


Fig. 5.2.9 Average Moisture Content Vs Time- Phase 1.

Average moisture content of the mixed MSW substrate at the end of 33 days of experiment was observed to be 48.5 %, which is a reduction of 20.81 % (the initial moisture content was 61.25 %). The error bars shown in standard deviation vary in the range 4.61-11.63, which is due to the non-uniform distribution of moisture inside the reactor matrix. The main cause of non-homogeneous moisture distribution inside the biodrying reactor was the condensation of evaporated water back in to the top of reactor matrix. The major achievement of the present pilot scale biodrying reactor design was that leachate production was completely eliminated in the process and the bottom zone of the reactor matrix was completely in a dry state after the reaction. This is the most important factor in the treatment of municipal solid waste with high moisture content.

5.2.5.5 Volume Reduction

Municipal solid waste accumulated in large volume is a critical factor affecting the handling, and storage of the same in addition to the difficulty in landfilling operations.

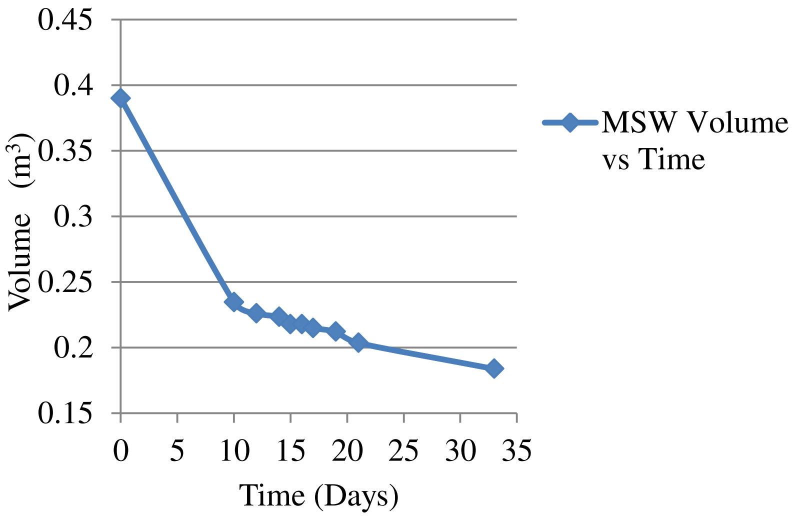


Fig.5.2.10 Volume Reduction- Phase 1.

The designed biodrying process was found to be very efficient in bulk volume reduction with the matrix height reduced from initial value of 1.38 m to final value of

0.60 m. The volume has been reduced from the initial value of 0.39 m^3 to final value of 0.169 m^3 in 33 days of biodrying process (Fig. 5.2.10. It is a reduction of 56.5% of volume in 33 days of biodrying reaction.

5.2.5.6 Bulk Density Increase in Biodrying Process

Bulk density is a significant factor affecting the energy density of a fuel. The in situ bulk density has been calculated on a dry basis as follows.

$$\text{Bulk density (dry basis)} = \frac{\text{Bulk density(wet basis)}}{(1+\text{moisture content})} \;\ldots\ldots\; (5.1)$$

In the present study, the bulk density has from the initial value of 173.59 kg/m^3 to final value of 251 kg/m^3 at the end of ten days of process (Fig.5.2.11).

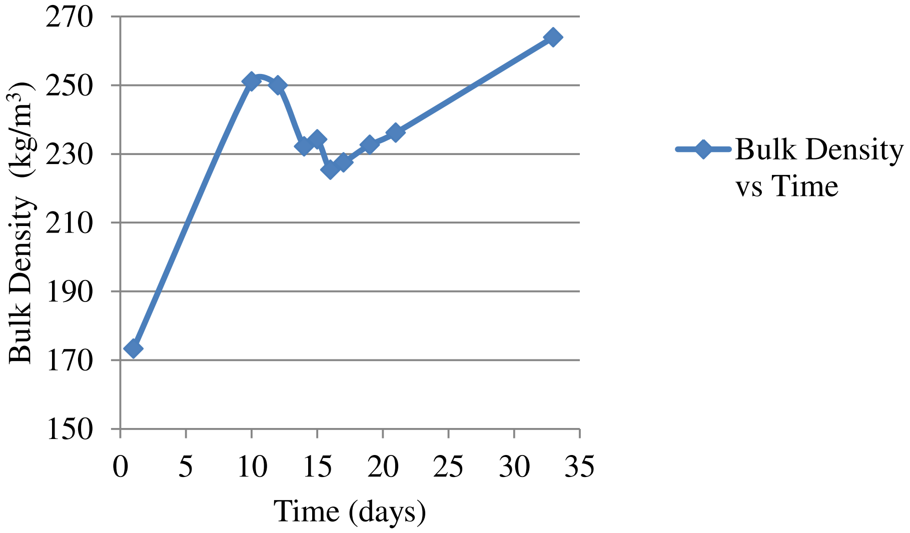


Fig. 5.2.11 Bulk Density Profile- Phase1.

Bulk density profile was showing a decreasing trend in the period from 10 to 20 days, and after that it started increasing again. The major increase in bulk density was achieved in the initial ten days of reaction itself. During the entire process of biodrying in 33 days, the bulk density of the mixed municipal solid waste substrate has been increased from the initial value of 173.59 kg/m^3 to the final value of 263.69 kg/m^3 (Fig. 5.2.11.).

The monitoring of the biodrying process has been carried out for 33 days and the bulk density has increased by 52 % at the end of 33 days of reaction. The weight reduction became negligible after 20 days of biodrying process but the bulk density was increasing beyond 20 days of reaction and hence further process monitoring has been carried out till 33 days.

5.2.5.7 Zero Leachate Process

High rate of leachate production is the critical constraint in municipal solid waste treatment units. Beyond that leachate production is the major factor affecting the landfiiling operations adversely. The innovatively designed biodrying reactor was able to achieve has complete elimination of the leachate production and that is the most important achievement in the treatment of municipal solid waste with high moisture content.

5.2.5.8 Chemical Analysis

Water soluble carbon analysis results verified the formation of two well defined zones inside the reactor matrix. The average value of water soluble carbon in the biodried bottom zone was 8.5 mg/gm, while the same in the biodegraded zone was only 3.9 mg/gm (Table 5.2.2). The Kjeldahl Nitrogen content in the bottom and top zones of the reactor matrix was found to be 7.65 mg/gm and 22.07 mg/gm respectively. This large variation in Kjeldahl nitrogen also verified the existence of well demarcated zones within the same reactor matrix. The pH values were almost the same throughout the reactor matrix, with slight deviations and hence the moisture presence has facilitated biodegradation reactions in the top region of the matrix.

Table. 5.2.2 Chemical Analysis Results- Phase 1

Sl No	Sample	Water Soluble Carbon (mg/gm)	Total Nitrogen (Kjeldahl method) mg/gm	pH
1	Dried Samples at bottom (Preserved)	8.5	7.65	6.38
2	Wet Samples at Top (degraded)	3.9	22.07	6.85

5.2.6 Discussions

In the first phase the monitoring of the innovative pilot scale biodrying reactor unit for treating mixed municipal solid waste has been carried out for duration of 33 days. The different parameters considered for the process analysis includes the substrate temperature, weight, moisture content, volume, and bulk density. The temperature development in the process was assumed to be in the range 50 °C to 60 °C for the psychrometric design, but the same was achieved only in the bottom region of the reactor matrix. This is primarily due to the active condensation of the evaporated water back in to the top region of matrix. The core region of reactor matrix initially at 50 cm to 80 cm height from air inlet was most effective in biodrying process, with a maximum temperature rise up to 59°C (Fig. 5.5).

This high temperature heating ensured that the resulting product is free from pathogens, since one hour heating in the range of 50°C to 55°C temperature will kill most of the common parasites and pathogens (Gottas, 1956). However, the formation of different zones of varying temperature is unavoidable in the biodrying process, as plotted in the temperature contour though the assumption of uniform temperature development has been considered in the design stage. Considering the effect of reaction time on temperature development, it was found that maximum temperature rise is taking place within the first six days of reaction and hence biodrying process is most effective in this period. The cyclic nature of temperature profile with two well defined peaks clearly indicated that as time proceeds reactions similar to composting took place inside the reactor.

The biological processes inside the biodrying reactor can be explained by studying the temperature profile as well as the chemical analysis results. The development of thermophilic range of temperature inside the reactor matrix showed that the raw substrate has enough carbon resource and nitrogen for metabolism of microorganisms. First stage of quick temperature rise has been attributed to the high rate of aerobic respiration process by the microbial species. This confirmed that the inherent moisture content of the mixed municipal solid waste substrate prepared was optimum for aerobic reactions, which is a favourable condition for the biodrying process. The nitrification process became prominent after 15 days of biodrying process which contributed to the second cycle of temperature rise. The mineralization of organic nitrogen in to NH_4^+ started in the region of optimum moisture presence that is clearly indicated by the average Kjeldhal Nitrogen content of 22.07 mg/g in samples collected from the top region of reactor matrix, while that was only 7.65 mg/g in the bottom samples.

Weight reduction is a significant parameter in municipal solid waste treatment facilities towards achieving the easiness for transportation, handling and storage. Hence the biodrying reactor developed with a considerable reduction in weight of the mixed MSW substrate is a promising accomplishment in solid waste management systems. However the weight reduction in the present case study was 33.94 % which can be improved by modifying the design with the provision of condensation prevention measures in the future. The average moisture reduction in the developed process was only 20.81 % mainly due to the condensation of the evaporated water back in to the reactor through the top side walls, which resulted in increased rate of degradation reactions and lesser rate of biodrying reactions. The non-homogeneous moisture reduction is the major limitation of the process which resulted in long error bars in the standard deviation values of moisture analysis results as shown in the moisture plot.

Bulk volume reduction was a major achievement in the present study; a reduction of 56.5 % of reactor matrix volume has been observed in the entire process. But it is evident that 40 % of the volume reduction was achieved in the initial 20 day period of time, which points out the fact that biodrying process optimization has to be done in the initial short duration of time unlike the composting process. Bulk Density augmentation is another promising result obtained from the innovative biodrying process. The bulk density and hence the energy density of the mixed municipal solid waste has been increased up to 52 % in the entire process. This is a very important development towards fulfilling the objective of feasible technological solutions in the field of waste to energy conversion processes.

5.2.7 Summary

In the first phase of experiment the innovatively designed pilot scale biodrying reactor for treating mixed municipal solid waste substrate with high moisture content has been demonstrated. The various parameters considered in the process analysis are temperature, weight loss, moisture content, volume, and bulk density. It was observed that high temperature of 59 °C was obtained in the reactor matrix in region of 50 cm to 80 cm height from air inlet, in the biodrying process due to the self heating of substrate. This ensured the antiseptic nature of the process output, but maintaining the high temperature range throughout the reactor matrix can ensure homogeneity of the output. Considering the weight reduction in the process, maximum weight reduction of 33.94 % has been achieved in the initial twenty day period of reaction and after that weight loss was found to be negligible. The moisture reduction in the process was 20.81 %. Comparing the weight reduction and moisture loss of first phase of study it is evident that biodegradation process was also prominent along with the biodrying process. Hence further innovation is required in this factor so that the biodrying process rules out the biodegradation process and the energy value of output can be preserved. This may be achieved by the provision of condensation prevention methods in the top region of the designed reactor unit. Bulk volume reduction of 56.5% along with bulk density augmentation of 52.3% was the major accomplishment of the first phase of experiment. The major constraint observed in the first study was that keeping the optimum balance between biodegradation process and biodrying process, so that better drying is possible. In addition to that the initial ten to fifteen day period was found to be critical in deciding the efficiency of the biodrying process and hence process optimization has to be carried out in that period.

Fig. 5.2.12 Phase1-Condensation Process in Top Region of Reactor.

5.2.8 Limitations

The major limitation observed in the first phase of experiment was that the efficiency of moisture removal in the biodrying process has been affected due to the exhaust air saturation and the resulting condensation of evaporated water back in to the reactor in the top region of the reactor matrix (Fig. 5.2.12).

5.2.9 Modifications

Inorder to avoid the condensation problem at the top region of the reactor matrix the next phase study has to be carried out by incorporating design modifications.

5.3 EXPERIMENTAL INVESTIGATION- PHASE 2- BIODRYING PROCESS IN MODIFIED REACTOR

5.3.1 Objectives

The major objective of the second phase of study was to improve the moisture removal efficiency of the biodrying reactor by controlling the condensation process at the top region of the reactor matrix. The secondary objective was to reduce the reaction time of the process.

5.3.2 Introduction

The second phase of investigation included the study of the feasible options for condensation prevention methods for reactors. The condensation prevention design has been incorporated at the reactor outlet and the airflow rate is maintained the same as the previous experiment.

5.3.3 Horizontal Air Flow System

The different methods for preventing condensation in reactor were studied. The major challenge was to select the feasible one by considering the safety aspect, since the waste materials produces explosive gaseous emissions. A detailed literature study has been conducted to select mixed cross flow with horizontal air flow (HAF) system.

The principle of HAF unit is that it utilizes the air that moves in a coherent horizontal pattern. It needs energy only enough to overcome the turbulence and friction loss to keep it moving (Fig.5.3.1). The moving air will replace the depleted air with fresh air, which helped to considerably reduce the odour from the process. This system will reduce the condensation reaction at the top region of the reactor matrix, since saturated air will be diluted with fresh air.

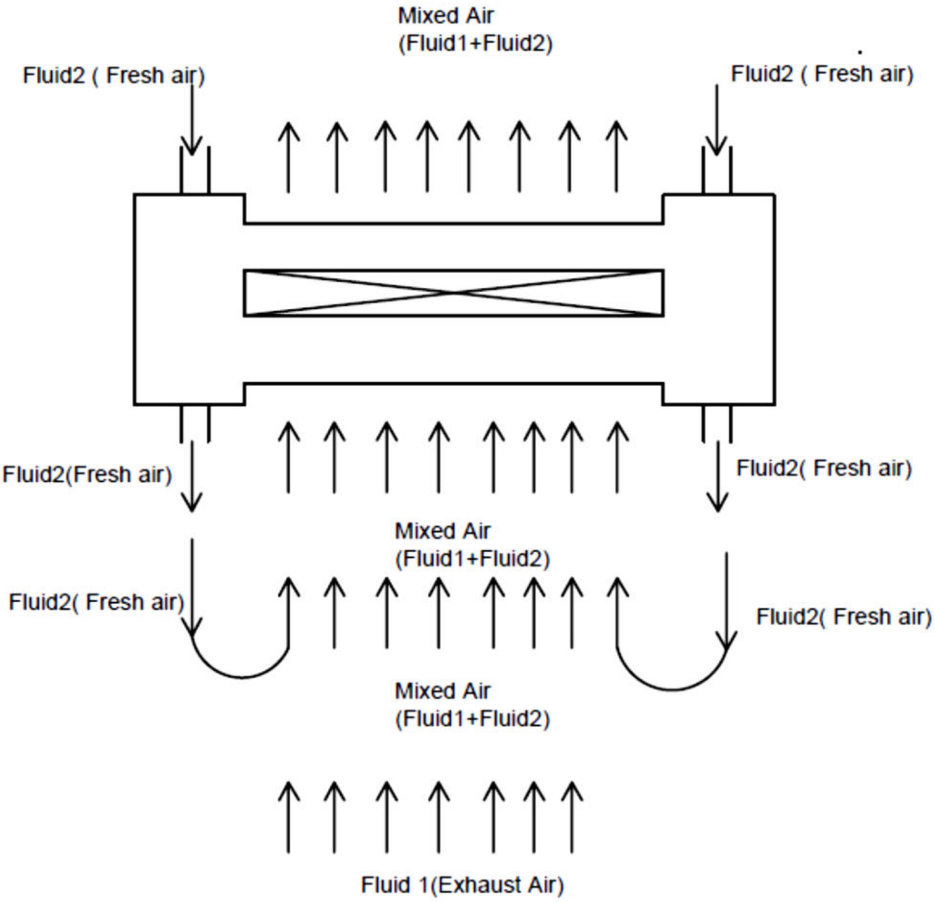


Fig.5.3.1 Principle of HAF system.

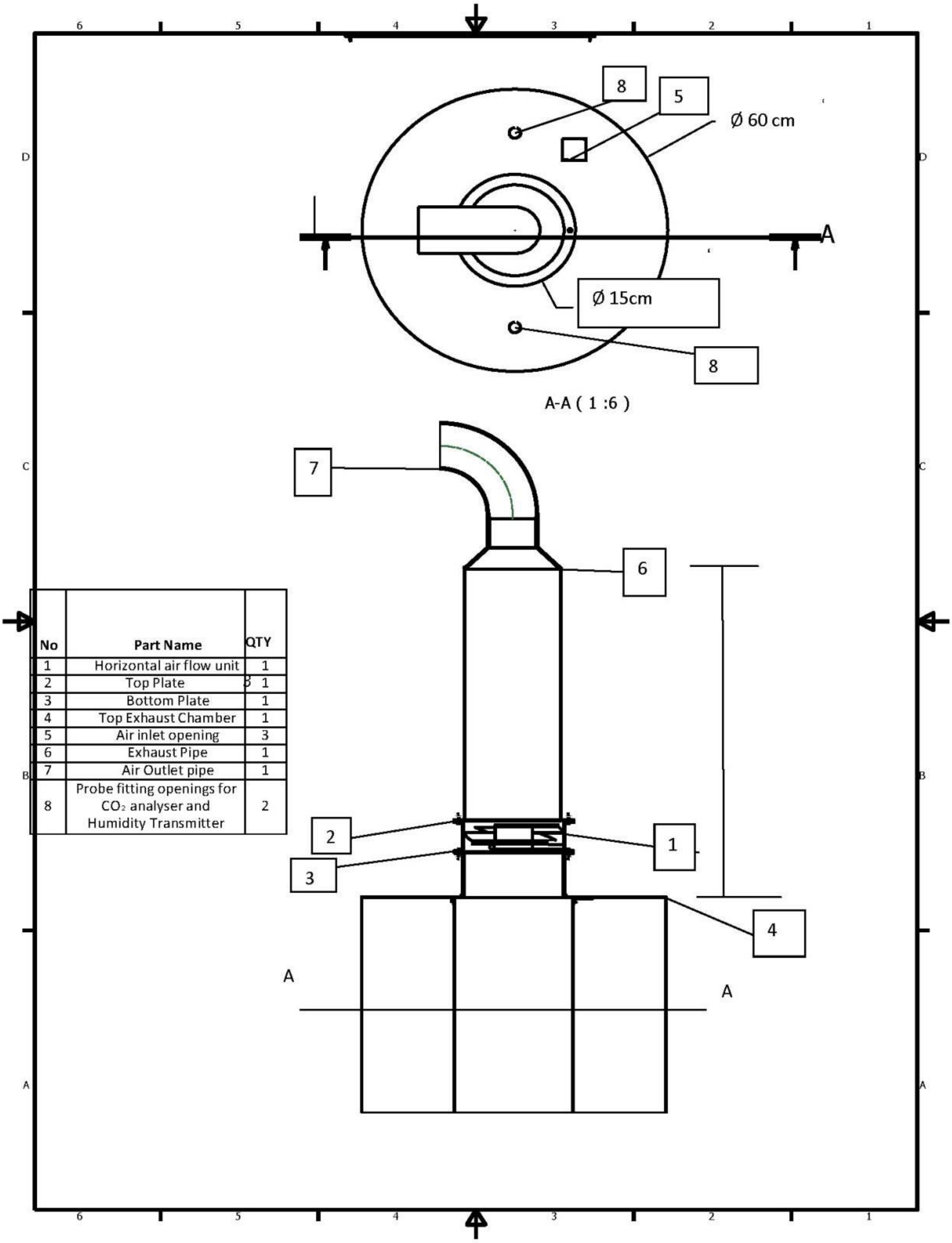
The different components of the fabricated HAF system has been shown in Fig. 5.3.2. In this system the HAF unit has been fabricated along with the exhaust air chamber. The top and bottom plates of the HAF unit helped to fix it along with the PVC pipe unit for exhaust air. The air holes on the exhaust air chamber will allow the fresh air to enter in it and then it is mixed with the exhaust air from the biodrying reactor. The diluted air will be sucked out through the HAF unit.

5.3.4 Modified Biodrying Reactor

In the second phase of experiment the biodrying reactor design has been modified with the addition of innovatively designed horizontal air flow (HAF) system (Fig.5.3.3). The reactor modification has been done with the aim of eliminating the condensation of evaporated water back in to the reactor matrix. The air dilution effect of the HAF system is kept in such a way that the relative humidity of the exhaust air is limited in the range of 75%-85 %

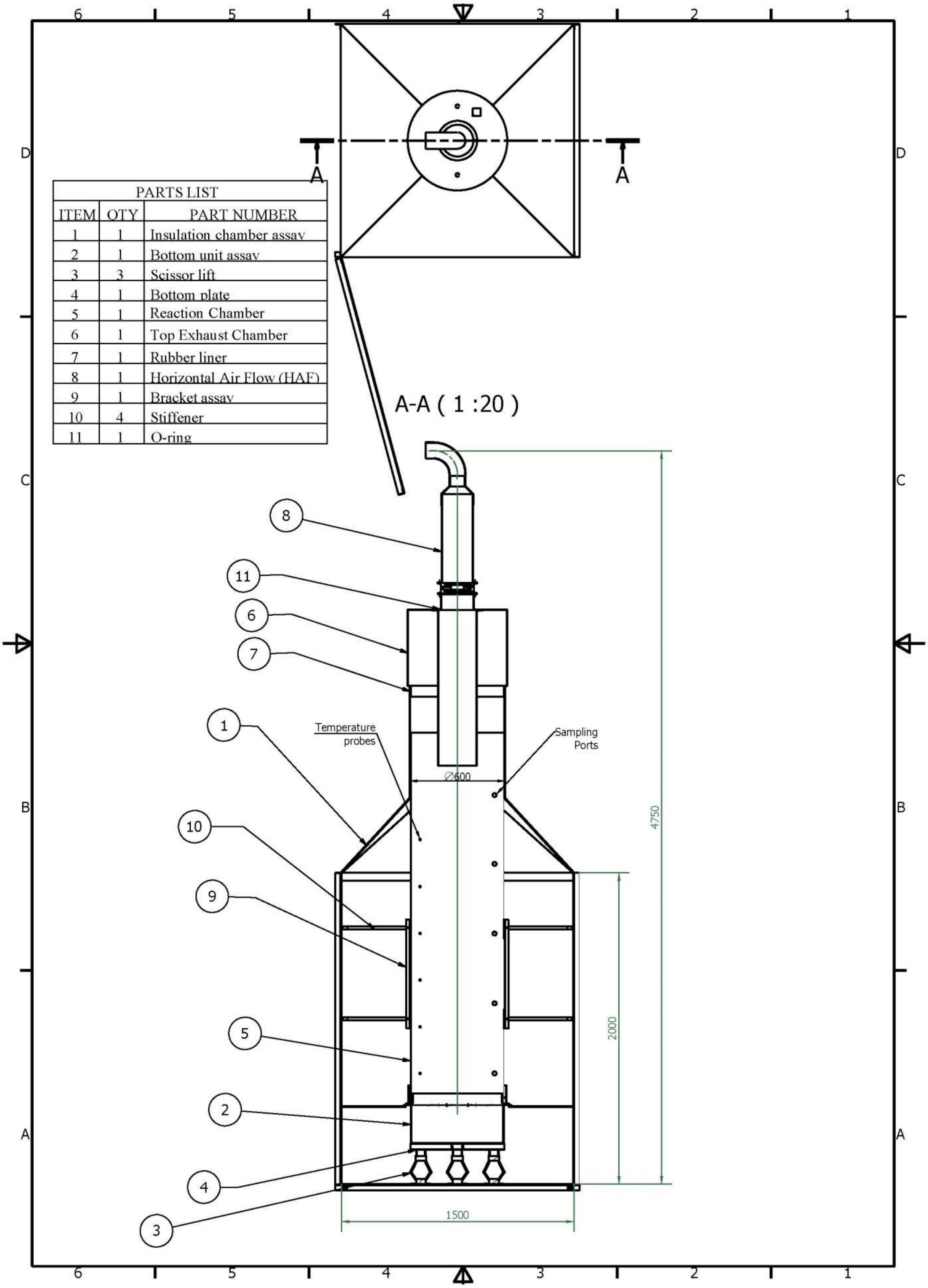
5.3.5 Materials and Methods

Mixed municipal solid waste substrate of 126 kg was synthetically prepared in the laboratory, by mixing the raw waste in proportion as shown in Table.5.3.1. Different components of the mixed municipal solid waste substrate were thoroughly mixed to yield a homogeneous mixture and 124 kg from this mixture has been used as the reactor feed.



No	Part Name	QTY
1	Horizontal air flow unit	1
2	Top Plate	1
3	Bottom Plate	1
4	Top Exhaust Chamber	1
5	Air inlet opening	3
6	Exhaust Pipe	1
7	Air Outlet pipe	1
8	Probe fitting openings for CO_2 analyser and Humidity Transmitter	2

Fig.5.3.2 Design Details of HAF system.



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Insulation chamber assay
2	1	Bottom unit assay
3	3	Scissor lift
4	1	Bottom plate
5	1	Reaction Chamber
6	1	Top Exhaust Chamber
7	1	Rubber liner
8	1	Horizontal Air Flow (HAF)
9	1	Bracket assay
10	4	Stiffener
11	1	O-ring

Fig.5.3.3.Modified Biodrying Reactor- Phase 2.

Table. 5.3.1 Mixed Municipal Solid Waste Substrate Composition- Phase 2

Component	**Particulars**	**Weight (kg)**	**Subtotal (kg)**	**Grand Total (kg)**
Organic components	Raw food waste	22	91.9	**126**
	Cooked food waste	55		
	Fibers	5		
	Dried leaves	6		
	Fresh leaves	4		
Paper and Cardboard	News paper	7.6	12.6	
	Print Paper	2		
	Cardboard	3		
Plastics	Crushed bottles	2.8	8.8	
	Milk Covers	3		
	Plastic Covers	3		
Textiles	Cotton	10	12.6	
	Polyester, Nylon	2.6		

The initial process conditions for the second phase of experiment include air supply at the volumetric rate of 40 L/m. The corresponding specific air flow rate was 0.465 m^3/kg.day. It was observed that the reactor matrix is having initial moisture content of 65.5 %. The biodrying reactor of 60 cm diameter was filled with the substrate up to a height of 1.4 m and the initial volume of the feed was calculated as 0.396 m^3. Initial bulk density of the reactor matrix was obtained as 189 kg/m^3.

5.3.6. Results and Discussions

The filled biodrying reactor at the beginning and end of 15 days of process in the second phase is shown in Fig. 5.3.4. The results considered for the process analysis were based on the parameters like temperature, weight loss, moisture content, relative humidity, volume reduction and bulk density augmentation. The major objective of the second experimental phase was to prevent saturation of air at the top region of the reactor matrix.

a) Before Biodrying process b) After biodrying process

Fig.5.3.4. Reactor at the Beginning and End of Biodrying Process-Phase 2.

5.3.6.1 Effectiveness of the Modified Reactor Design

It was observed that till the end of 15 days of process no condensation problem was observed in the top region of the reactor, and the exhaust air relative humidity has been sustained in the range of 75 % to 85 % during the entire reaction period. It was a major achievement in the second phase of experiment. The top side walls of the reactor was visibly free form water drops (Fig. 5.3.4). Only the side wall condensation has occurred, which is very less when compared to the volume of the reactor matrix. It is to be noted that the actual field conditions in the scaling up process of reactors, the surface area to volume ratio is very less and hence the side wall condensation can be neglected.

5.3.6.2 Leachate Free Process

The leachate production is the major issue faced by most of the municipal waste treatment systems. The designed biodrying process was versatile with since the leachate production has been completely eliminated in the process.

5.3.6.3 Temperature Profile

The initial eight hour variation of temperature has been plotted against time (Fig. 5.3.5). In the second study the maximum temperature rise has been shifted to the bottom portion of the reactor near to the air inlet. The maximum temperature of 41ºC has been recorded at the probe 30 cm distant from the air inlet.

It was observed from the temperature profile study that a temperature gradient has existed along the height of the self heating reactor matrix (Fig.5.3.6). In the second experimental phase high temperature lasted for a longer time (10 to 12 days) which has resulted in increasing the drying efficiency of the process as observed in the contour plot (Fig. 5.3.7). It was noted that in the second study the temperature rise along the height of the reactor is less compared to that in the first phase.

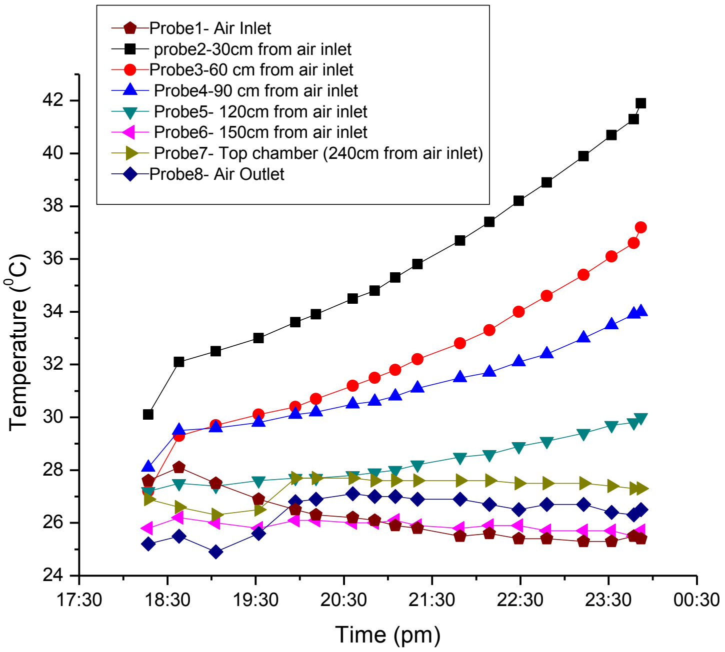


Fig. 5.3.5 Temperature Profile During the First Eight Hours of Reaction-Phase 2.

The comparison study of the temperature profile of the first and second phase of investigations has helped to understand the biodrying process in detail. The temperature contour for 15 days of biodrying process for the two studies were analysed (Fig.5.3.7 & Fig.5.3.8). The formation of temperature gradient was observed along the height of the self heating reactor matrix in both phases of experiment. In the first phase high temperature (in the range of 55 °C -59 °C) has lasted for a short duration of 4 days. In the second phase the high temperature heating continued for long duration of 11 days in the second experiment (Fig. 5.3.7). The second phase of experiment was more effective in self heating with the exception that, the top region of reactor matrix,(above 90 cm from the air inlet) was not able to achieve high range of temperature.

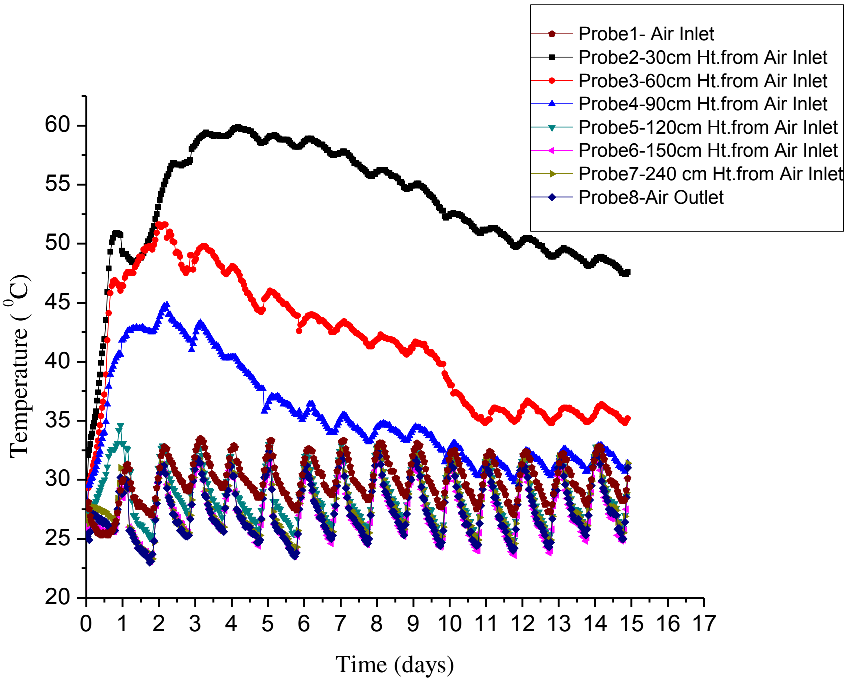


Fig. 5.3.6 Temperature Profile in 15 days – Phase 2.

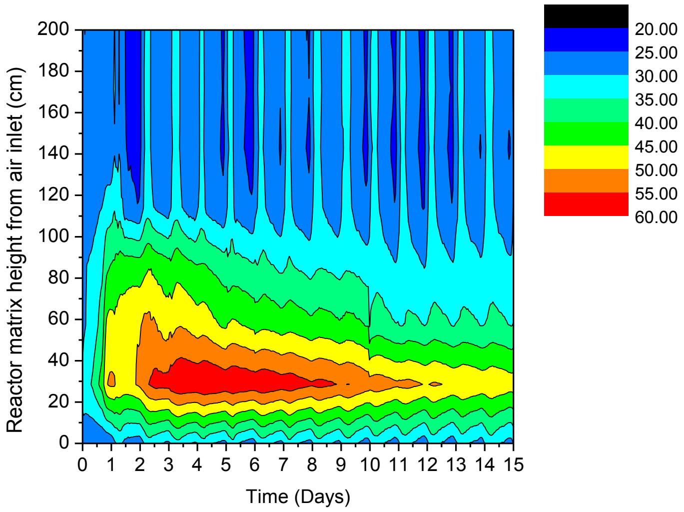


Fig .5.3.7 Temperature Contour- Phase 2.

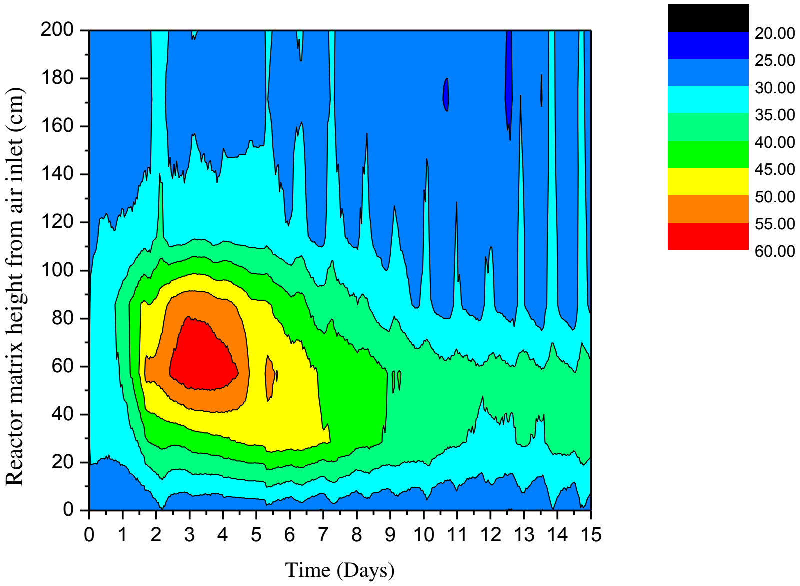


Fig .5.3.8 Temperature Contour for 15 days- Phase 1.

5.3.6.4 Weight Reduction

The greatest achievement in the second phase of experiment is that the condensation prevention measure incorporated in the design was able to eliminate saturation of air above the reactor matrix. The steep slope of the weight loss profile of the substrate shows increased process efficiency (Fig. 5.3.9). Weight reduction has been monitored continuously using electronic load cell. The entire reactor unit is placed over the load cell. The weight loss is calculated in every second of time and the data transferred through the data acquisition system and reading taken on the monitor of computer. In the second phase, the weight of the reactor matrix has been reduced from the initial value of 124 kg to 75.4 kg in 15 days of reaction. This accounts for a reduction of 39.2 % of the weight. That is an increase of 7 % in weight reduction when compared to the first study, where 32 % weight loss has been resulted in 15 days of experiment.

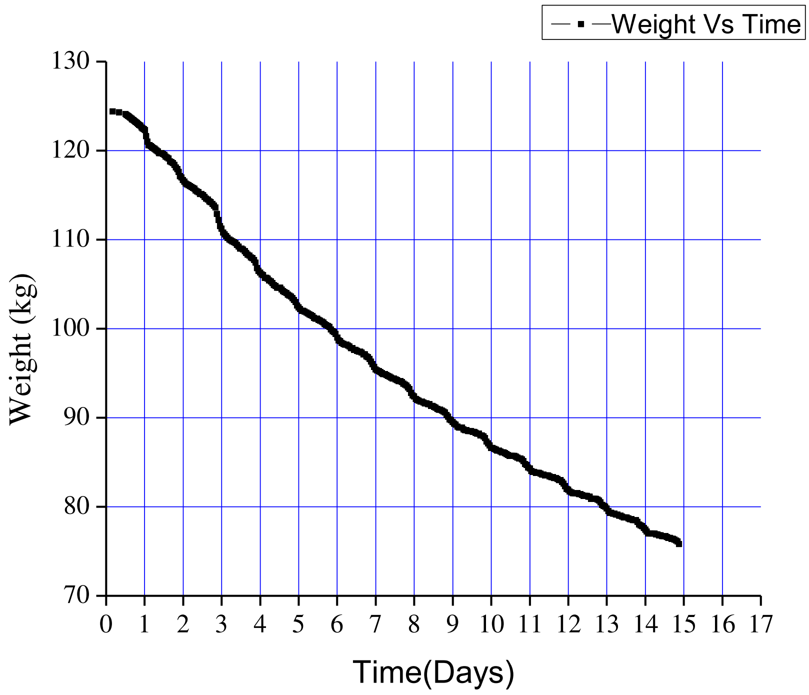


Fig. 5.3.9 Weight Reduction Profile- Phase 2.

The weight reduction percentage has been plotted against time for the first and second studies for 15 days of reaction and is shown in Fig. 5.3.10. It has been observed that on an average weight reduction rate was 1.85 kg/day in first phase of experiment while that was increased to 3.24 kg/day in the second experiment. The weight of the reactor matrix has been reduced from the initial value of 124 kg to 75.4 kg in 15 days of the process which accounts for a total weight reduction of 39.2 %. The weight reduction was 32% in the first study for the same duration. Therefore the second phase of study was more effective in weight reduction when compared to the first one.

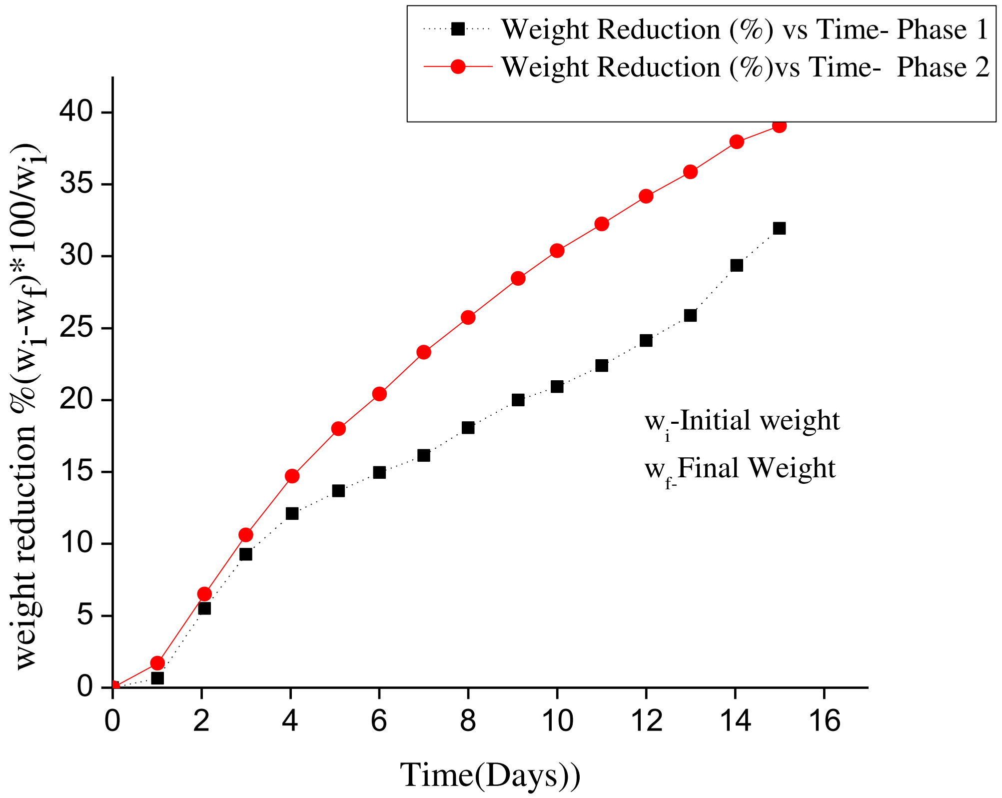


Fig. 5.3.10 Weight reduction % Vs Time-Comparison of First and Second Phase of studies.

5.3.6.5 Moisture Profile

The average value of moisture content has been plotted against time along with the standard deviation bars (Fig.5.3.11). The initial moisture content of 65.5 % has been reduced to 43.9 % in the entire process time of 15 days. Moisture reduction of 33 % has been resulted from the second study which is much higher than the same period reduction of 22 % obtained in the first phase of experiment. Also the second phase of study was found to be very successful in completely eliminating the condensation of evaporated water in the top region of reactor matrix, which resulted in retrieving a more or less homogeneous output from the process.

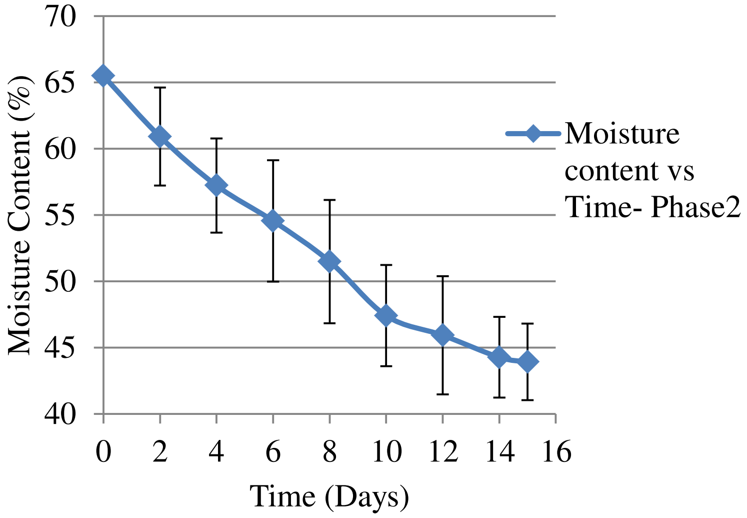


Fig. 5.3.11 Average Moisture Profile- Phase 2.

The moisture reduction profiles of the first and second phases of experiments were compared as shown in Fig.5.3.12.

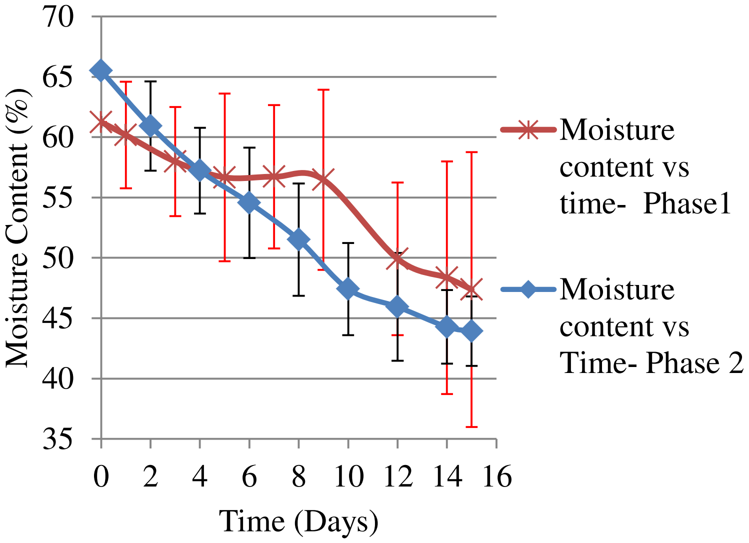


Fig. 5.3.12 Average Moisture Content- Variation in 15 Days for First and Second Phases.

The uniformity of the biodried output in terms of moisture reduction was better in second study (standard deviation (S.D) 2.6-4.8), when compared with first study (S.D, 4.61 -11.63). There exists a region of side wall condensation in a thin wet layer of reactor feed where the moisture content is 49 %. This side wall condensation can be neglected since in commercial scale reactors the ratio of surface area to volume is very less.

5.3.6.6 Volume Reduction

Bulk volume of the mixed municipal solid waste is a major crisis faced by most of the municipal solid waste treatment units. The modified biodrying process in the second phase was able to achieve a volume reduction of 42.85 % in 15 days of reaction as shown in Fig. 5.3.13.

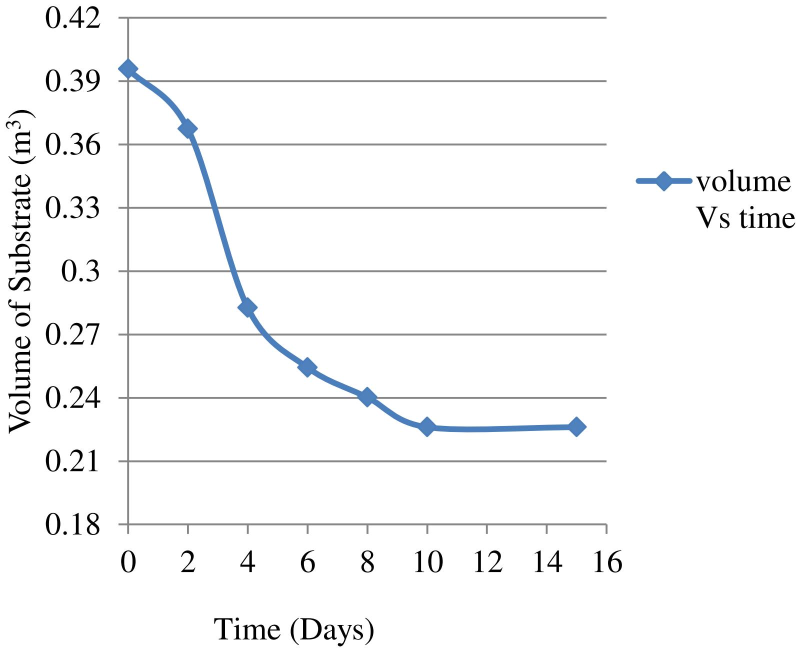


Fig. 5.3.13 Volume Reduction in Biodrying –Phase 2.

The mixed MSW substrate volume has reduced by 44.2 % and 42.86 % (Fig. 5.3.14), in first and second studies respectively at the end of 15 days of reaction. Hence comparable results were obtained for two phases in terms of volume reduction.

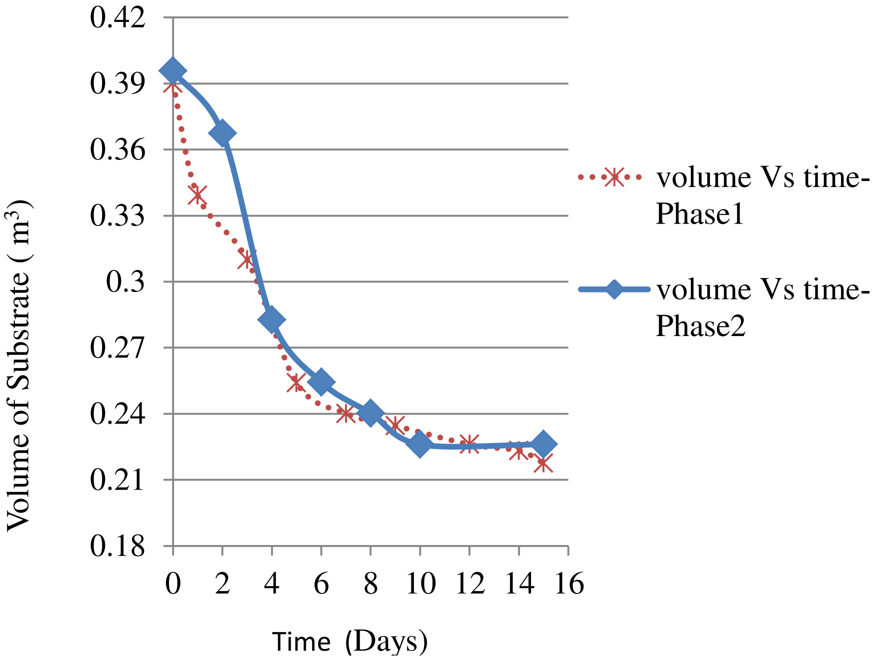


Fig. 5.3.14 Bulk Volume Reduction-Comparison of First and Second Phases.

5.3.6.7 Bulk Density

The energy value of any material is affected by the bulk density. The higher the bulk density of fuel the more the energy value will be. The in situ bulk density has been calculated as per equation 5.1.

Bulk density has been increased from the initial value of 189 kg/m^3 to the final value of 233 kg/m^3 at the end of 15 days of biodrying reaction in the second phase of experiment (Fig.5.3.15). The maximum bulk density during the entire process period occurred by the tenth day of reaction (258 kg/m^3), and after that bulk density decreased to 233 kg/m^3. This clearly indicated a decline in microbial reactions after the tenth day of biodrying process. The increase of bulk density is 23 % at the end of 15 days of reactions in the modified process (Fig. 5.3.15).

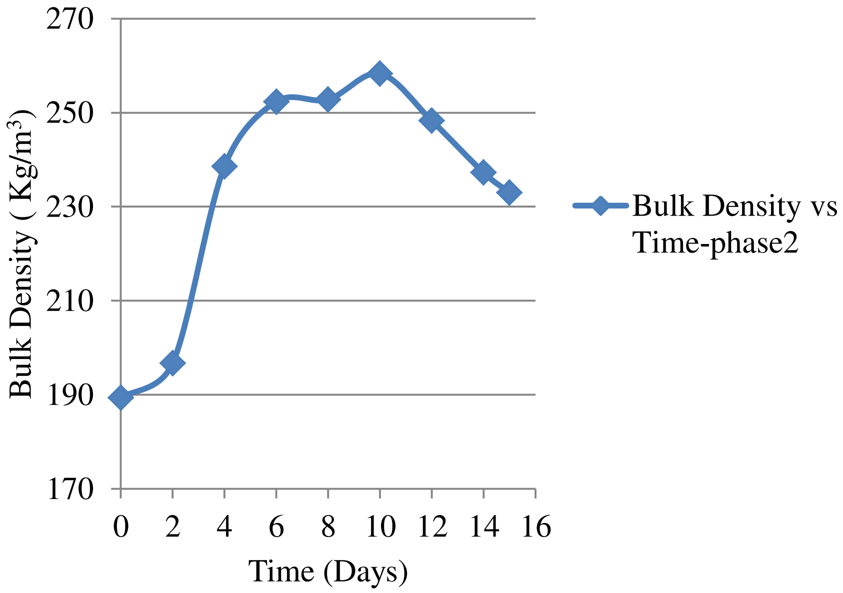


Fig. 5.3.15 Bulk Density Profile- Phase 2.

The comparison of first and second phases of study has shown that the first experiment has resulted in 35.09 % increase in bulk density during the period of 15 days (Fig.5.3.16). Therefore first phase of experiment was more successful in terms of bulk density improvement. It is due to the fact that presence of moisture due to condensation of evaporated water back in to the reactor facilitated high rate of microbial activity, which increased the biodegradation process along with the biodrying process in the first phase of experiment. The variation of these two processes leads to better drying efficiency.

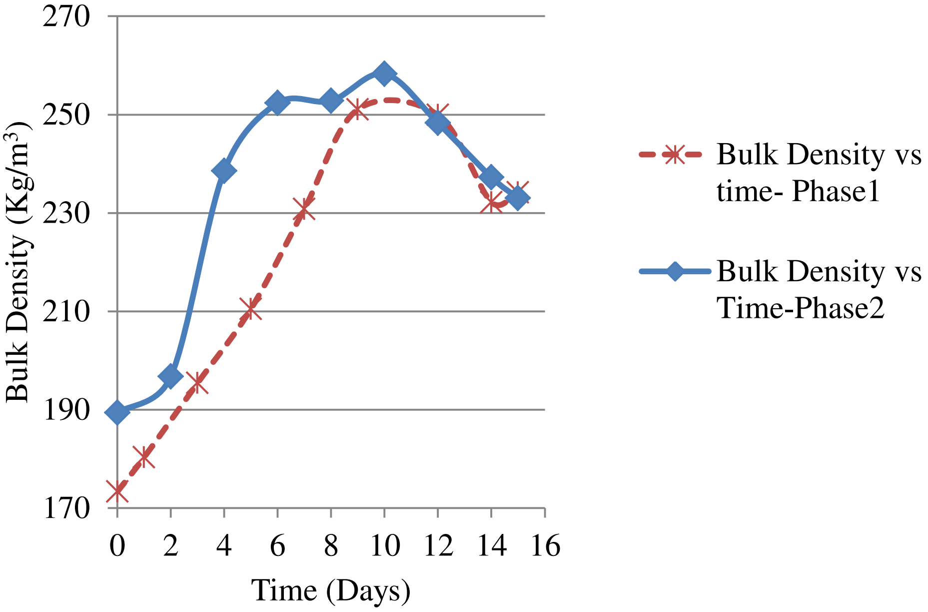


Fig. 5.3.16 Bulk Density Profile – Comparison of First and Second Phases.

5.3.7 Summary

The reactor design has been modified in the second phase with the provision of innovatively designed heat exchanging system to avoid exhaust air saturation. It was observed that the modified design was able to achieve complete elimination of condensation in the top region of the reactor matrix by maintaining the relative humidity of exhaust air in the range 75 % to 85 %. Also the maximum temperature rise of 59.2 °C lasted for a long duration of 7 days in the modified design. In addition to that the second study was very successful with a weight reduction of 39.2% occurred in 15 days of experiment, while that was 32 % in the first experiment for the same duration.

The moisture content of the mixed municipal solid waste substrate has reduced from the initial value of 65.5 % to final 43.9 % in the second experimental phase. A moisture reduction of 33 % has been achieved in the second study during 15 days of reaction, which is much higher than moisture reduction of 22% in the first experiment. Also the volume reduction of 42.85 % and bulk density increase of 23 % occurred in fifteen days of biodrying process in the second phase with humidity control. The fifteen day results of volume reduction and bulk density increase was more in the first phase, with a reduction of 44.2 % of volume and 35.09 % increase in bulk density. This may be due to the fact that moisture presence facilitated high rate of biodegradation process along with the biodrying process in the first study that resulted in increased bulk density of the reactor matrix. Considering the biodrying reaction the second phase of study with humidity control measure incorporated in the biodrying reactor design was more successful .The predominance of biodrying reaction over the biodegradation process is favourable for waste to energy conversion technology.

5.3.8 Limitations

The temperature gradient formation has been observed in the first and second phase. The temperature gradient has to be minimised to achieve more or less uniform heating of the biodried material. In the first phase temperature rise was in vertical direction along the reactor height, while it was in horizontal direction along the time axis in the second phase.

5.3.9 Further Modifications

It needs further study to analyse whether it is possible to maintain uniform self heating in static biodrying process. The self heating process with respect to the increase in filled height of reactor matrix needs to be studied for further process improvement.

5.4. EXPERIMENTAL INVESTIGATION- PHASE 3- EFFECT OF SPECIFIC AIR FLOW RATE AND REACTOR MATRIX HEIGHT ON BIODRYING REACTION

5.4.1. Objectives

The major objective in the third phase of experiment was to study the effect of variation in specific air flow rate and increasing the reactor matrix height on the biodrying process efficiency.

5.4.2 Introduction

In the third phase of study the increased reactor matrix height on biodrying process has been studied. Also the reducing specific air flow rate on temperature profile of the reactor matrix has been studied in detail. The effect of both these factors in elevating the temperature throughout the reactor matrix and especially in the top zone of the reactor matrix has been investigated.

5.4.3. Materials and Methods

In the third phase of study, the addition of weight has resulted in increasing the height of reactor pile by 25 cm. Municipal solid waste substrate of 172.55 kg has been synthetically prepared in the laboratory, by mixing the raw waste in proportion as given in Table. 5.4.1.

Table. 5.4.1 Substrate Composition- Phase 3.

Component	**Particulars**	**Weight (kg)**	**Subtotal (kg)**	**Grand Total (kg)**
Organic components	Raw food waste	38	124.56	**173**
	Cooked food waste	56		
	Fibers	3		
	Dried leaves	12.56		
	Fresh leaves	15		
Paper and Cardboard	News paper	12	19	
	Print Paper	3		
	Cardboard	4		
Plastics	Crushed bottles	3	13.84	
	Milk Covers	7.84		
	Plastic Covers	3		
Textiles	Cotton	11	17.4	
	Polyester	6.4		

Different components of the mixed municipal solid waste substrate were thoroughly mixed to yield a homogeneous mixture an 167 kg from this mixture was used as the reactor feed (Table 5 .4.1). The inlet air supply was given at a volumetric rate of 40 L/m, which accounts for a specific air flow rate of 0.345 m^3/kg.day, which is lesser than that of previous study. The innovatively designed horizontal air flow system (HAF) system has been provided in this phase also so that the exhaust air humidity is in the range 75-85 %. The initial moisture content of the substrate was calculated by weighted average method by summation of the moisture contents of the individual component present in the mixed municipal solid waste.

Fig.5.4.1 Filled Reactor Core- Phase 3.

It was observed that the reactor matrix is having high initial moisture content of 62.45 %. The biodrying reactor of 60 cm diameter was filled with the substrate up to a height of 1.65 m. The initial volume feed was calculated as 0.466 $m^3$and the initial bulk density of the filled reactor matrix was obtained as 220.20 kg/m^3.The process instrumentation design was kept similar to the second phase of experiment.

5.4.4. Results and Discussions

The condensation problem has been completely eliminated at the top region of the reactor similar to second phase. The reactor matrix height has been reduced from the initial 1.65 m to final 1.01m at the end of 15 days of reaction. Leachate production has been completely eliminated in the bottom chamber, like the previous studies. It was observed that biodegradation reactions occurred in the bottom zone which has resulted in visible patches of wet zones. Minimising the degradation process is found to be beneficial for the biodrying purpose. At the same time high temperature development favours active hygienisation of the reactor matrix.

5.4.4.1 Temperature Profile

It was observed that in the first eight hours of reaction the maximum rise of temperature occurred (Fig.5.4.2). The maximum temperature rise in the initial hours has been similar to that of second phase with a maximum temperature of 48.9ºC recorded at the probe 30 cm distant from the air inlet. The temperature profile for 15 days of biodrying process has revealed the existence of temperature gradient along the height of the self heating reactor matrix (Fig. 5.4.3). Peak temperature of 65.5ºC has been recorded at 30 cm from air inlet by the sixth day in this phase of experiment.

Active self heating has observed throughout the reactor matrix in this study, where the temperature of the substrate has been increased to a maximum value of 59ºC at 90 cm from the air inlet. In the previous phase of experiments temperature has not raised above 45ºC in the same probe. Therefore self heating process was more prominent throughout the reactor matrix ensured effective sanitisation in the third phase of study.

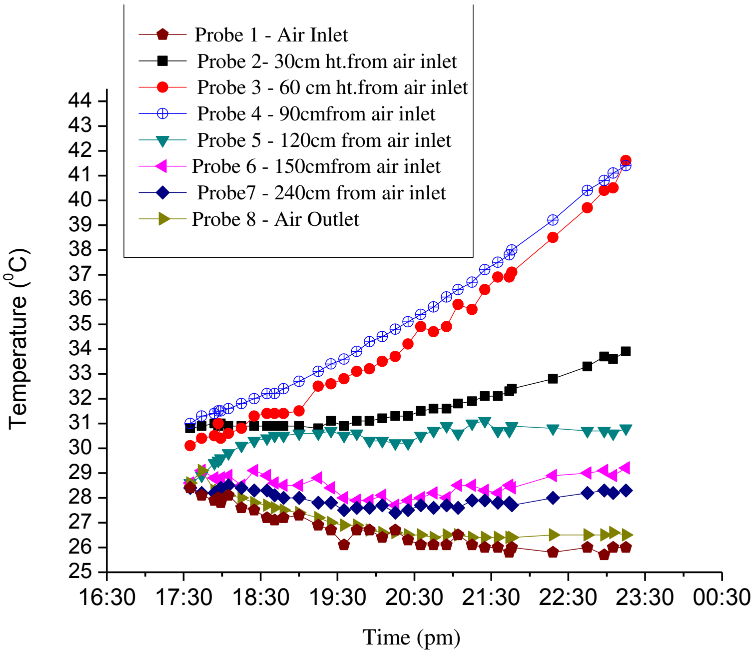


Fig. 5.4.2 Temperature Profile During the First Eight Hours of Reaction- Phase 3.

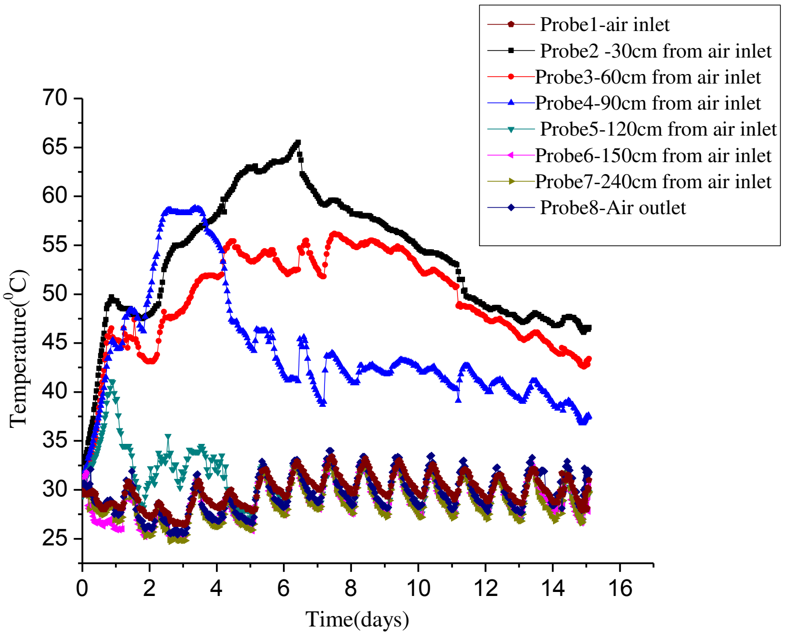


Fig. 5.4.3 Temperature profile in 15 days – Phase 3.

It was noted that more self heating reaction spreaded along the height of reactor matrix in the third phase, which is advantageous while compared to the second study.

Also the analysis of temperature contour of third phase has revealed that the self heating process has been prominent along the horizontal time axis was well as in vertical direction (along height of reactor) (Fig.5.4.4).

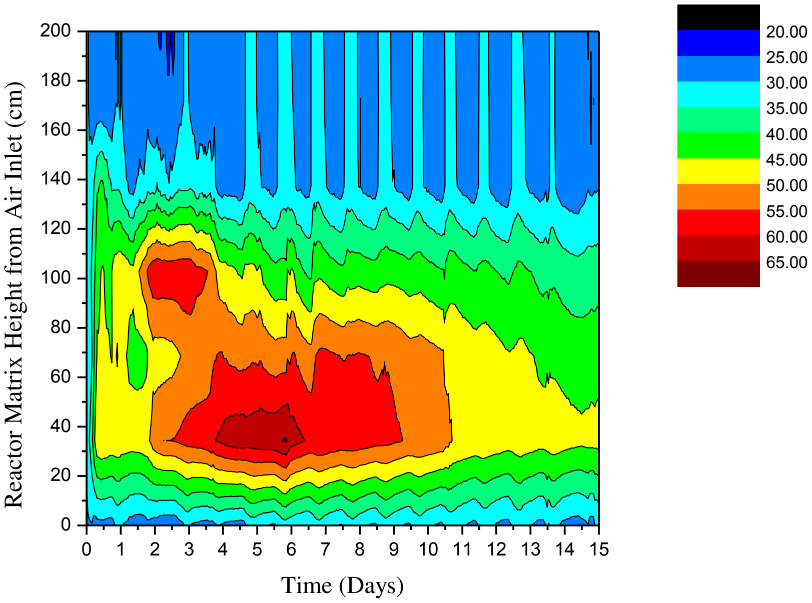


Fig. 5.4.4 Temperature Contour- Phase 3.

The high temperature core formation was observed at two locations in the third phase as seen in contour plot (Fig.5.4.4). This shows localised zones of active biodegradation inside the reactor matrix in the third phase of study.

The third study was successful in maintaining high temperature throughout the reactor matrix. The temperature rise above 60°C indicates the active biodegradation reactions in some local zones inside the reactor matrix. This is useful for sanitation of the biodried product. It was found that the third phase of experiment was successful in raising the temperature at the top region of the reactor, while compared to the second phase of investigation (Fig. 5.4.4). The peak temperature inside the reactor matrix went on increasing and a maximum value of 65.5ºC has been recorded at the probe 30 cm from air inlet. The stratification of temperature has been increased along the reactor matrix height.

5.4.4.2 Weight Reduction

Weight reduction has been monitored continuously using electronic load cell. The entire reactor unit is placed over the load cell. The weight loss is calculated in every second of time and the data transferred through the data acquisition system and reading taken on the monitor of computer. In this phase, the weight of the reactor matrix has been reduced from the initial value of 167 kg to 108.6 kg in 15 days of the process (Fig.5.4.5.). The third phase has resulted in weight reduction of 34.89 % weight in 15 days of reaction. The weight loss profile during the biodrying process was plotted against time for the second and third phase of investigations as shown in Fig. 5.4. 6.

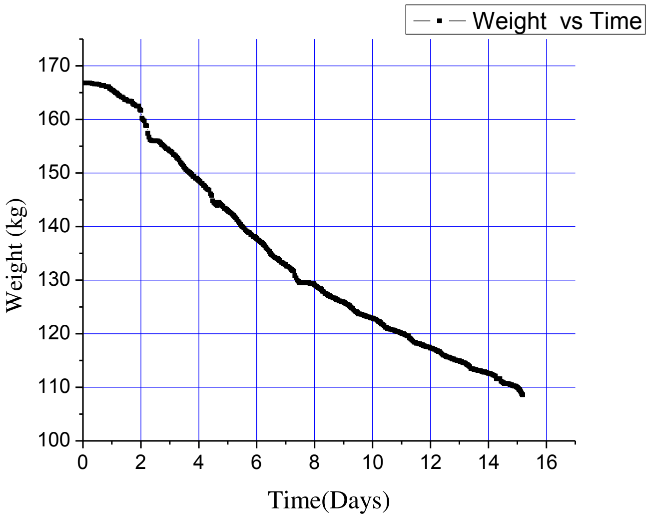


Fig. 5.4.5 Weight Reduction profile- Phase 3.

The total weight loss percentage was 39 % in the second phase while it was 34.9 % in the third phase of study.

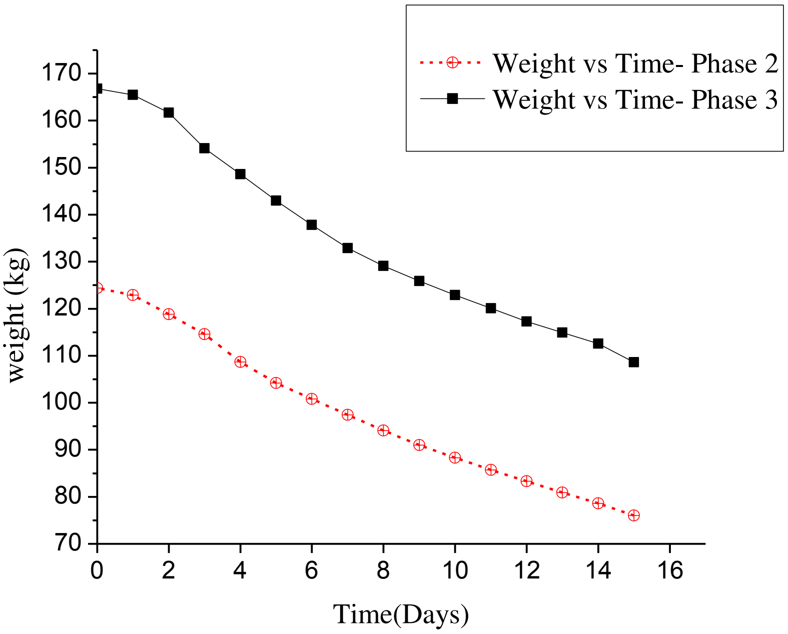


Fig. 5.4.6 Weight Reduction Profile -Comparison of Second and Third Phase.

5.4.4.3 Moisture Profile

The biodrying process is advantageous over the conventional drying process since biological heat is used for moisture reduction. The average value of moisture content has been plotted against time along with the standard deviation bars as shown in Fig. 5.4.7. The initial moisture content of 62.45 % has been reduced to a final value of 43.5 % in the entire biodrying process in 15 days of reaction. This accounts for a moisture reduction of 30.3 % in the third phase of experiment. In the third phase the standard deviation of moisture analysis results was in the range 1-5 (Fig.5.4.7).

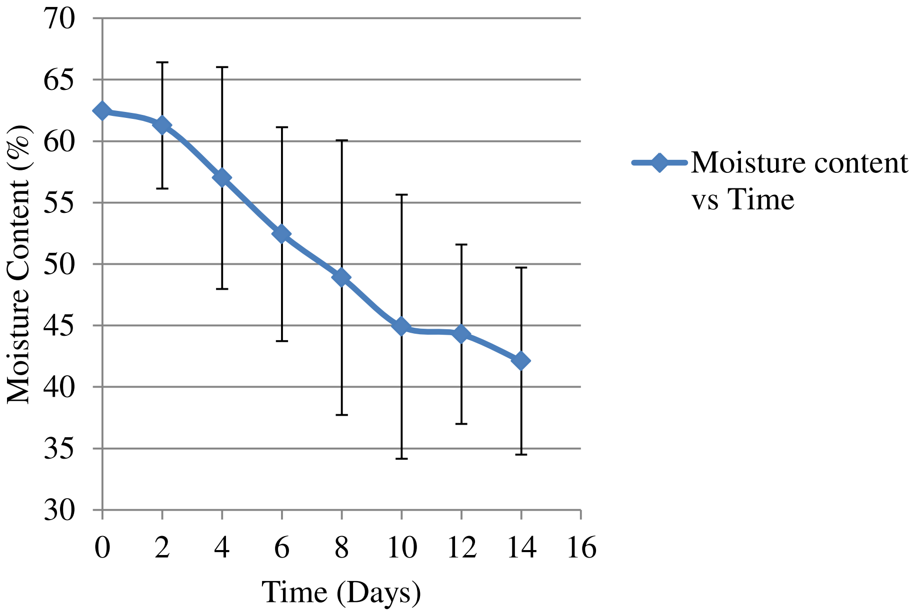


Fig. 5.4.7 Average Moisture Profile during the Biodrying Process- Phase 3.

The comparison study of moisture profile for the second and third phase investigations has been carried out (Fig. 5.4.8). It was observed that a moisture reduction of 33 % and 30 % has been achieved in the second and third phase of reaction respectively. The final moisture content of the substrate was 43.9 % and

43.5 % in the second and third phase respectively (Fig.5.4.8). It was observed that non-uniform moisture distribution of the biodried product is unavoidable while dealing with the solid substrate like mixed MSW in static biodrying reactors.

The higher compaction due to the increased depth of reactor matrix favoured local zones of active biodegradation in the third phase of study. Therefore reactor matrix height is one of the factors deciding the biodrying process. The air flow in biodrying process should be such that it not only enough to activate the biodegradation reaction but also to promote drying reaction.

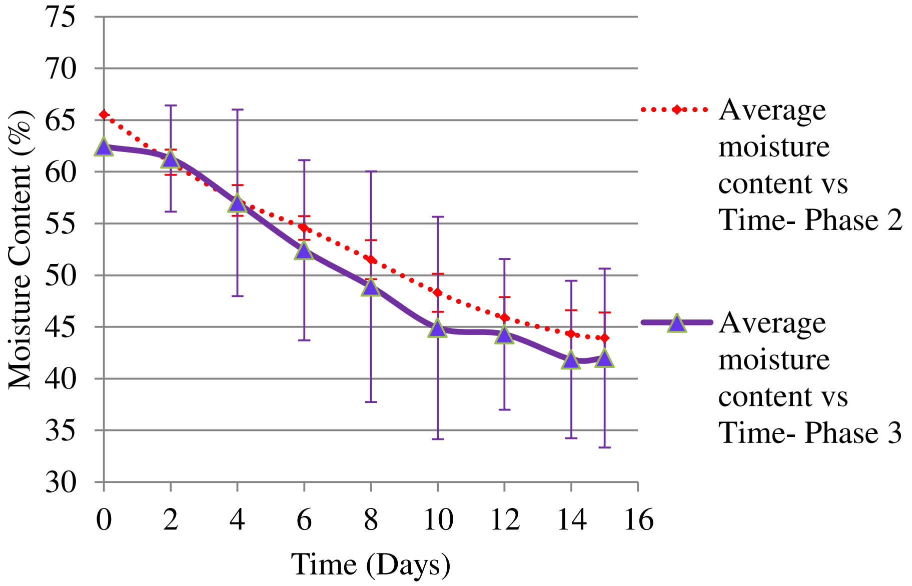


Fig. 5.4.8 Average Variations in Moisture Profile- Comparison of Phase -2 and Phase -3.

5.4.4.4 Volume Reduction

In the third phase of study the bulk volume of the mixed municipal solid waste substrate has been reduced from the initial value of 0.466 m^3 to final value of 0.285 m^3 in the third phase of biodrying process (Fig.5.4.9).

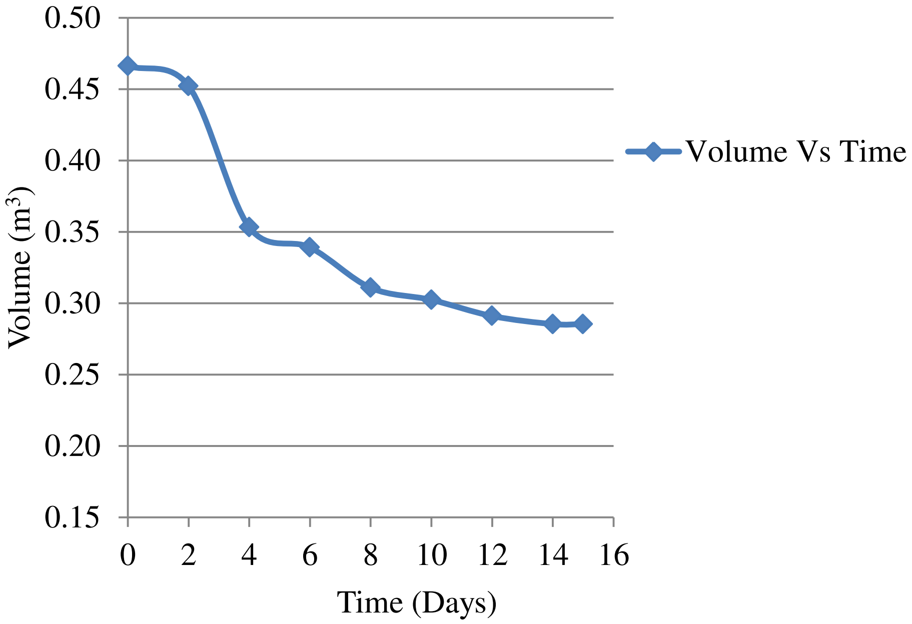


Fig.5.4.9 Volume Reduction in Biodrying- Phase 3.

This accounts for a volume reduction of 38.84 % in 15 days of biodrying reaction. The volume reduction during the second and third phase of study has been plotted against time as shown in Fig.5.4.10. Bulk volume reduction of 43 % has been achieved in 15 days of the process in the second phase while that was 39 % in the third study (Fig. 5.4.10). The non-uniform subsidence of the reactor pile was also observed in the third phase of investigation.

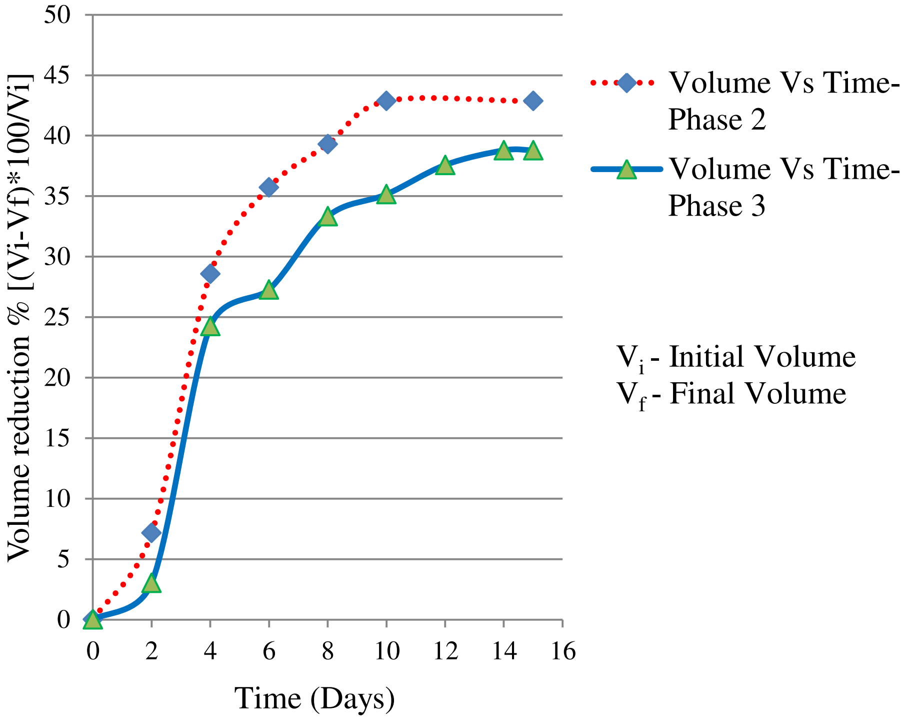


Fig. 5.4.10. Volume Reduction Profile - Second and Third Phase.

5.4.4.5 Bulk Density

The in situ bulk density has been calculated as per equation 5.1. In the third phase, the bulk density has been increased from the initial 220.20 kg/m^3 to final value of 265.14 kg/m^3 at the end of 15 days. The maximum bulk density of 280.94 kg/m^3 has been achieved by the tenth day of biodrying process and after that it started decreasing. The increase of bulk density is 21 % at the end of 15 days of reaction in the third phase of study (Fig. 5.4.11).

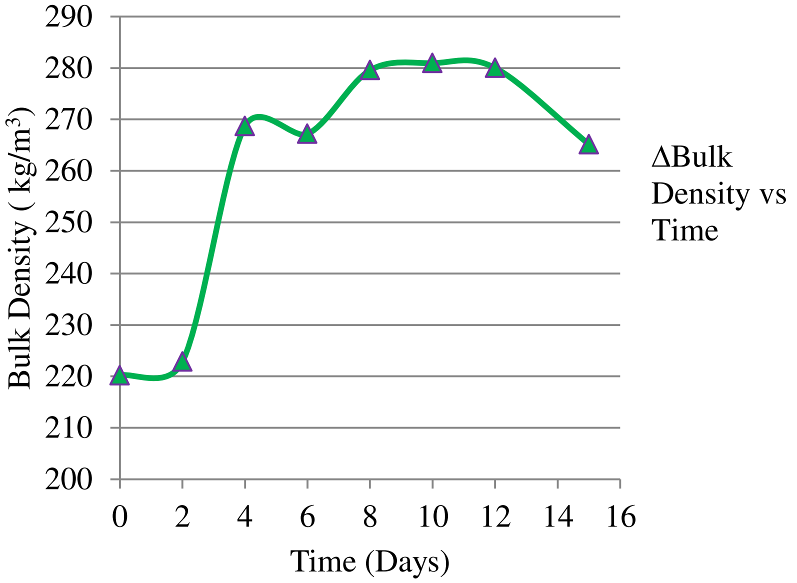


Fig. 5.4.11 Bulk Density Profile of Third Phase.

The bulk density results for the second and third phase of investigations were plotted as shown in Fig. 5.4.12.

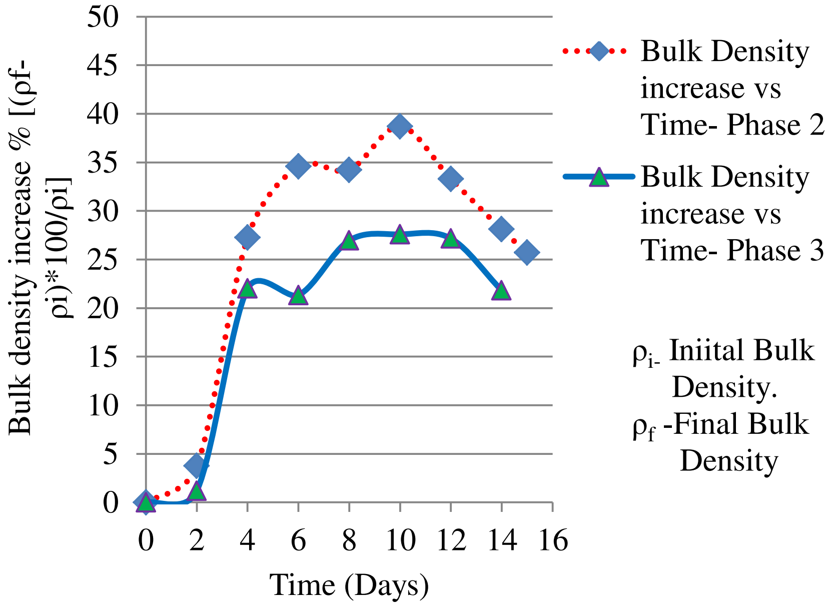


Fig. 5.4.12 Comparison of Bulk Density Profile for the Second and Third Phase of studies.

It can be observed that 26 % increase of bulk density has been achieved in the second phase, while that was 22 % in the third study (Fig.5.4.12).

5.4.5 Summary

The third phase of experiment has resulted in high temperature rise and better self heating throughout the reactor matrix. Active self heating in vertical direction along the height of reactor matrix, as well as during the entire reaction time has been achieved in the third phase of experiment. Maximum temperature of 65.5°C has been recorded in the zone at 30 cm from the air inlet. High temperature heating has resulted in hygienisation of the biodried output and hence safe handling and sorting of the same is possible. A number of high temperature core formations inside the reactor matrix have revealed the formation of local zones of biodegradation. The weight of the reactor matrix has been reduced from the initial value of 167 kg to 108.6 kg in 15 days of the process, which is a reduction of 34.89 %. The moisture reduction was 30 % in the third phase of investigation.

The third phase has resulted in volume reduction of 38.84 % in 15 days of biodrying reaction. Also bulk density increase of 21 % has been achieved in the third study. Comparing the results of second and third studies it can be seen that the third experiment was successful in terms of self heating profile. Considering the homogeneity of biodried output the second phase was more advantageous. This is mainly due to the formation of local zones of degradation inside the reactor matrix. The self heating reaction has a positive influence when the filled height of reactor feed is increased. The biodrying process using solid substrate like mixed MSW substrate, it was observed that the effect of reactor matrix height as well as the specific air flow rate is important factors deciding the homogeneity of the biodried output.

5.4.6 Limitations

The increased non-homogeneity of the biodried output was the major limitation observed in the third phase of study while compared to the second one. The local zones of biodegradation has to be avoided to get a homogeneous biodried output

5.4.7. Further Process advancement

The temperature profile change with respect to filled height of reactor matrix needs more investigations. It needs further study to analyse whether further increase of height of reactor matrix will affect or not the self heating profile as well as the homogeneity of the output.

5.5 EXPERIMENTAL INVESTIGATION- PHASE 4- COMBINED EFFECT OF PACKING AND REACTOR MATRIX HEIGHT ON BIODRYING PROCESS

5.5.1 Objectives

The major objective in the fourth phase was to study the combined effect of increased filled height of the reactor matrix and the substrate packing on the biodrying process.

5.5.2 Introduction

It needs investigation on the effect of increasing reactor matrix height on biodrying process. In the present phase the reactor matrix height has been increased and loose packing of substrate has been provided.

5.5.3 Materials and Methods

Mixed municipal solid waste substrate of 218 kg has been synthetically prepared in the laboratory, by mixing the raw waste in proportion as given in Table. 5.5.1. The different components are thoroughly mixed and from the mixture 172 kg has been used as feed for filling the reactor. The height of reactor matrix has been increased by 35 cm so that the reactor was fully filled to 2.0 m height which is the maximum capacity of the biodrying reactor. The substrate was loosely packed and the full volume of 0.565 m^3 was filled in the fourth study.

The volumetric air flow has been maintained at the same rate of 40 L/m used in the previous study. The corresponding specific air flow rate was 0.335 m^3/kg.day. The initial moisture content of the mixed MSW substrate was calculated by the weighted average method.

Table. 5.5.1 Proportion of MSW- Phase 4

Component	Particulars	Weight (kg)	Subtotal (kg)	Grand Total (kg)
Organic components	Raw food waste	60	151.9	**217.55**
	Cooked food waste	70		
	Fibers	5		
	Dried leaves	10		
	Fresh leaves	6.9		
Paper and Cardboard	News paper	13	26.04	
	Print Paper	6		
	Cardboard	7.04		
Plastics	Crushed bottles	2.36	17.36	
	Milk Covers	8.3		
	Plastic Covers	6.7		
Textiles	Cotton	13	21.7	
	Polyester	8.7		

It was observed that the reactor matrix is having initial moisture content of 66.4 %. Initial bulk density of the filled reactor matrix was obtained as 220.20 kg/m^3.

5.5.4 Results and Discussions

5.5.4.1 Temperature Profile

The detailed temperature profile of the biodrying reaction in the fourth phase of study is shown in Fig. 5.5.1. It was observed that increase in reactor fill has not resulted in increase of the self heating temperature in the fourth study. In fourth study the peak temperature attained was 58°C, which is less than the third study where 65°C has been achieved. The peak temperature in the fourth study has been recorded in the probe placed at 60 cm from the air inlet. Self heating was not effective in fourth study when compared with the third study that is visible from the contour plot as shown in Fig.5.5.2. The loose packing of the reactor feed has resulted in air channelisation and short circuiting, which affected the aerobic reactions due to lack of air flow inside the reactor matrix.

The effect of air flow on self heating reaction has been studied by conducting a series of air reduction as well as air evacuation tests in the fourth phase of experiment. The air evacuation test has been carried out through the air inlet chamber on the 5th and 6th day of experiment . In air evacuation test the air was ejected using a vacuum pump at a rate of 15 L/m, and it was found that a sudden temperature rise took place inside the reactor matrix.

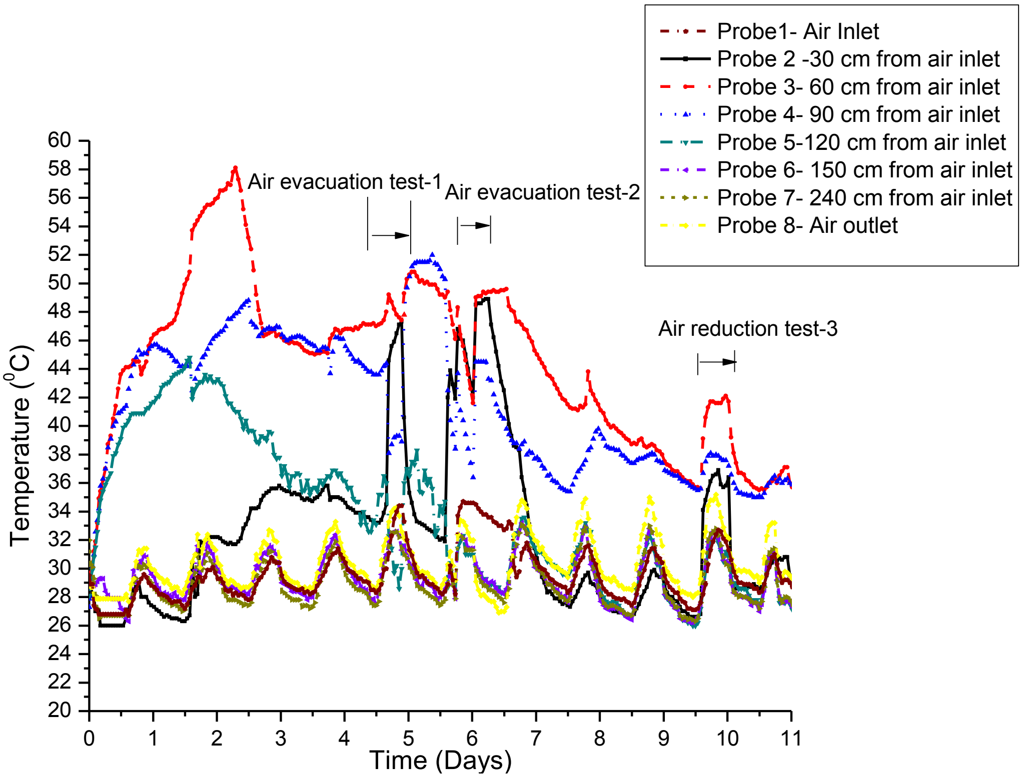


Fig. 5.5.1 Temperature Profile – Phase 4.

In fourth phase of experiment, five hours of evacuation test has been conducted on the fifth day of reaction. The temperature rise of 13.5°C has been observed in the probe at 30 cm distant from air inlet, whereas a drop of 6°C in temperature has been observed in the probe at 90 cm distant from inlet (Fig.5.5.1). On the sixth day also air evacuation test has been carried out for a period of one hour. A temperature rise of 13ºC has been observed on the probe at 30 cm from air inlet, and a temperature fall of 10°C has been recorded at the probe 90 cm from air inlet. In other probes no much variation was observed in the temperature profile. The air reduction test has been conducted on the 10th day of the fourth phase of experiment by reducing the air flow to 15 L/m. The air reduction test for nine hours has resulted in temperature rise at all probes in the reactor matrix irrespective of location (Fig.5.5.1). Temperature rise of

9.4°C (from 26.6°C to 36°C) has been recorded on the probe at 30 cm from air inlet during the air reduction test. The temperature rise was 5°C on the probe at 60cm and 2°C on the probe at 90 cm.

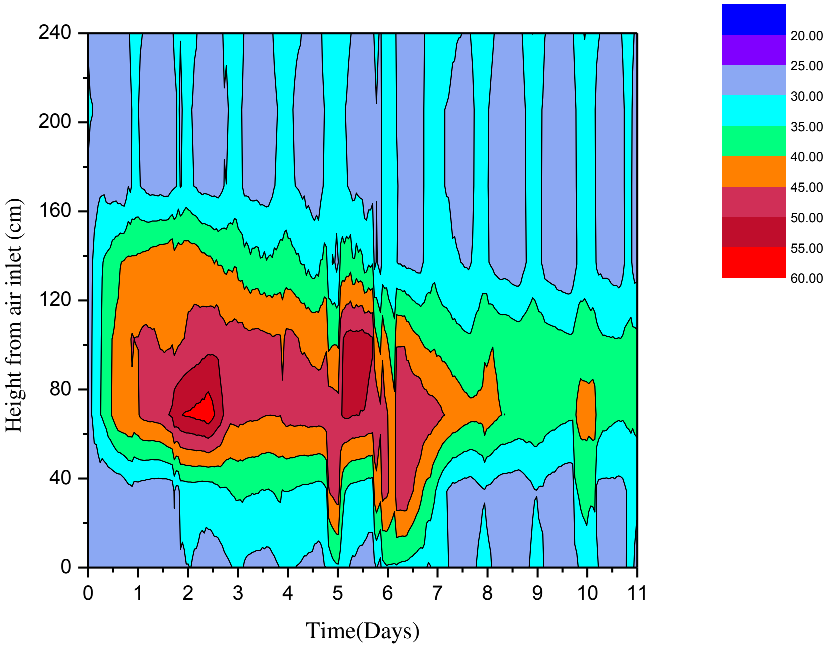


Fig. 5.5.2 Contour Plot - Phase 4.

The loose packing of the reactor matrix with respect to increased height as well as the lower specific air flow rate provided in the fourth phase has resulted in lower temperature rise than third phase. The loose packing of the bulk sized substrate inside the reactor matrix has resulted in short circuiting of air supply. Considering the fourth phase of experiment (initial reactor matrix height of 2.0 m) the temperature rise at the probe at 30 cm from air inlet was found to be very less (Fig.5.5.2) compared to that in the third study. The peak value of temperature has been recorded by the third day of reaction at the probe 3 held at 60 cm from the air inlet.

5.5.4.2 Weight Reduction

Weight reduction has been monitored continuously using electronic load cell. The entire reactor unit is placed over the load cell. The weight loss is calculated in every second of time and the data transferred through the data acquisition system and reading taken on the monitor of computer. The weight of the mixed municipal solid waste substrate has been reduced from the initial 172 kg to the final 136.9 kg in 11 days of reaction in the fourth phase as shown in Fig. 5.5.3. This accounts for a reduction of 20.04 % in weight of the substrate in the biodrying reaction.

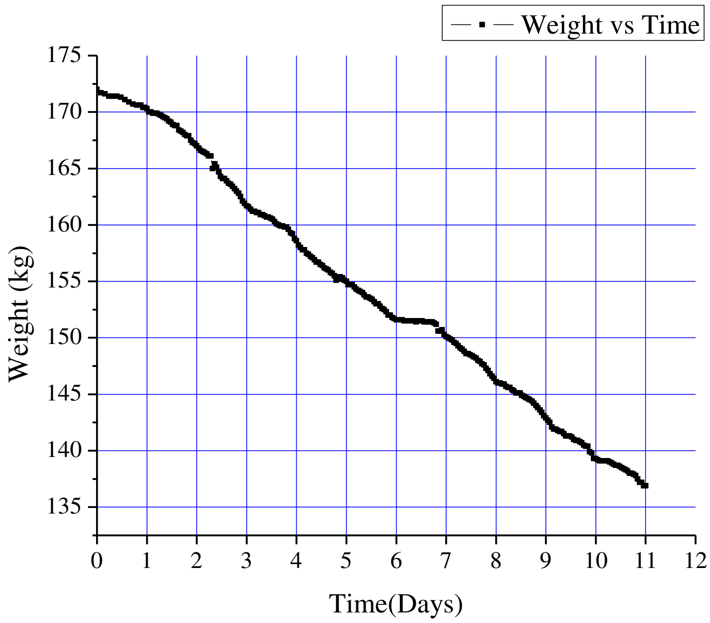


Fig.5.5.3 Weight Reduction - Phase 4.

Weight reduction profile for 11 days of reaction has been plotted for third and fourth phase experiments as shown in Fig. 5.5.4. Weight reduction obtained in the fourth study was 20.04% which is lesser than that of 28.1% achieved in the third study during the same duration. Weight reduction of 28.1% has been achieved during 11 days duration in the third phase of experiment. Therefore the insufficient air supply has affected the self heating reaction in the fourth phase of experiment. Also the air channelisation occurred due to loose packing of the reactor matrix which is one of the factor that reduced the biodrying process efficiency.

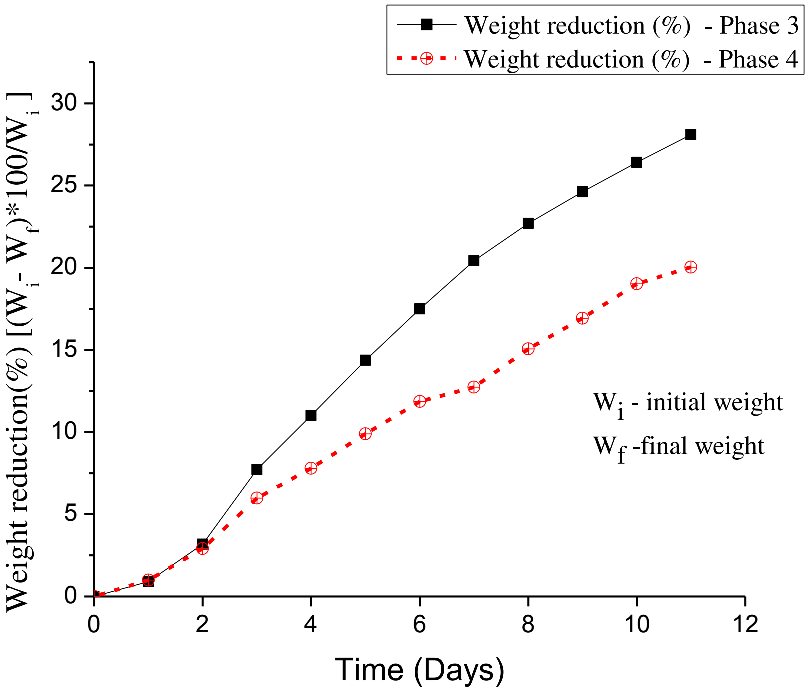


Fig. 5.5.4 Weight Reduction Profile –Comparison of Third and Fourth Phases.

5.5.4.3 Moisture Profile

In the fourth phase, the moisture content of the municipal solid waste substrate has been reduced from the initial value of 66.4 % to the final value of 55.02 % in 11 days of biodrying reaction (Fig.5.5.5). It was observed that the moisture content has been reduced by reduction of 17 % in the fourth phase. The statistical analysis of the moisture results has revealed that a high value of standard deviation (S.D) in the range 6-18 was observed, as shown in Fig. 5.5.5.

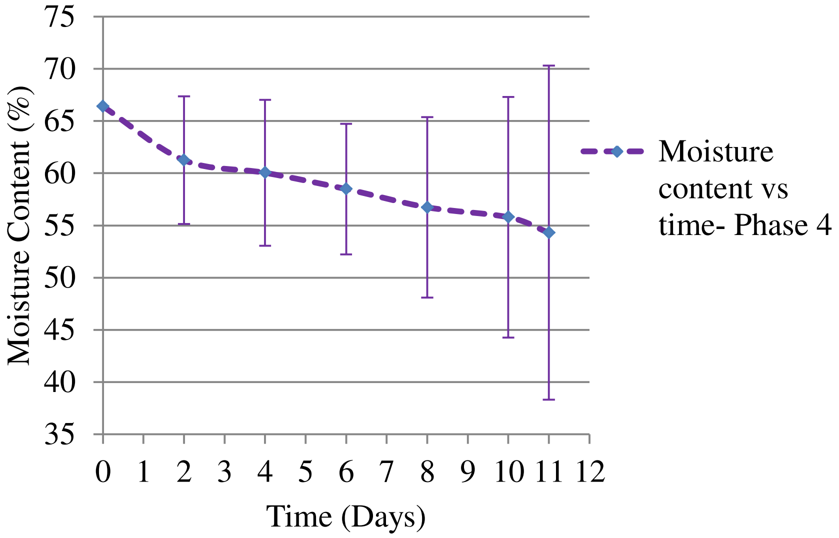


Fig.5.5.5 Moisture Profile –Phase 4.

The average moisture reduction profiles for the third and fourth phase of studies were compared in Fig.5.5.6. It was observed that average value of moisture content was reduced by 24.26 % in 11 days of reaction in the third study, which is higher than the same period moisture reduction in the fourth study. The non-uniformity of the biodried output has also increased in the fourth study while compared with the third study. Therefore the aim of producing uniform nature of biodried output has not achieved in the fourth phase of experiment.

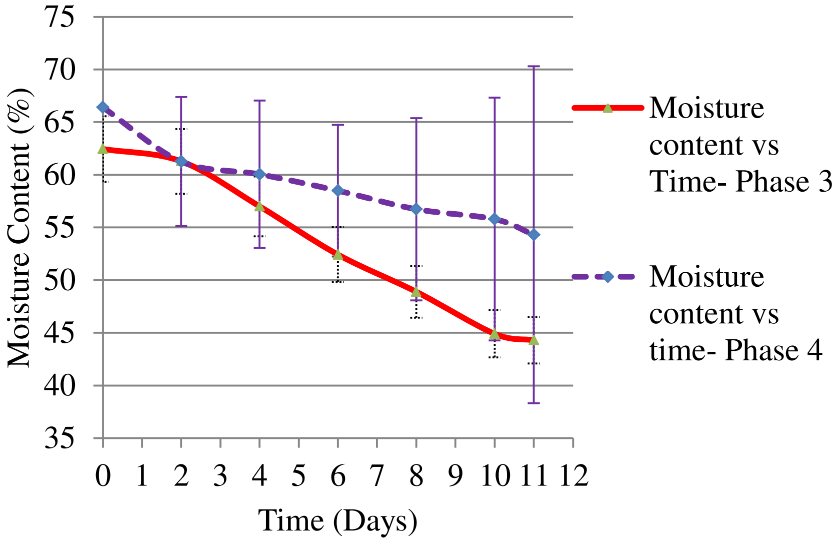


Fig. 5.5.6 Moisture Profile -Third and Fourth Phase.

5.5.4.4 Volume Reduction

The biodrying reactor was filled to the full height of 2.0 m in the fourth phase which accounts for bulk volume of 0.565 m^3 as plotted in Fig.5.5.7. The final height of the mixed msw substrate inside the reactor was 1.13 m, which included the bulk volume of 0.319 m^3. The volume reduction achieved in the fourth phase was of 43.5 % after 11 days of biodrying reaction. Volume reduction profile for third and fourth phase of studies were plotted as shown in Fig.5.5.8. It was observed that volume reduction in the fourth phase of experiment was 43.5 % while that was 35.1 % in the third phase of study after 11 days of reaction. Therefore Volume reduction is in the fourth phase is considerably higher than that in the third experiment The volume reduction is an indication of active biological decomposition and hence biodegradation process was prominent along with biodrying process in the fourth phase. Also it is an indication that air supply is insufficient in the biodrying process which has triggered the degradation reactions.

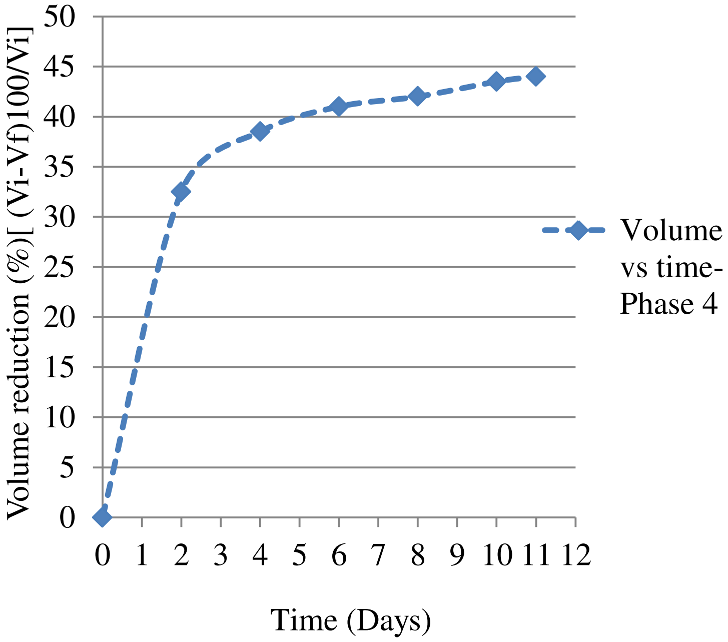


Fig.5.5.7 Volume Reduction Profile –Phase 4.

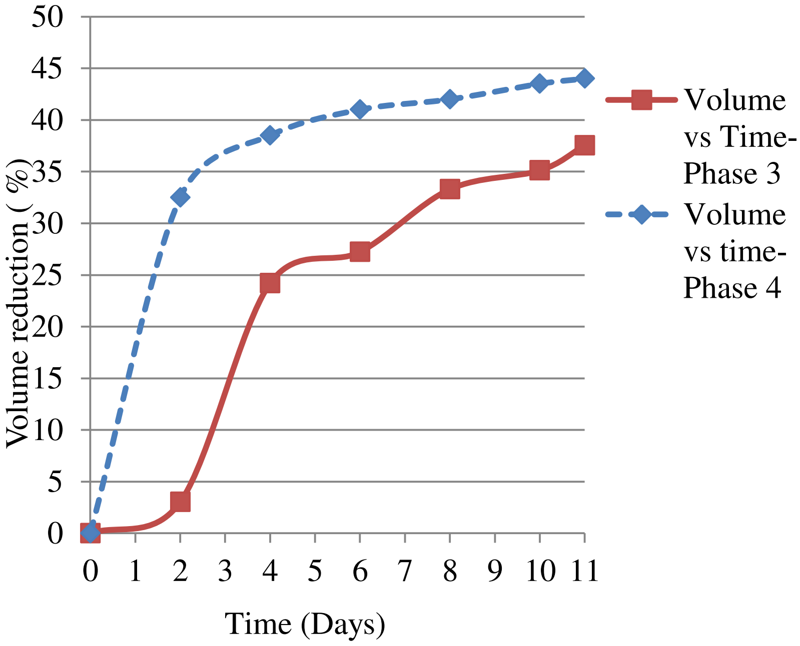


Fig. 5.5.8 Volume Reduction – Third and Fourth Phase of Study.

5.5.4.5 Bulk Density

Bulk density of the solid substrate like mixed municipal solid waste is an important factor affecting the air controlled processes like biodrying. The in situ bulk density has been calculated on a dry basis as per equation 5.1.

The initial in situ bulk density of the substrate was 182.88 kg/m^3 that has been increased to 280 kg/m^3 in 11 days of biodrying reaction (Fig.5.5.9). It accounts for an increase of 53.1% of bulk density in the fourth phase of biodrying experiment.

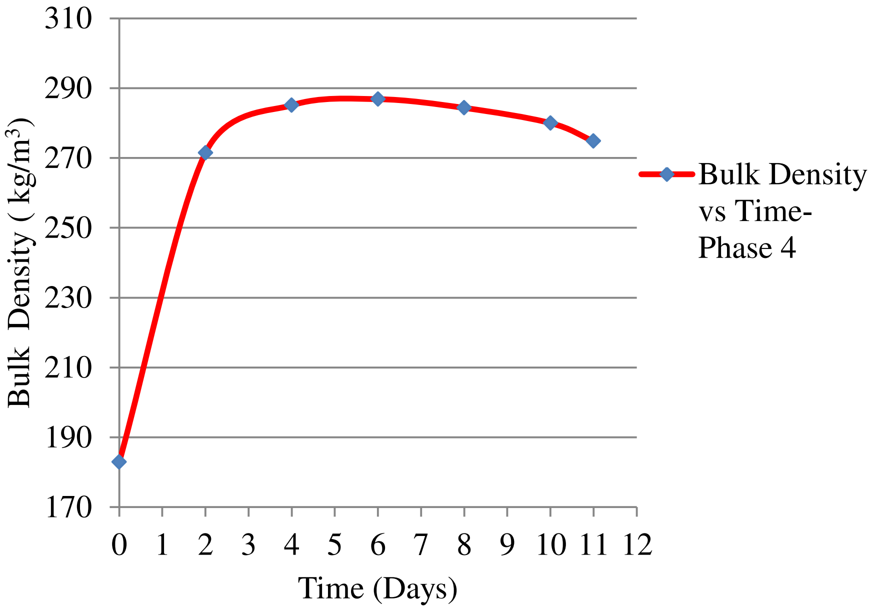


Fig.5.5.9 Bulk Density Profile- Phase 4.

The bulk density profiles for the third and fourth phase of study during the initial 11 days of reaction have been plotted as shown in Fig.5.5.10. In the third phase of experiment bulk density increase was only 27.58 %. It is clearly evident that bulk density increase is higher in the fourth phase while compared with third phase.

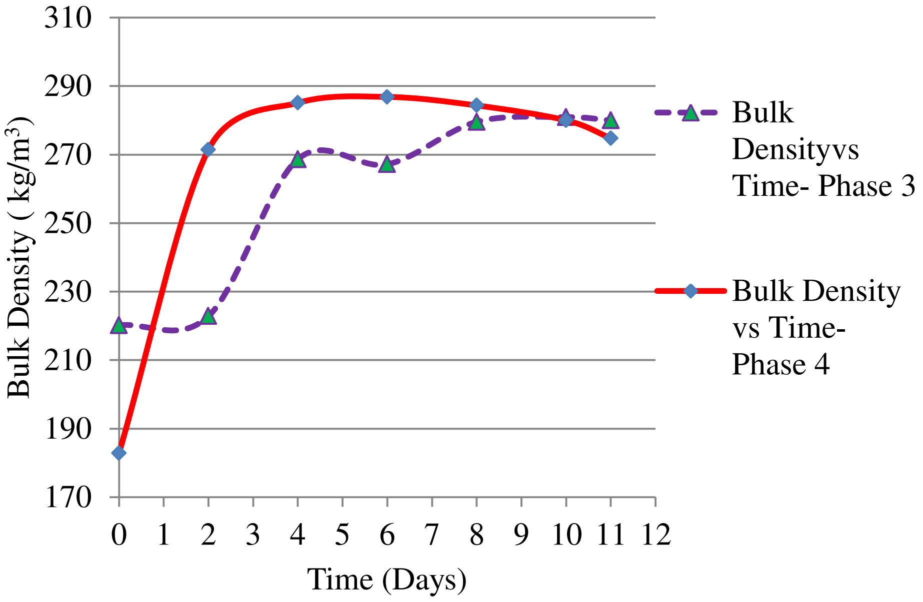


Fig. 5.5.10 Bulk Density Profile of Phase 3 and Phase 4.

5.5.5 Summary

The fourth phase of experiment was very successful in terms of volume reduction and bulk density enhancement with 43.5 % reduction in volume and 53.1% increase in bulk density achieved in 11 days of reaction. On the other hand the weight reduction and moisture reduction was less than the previous studies with only 20.4 % reduction in weight and 17 % loss in moisture content obtained in 11 days of biodrying reaction. This investigation has revealed the fact that air scarcity in biodrying reactor has lead to biodegradation reactions more than biodrying reactions. The comparison of the third and fourth phase studies was very advantageous to understand the limitations of biodrying process. The air channelisation due to loosely packed reactor feed has lead to anaerobic conditions at some portion of the reactor matrix. The air evacuation and reduction experiments helped to identify the effect of air scarcity in biodrying reaction. The temperature profile variations also confirmed that biodrying process was more effective in third phase while compared to fourth phase. The increased the reactor matrix height and the loose packing of substrate has favoured biodegradation process in the fourth study which has decelerated drying reaction. The present investigations have concluded that reactor matrix heights as well as packing of reactor matrix are important factors affecting the biodrying process efficiency.

5.5.6 Limitations

The biodrying process efficiency has been reduced due to the increased reactor matrix height at the selected specific air flow rate. The loosely packed reactor feed has not reduced the heterogeneity of the product and rather it resulted in air channelisation and short circuiting.

5.5.7 Further Process Advancement

The next of phase of investigations has to be carried out to improve the biodrying process efficiency. Since there is no further improvement of biodrying process in the fourth phase at the selected specific air flow rate it should be increased in the next investigation.

5.6 EXPERIMENTAL INVESTIGATION- PHASE- 5- EFFECT OF INCREASING THE SPECIFIC AIR FLOW RATE ON THE BIODRYING PROCESS EFFICIENCY

5.6.1 Objectives

The fifth phase of experiment has been conducted in order to study the effect of increased rate of air flow on the biodrying performance.

5.6.2 Introduction

Air flow was provided at a rate of 40 L/m in the previous studies, which has been increased to 80 L/m in the fifth phase. The initial temperature increasing phase of biodrying reaction is critical for removing the bound water such as vicinal water and water of hydration; whereas the free water that can be evaporated by airflow is very less (Vesilind, 1994). Therefore airflow rate is an important factor affecting the biodrying process which needs investigation.

5.6.3 Materials and Methods

In the fifth phase of study the pilot scale reactor was filled with 180 kg of mixed MSW substrate. The filled height of the reactor matrix was 2.0 m. The preparation of synthetic mixed MSW substrate for the fifth phase consisted of 66 % of organic components, 17 % of Paper components, 7.5 % of plastics and 9.5% of textiles as shown in Table.5.6.1. The process air supply has been doubled from the previous value of 40 L/m to 80 L/m in the fifth phase of experiment. This accounts for a specific air flow rate of 0.640 m^3/kg.day.

Table 5.6.1 Composition of Mixed MSW

Component	**Particulars**	**Weight (kg)**	**Subtotal (kg)**	**Grand Total (kg)**
Organic components	Raw food waste	36	125.4	**190**
	Cooked food waste	67		
	Fibers	5		
	Dried leaves	7.4		
	Fresh leaves	10		
Paper and Cardboard	News paper	16	32.3	
	Print Paper	5.3		
	Cardboard	11		
Plastics	Crushed bottles	3	14.25	
	Milk Covers	10		
	Plastic Covers	1.25		
Textiles	Cotton	10	18	
	Polyester	8		

5.6.4 Results and Discussions

5.6.4.1 Temperature Profile

It was observed that doubling the air flow rate has a cooling effect on the substrate, which reduced the peak temperature value to 50°C in the fifth phase of study. Detailed temperature profile along the height of the reactor matrix is shown in Fig. 5.6.1. It was observed that maximum temperature of 50°C has been recorded in the probe at 60 cm from air inlet by the third day. The temperature rise was less inside the reactor matrix when compared with the previous studies.

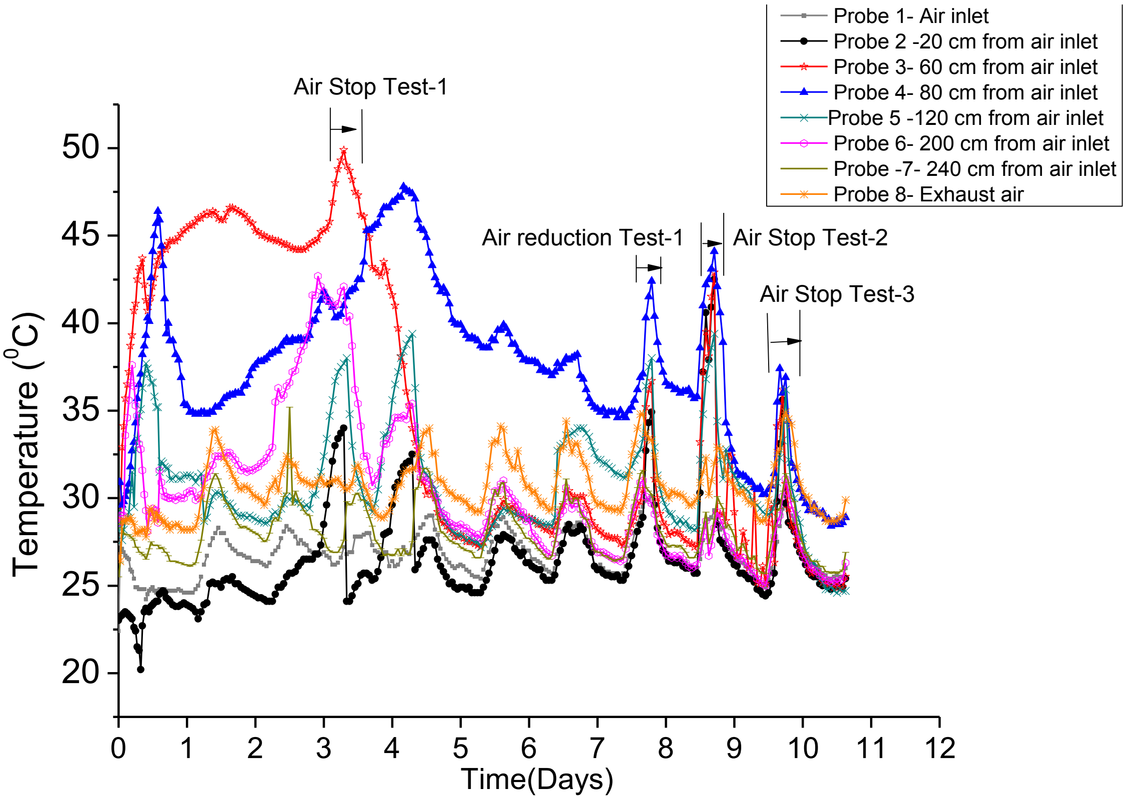


Fig.5.6.1 Temperature Profile of Fifth Phase.

The detailed investigations on temperature profile have been carried out by conducting a number of air reduction test as well as air stop test during the fifth phase of experiment. Air stop test has been carried out for four hours on the fourth day, which has increased the temperature from 44°C to 50°C on the probe 3 kept at 60 cm from the air inlet. Also the air stop test was conducted for 5 hours duration on the 8th day of experiment, which has resulted in heating up the pile (Fig.5.6.1). Maximum temperature rise of 12°C has been observed in the probe at a distance of 20 cm from air inlet port (30°C to 42°C). Also the probes at 60 cm and 80 cm from air inlet port have recorded a rise of 5.5°C.

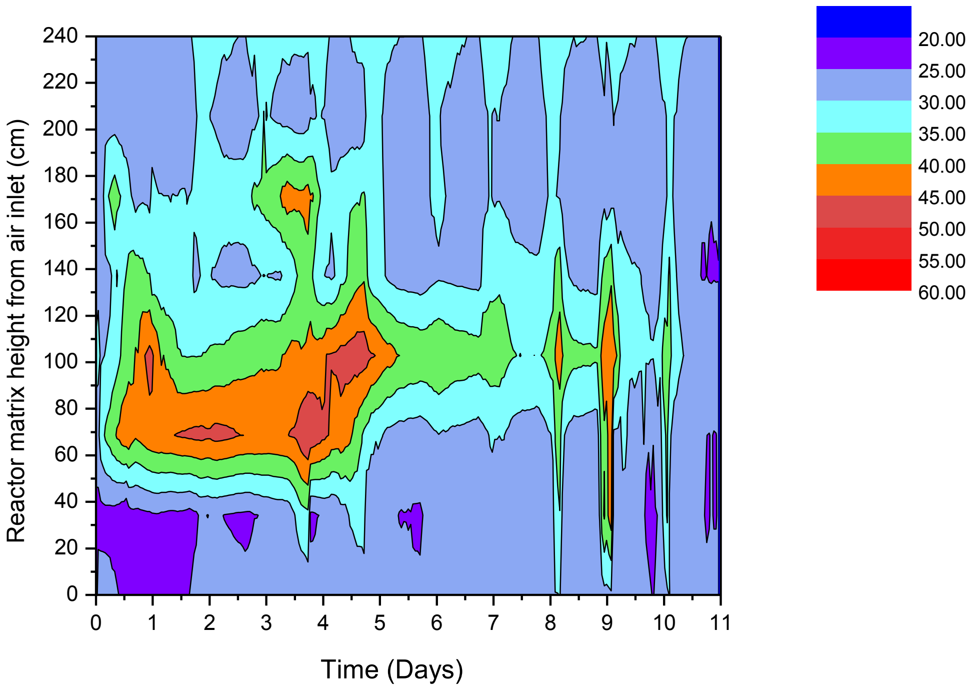


Fig.5.6.2 Contour Plot - Fifth Phase.

Another air stop test has conducted on the 10th day of second experiment and the maximum temperature rise during this period was 6°C observed on the probe at a distance of 20 cm from the air inlet. It was observed that the temperature rise during air off period has decreased suddenly from 12°C on the 8th day to 5°C on the 10th day. The air reduction test has been conducted on the 7th day of reaction, by reducing the air flow to 25 L/m for a period of three hours. The air reduction period has recorded a sudden temperature rise of 5°C (37.1°C to 42.4°C) throughout the matrix as shown in Fig 5.6.1. Therefore the dominance of drying over decomposition has decreased considerably by the 10th day of reaction, which is indicating the vicinity of the end point of biodrying reaction. The important result observed in these air stop/reduction investigations is that it helped to decide the end point or duration of the biodrying reactions. These investigations points out the limiting time of biodrying reaction i.e., when the decomposition process overtakes the drying process. The temperature contour of the fifth phase of experiment is plotted in Fig.5.6.2, which shows the self heating temperature distribution inside the reactor matrix. It was observed that temperature in the core region of the reactor matrix has shown an increase in both horizontal direction with respect to time as well as in vertical direction with respect to reactor matrix height. The temperature rise is shifted to 40ºC to 50ºC range in this phase, while compared to previous phases temperature peak was lesser.

5.6.4.2 Weight Reduction

.Weight reduction has been monitored continuously using electronic load cell. The entire reactor unit is placed over the load cell. The weight loss is calculated in every second of time and the data transferred through the data acquisition system and reading taken on the monitor of computer. It was observed that, the weight reduction has significantly increased by doubling the air flow rate and this facilitated moisture removal at an accelerated rate in the fifth phase.

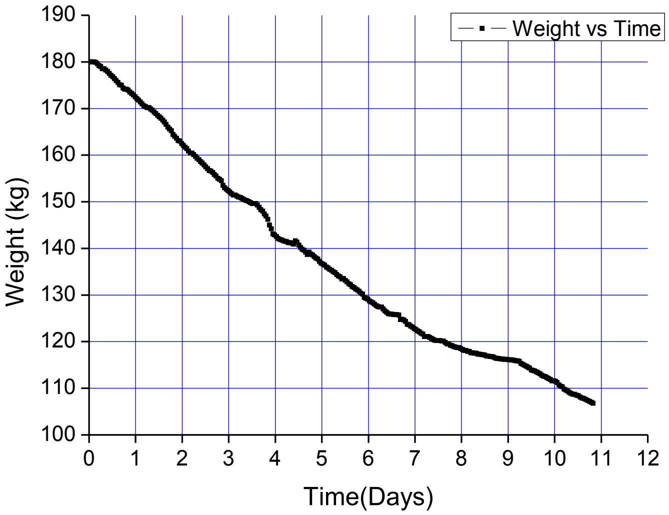


Fig.5.6.3 Weight Reduction in the Fifth Phase.

Weight reduction profile for fourth and fifth phase of investigations were plotted as in Fig.5.6.4. It was observed that the weight of the mixed municipal solid waste substrate has been reduced from the initial value of 180 kg to the final value of 106.8 kg in 11 days of biodrying reaction as shown in Fig.5.6.3. This accounts a weight reduction of 40.67 % in 11 days of the process. It is a major achievement in the fifth phase of study where the highest weight loss has been reported, while considering the previous studies.

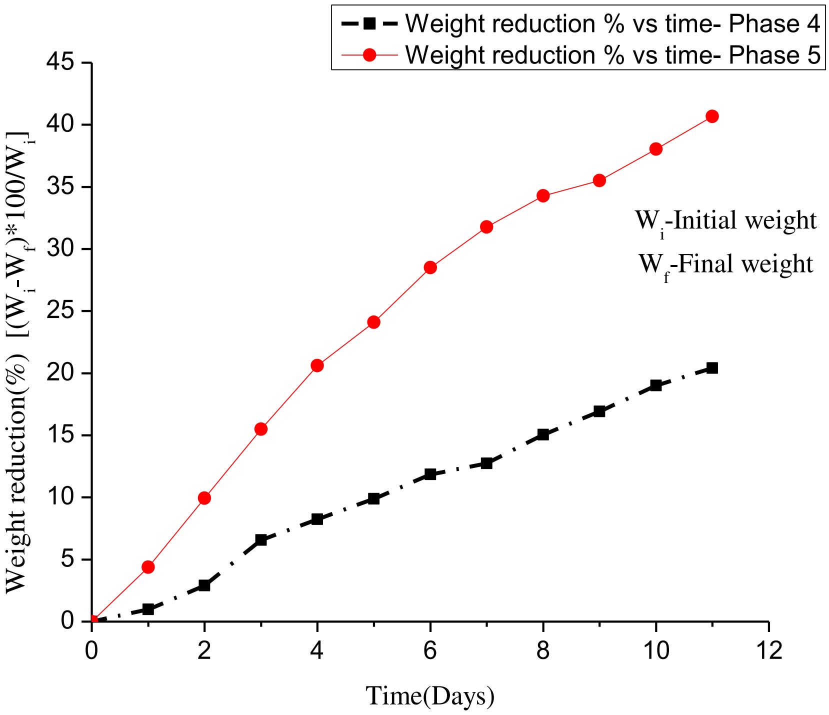


Fig. 5.6.4 Weight Reduction % Vs Time- Phase 4 and Phase 5.

In the fourth phase of experiment conducted at an airflow rate of 40 L/m, the weight reduction of 20.41 % has been obtained after 11 days of controlled biodrying reactions. A weight reduction of 40.67 % has been achieved after 11 days of reaction in the fifth phase of experiment. It shows that better weight reduction due to evaporative cooling took place at the optimum air flow rate whereas, air scarcity lead to deceleration of biodrying reaction.

5.6.4.3 Moisture Profile

The moisture reduction profile for the fifth phase of study is shown in Fig.5.6.5. The moisture content has been reduced from the initial value of 60.06 % to final value of 36.74 % in 11 days of reaction. It can be observed that doubling the air flow rate in the fifth phase was more effective in terms of moisture reduction with average moisture reduction of 38.83 % achieved in 11 days of reaction. It is the highest reduction in the shortest period of time, while considering the previous phases of experiments.

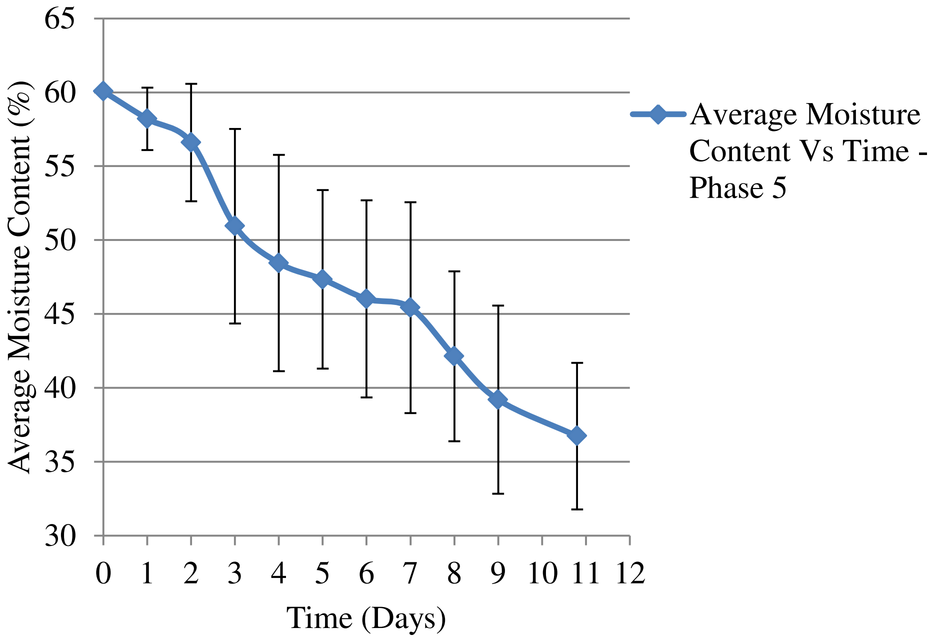


Fig. 5.6.5 Average Moisture Profile - Fifth Phase.

The standard deviation (S.D.) of moisture analysis results was considerably less in this experiment with S.D values in the range 2-7, that indicates more homogeneous nature of the biodried output.

The moisture profiles for the fourth and fifth phase of investigations were plotted in Fig.5.6.6. The non-homogeneity in moisture distribution of biodried output is higher in fourth phase with standard deviation (S.D) of 15 at the end of 11 days, while compared to 4.9 in the fifth phase. The maximum drying efficiency has been obtained in the fifth phase of study when the air flow rate is doubled.

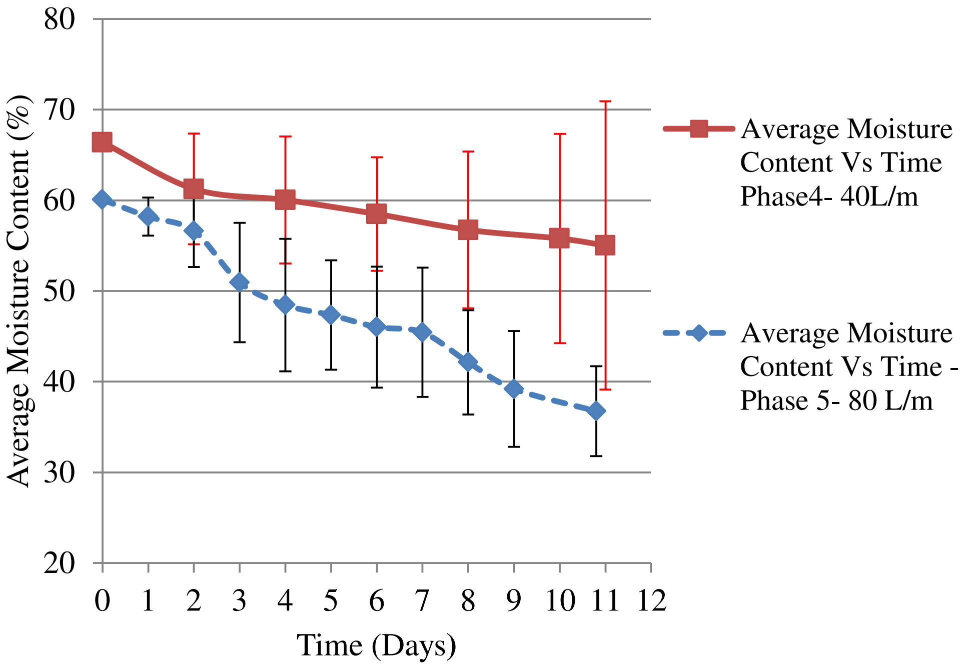


Fig.5.6.6 Moisture Profile -Phase 4 and Phase 5.

5.6.4.4 Volume Reduction

The volume reduction profile obtained in the fifth phase of study is shown in Fig.5.6.7. The reactor was filled to the maximum capacity of 2.0 m height in fifth phase of study and the initial filled volume was 0.565 m^3. After 11 days of biodrying reaction the height of reactor matrix has been reduced to 1.24 m with the final volume of 0.35 m^3. The volume reduction was 38 % in 11 days of biodrying reaction in the fifth phase.

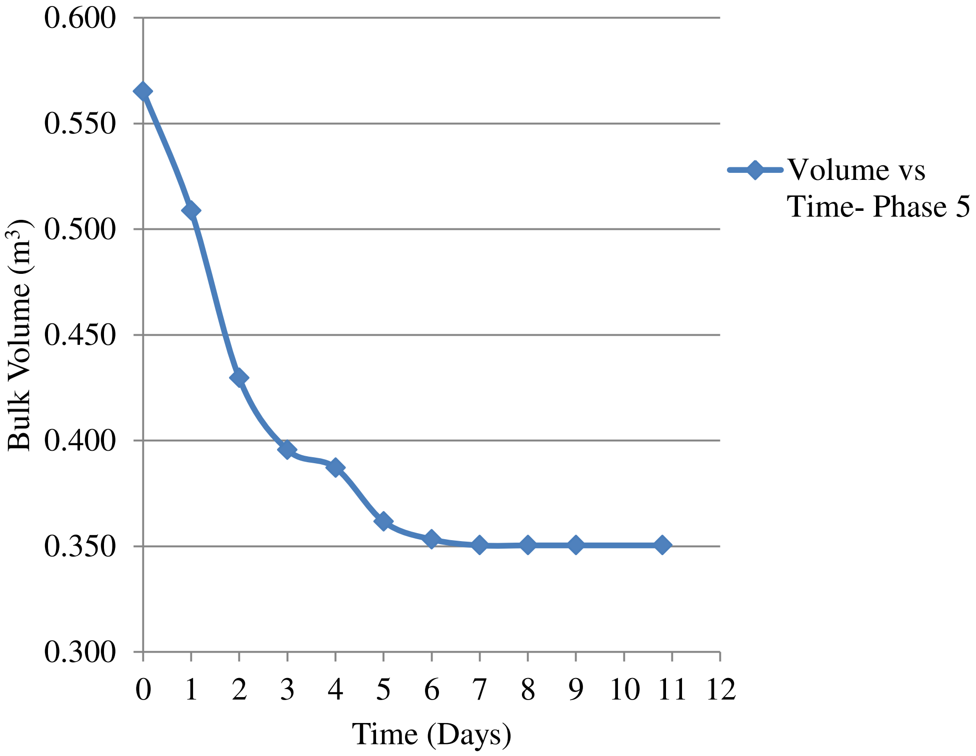


Fig. 5.6.7 Volume Reduction – Phase 5.

The volume reduction for the fourth and fifth phase of investigations has been compared in Fig.5.6.8. It can be observed that the volume reduction achieved with in the fourth phase was higher than that achieved in the fifth phase. This clearly shows the significance of doubling the air flow rate on biodrying reaction. The biodegradation and biodrying process together contribute to volume reduction. However the biodegradation process contributes more to volume reduction than the biodrying process. The volume reduction achieved in 11 days of the biodrying reaction was 38 % in the fifth phase of experiment, while it was 43.5 % in the fourth phase (Fig. 5.6.8). Therefore the rate of air supply is an important limiting factor deciding the extent of biodrying and biodegradation reactions.

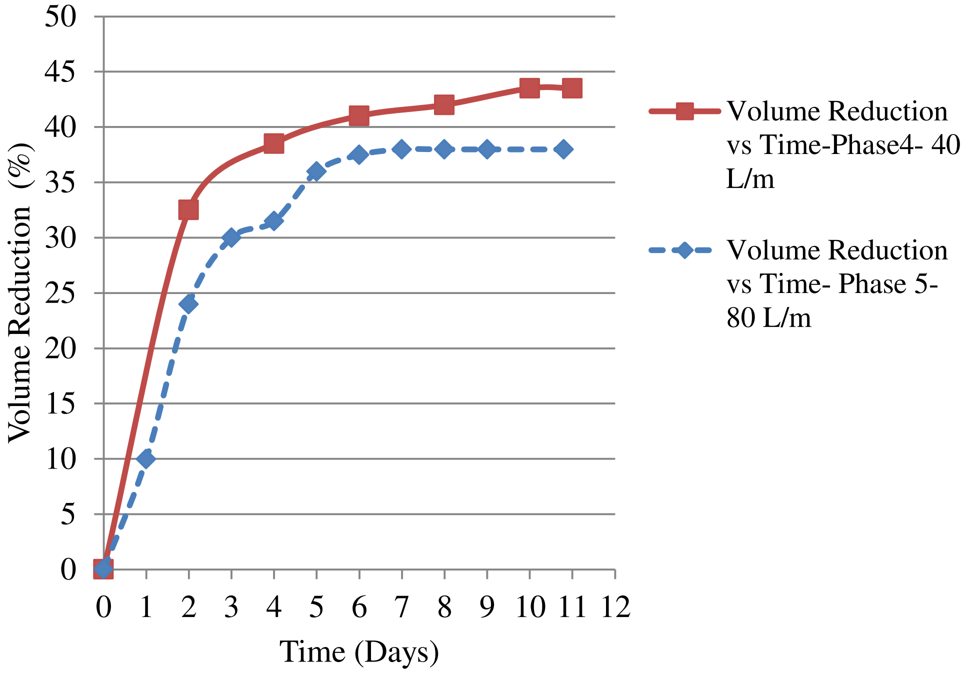


Fig. 5.6.8 Volume Reduction Percentage Vs Time-Phase 4 and Phase 5.

5.6.4.5 Bulk Density

The in situ bulk density has been calculated as per equation 5.1. The in situ bulk density of the substrate has been increased from the initial value of 198.7 kg/m^3 to final value of 222.89 kg/m^3 in the entire experiment period of 11 days in the fifth phase (Fig.5.6.9). Maximum bulk density of 257 kg/m^3 has been observed by the 5th day of reaction and after that it decreased which a common trend is observed in all the studies. Bulk density increase was only 12 % in the fifth phase of study where the high airflow rate of 80 L/m has used. This is pointing out the fact that though volume reduction of 38 % has occurred, the drying process was very efficient which is reflected in the in situ bulk density of the substrate.

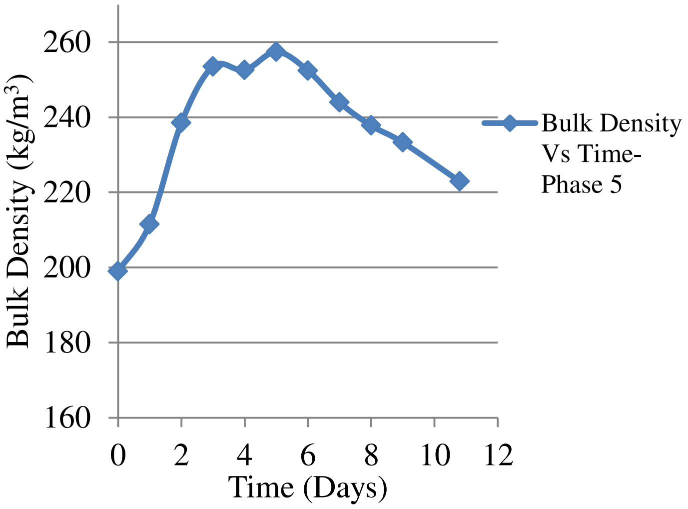


Fig.5.6.9 Bulk Density Profile- Phase 5.

Considering the bulk density profile for the fourth and fifth phases of experiments, it can be observed that the maximum increase of bulk density has occurred within the initial five to six days of reaction (Fig.5.6.10). It reveals the fact that biological reactions are most active in this period. The peak temperature formation also confirms the same. After that the initial period of active reaction the moisture deficiency slows down the biological reaction.

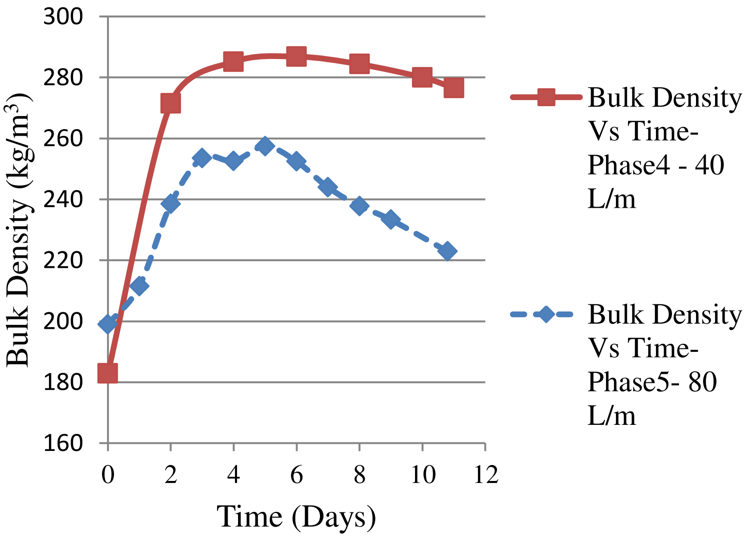


Fig. 5.6.10 Bulk density Vs Time- Phase 4 and Phase 5.

The bulk density profile for the fourth and fifth phase of experiments are very significant in delineating biodrying process. It is clear from the graph that bulk density increase is more in fourth phase when compared with fifth study. The maximum bulk density value of 286 kg/m^3 has been achieved on the sixth day in the fourth phase of experiment. (Fig.5.6.10). In the case of fifth experimental phase, the maximum bulk density increase was 29.38 % which is obtained by the 5th day. In the falling zone of bulk density profile of the fifth experiment, after the initial 5-6 days, a reduction of 13.42 % in bulk density has been observed, which improved the air circulation. But the bulk density fall was only 4 % in the experiment conducted at 40 L/m of air flow. The comparisons of the fourth and fifth phase of experiments are extremely helpful to decide the limiting conditions in biodrying technology development.

5.6.4.6 Air Porosity

The air porosity study has been carried out for fourth and fifth phase of investigations where the volumetric air flow rate was doubled. The air porosity variation of the fourth and fifth experiments will help to find out the physical relationship among the solid, liquid and gaseous phases of substrate in biodrying process (Schulze 1962; Hillel 1982; Jury et al., 1991; Van Ginkel et al., 1999).

The air porosity is calculated by using the following equations.

$E=1-(\gamma/\gamma_d)$ ………………..(5.6.1) ,

where E – Total porosity

γ – Total bulk density

γ_d- Dry density

Ew (Porosity of water)= $\frac{(100-\text{average moisture})\times\text{extra moisture}}{100\times1000}$ ----(5.6.2)

E_a (air porosity) = E - E_W………………….. (5.6.3)

It can be seen that in the fourth phase of experiment with air flow rate of 40 L/m , the air porosity reduction is 57.44 % at the end of 11 days of reaction (Fig.5.6.11).

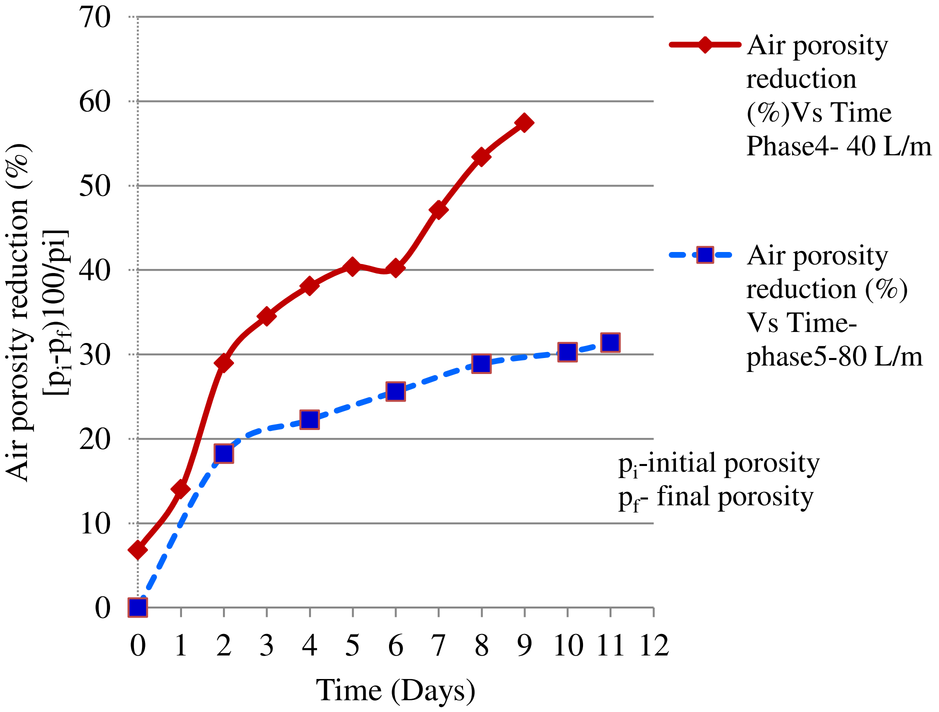


Fig. 5.6.11 Air Porosity Reduction With Respect to Time -Phase 4 and Phase 5.

It shows a decline in biological activity after the initial reaction period of two days. On the other hand, doubling the airflow rate has decreased the air porosity reduction to 31.38 %which is shown in the plot. The even nature of biological reactions during the entire period of 11 days of process has been observed form the air porosity reduction graph of fifth phase of experiment. Therefore, the regular temperament of biological reaction obtained at higher air flow rate is useful to get a more homogeneous product, with enhanced utilisation of self heating process.

5.6.6 Summary

The fifth phase of experiment with high airflow rate of 80 L/m was found to be efficient in terms of biodrying reaction. Weight reduction of 40.7 % and moisture reduction of 38.8 % were the major achievements in the fifth phase. The higher air flow rate has resulted in decreasing the rate of self heating. It was observed that the lower the airflow rate the lesser the biodrying efficiency, but the higher the air flow rate the lesser the biological heating. These contradictory conditions noted in the fourth and fifth phases of investigations points out that air flow rate is an important aspect in static biodrying reactors. The fourth experiment at lower air flow rate of 40 L/m was more successful in terms of volume reduction and bulk density increase. Also the self heating process was better at lower air flow rate with maximum temperature development of 58 ºC. The self heating temperature rise in the fifth experiment was lesser with peak value of 50 ºC. It was observed that when the air flow rate was doubled by keeping the same reactor matrix height under selected experimental conditions, the biodrying process efficiency has been increased up to 2.3 times. The air flow variation studies conducted at selected intervals during these investigations are relevant in limiting the process time under particular experimental conditions.

5.6.7 Limitations

The self heating and temperature rise inside the reactor matrix was lesser in the fifth phase, which is a limitation while considering the sanitisation point of view.

5.6.8 Further Advancements

The mode of aeration on biodrying process has to be studied to delineate the process variations.

5.7 EXPERIMENTAL INVESTIGATION- PHASE-6- DOWN FLOW MODE OF AERATION IN BIODRYING PROCESS

5.7.1 Objectives

In the sixth phase of experiment the air flow direction has been changed from the up flow mode to the down flow mode, in order to study the effect of the mode of aeration on biodrying process.

5.7.2 Introduction

Homogeneous output from the biodrying reaction necessitates uniform temperature rise. The lower part of the reactor matrix was drier compared to the upper parts in the previous phases of experiments, where up flow mode of aeration was used. An innovative small scale reactor system has been designed and run to study the biodrying process variation in down flow mode (Fig.5.7.1).

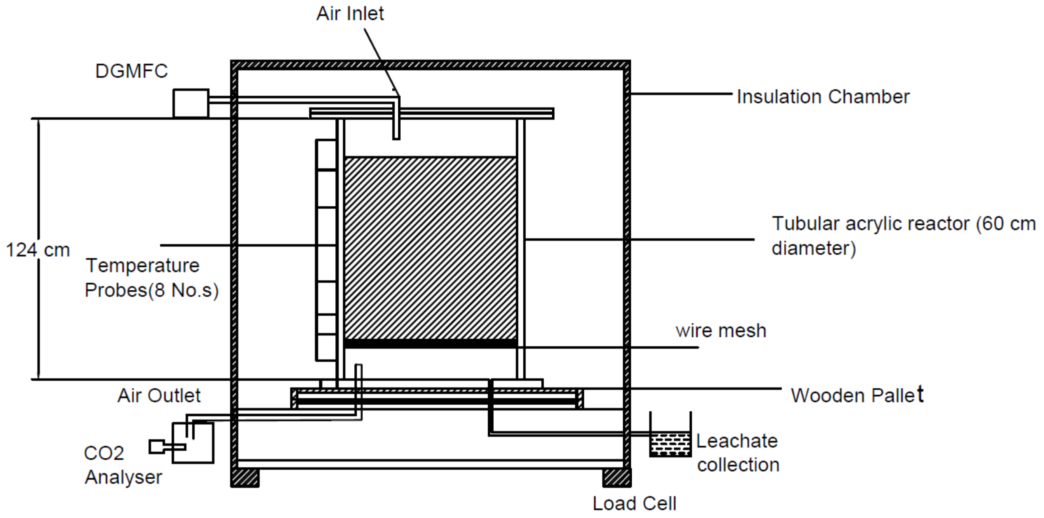


Fig. 5.7.1 Schematic Sectional View- Modified Design for the Down Flow Aeration System.

The rewetting of the dried reactor matrix in the top region is observed to be reason for temperature gradient inside the reactor matrix in up flow mode of aeration. In order to avoid this limitation down flow mode of aeration has been used in the sixth phase of study.

5.7.3 Materials and Methods

The reactor unit consisted of an acrylic reactor chamber which is having a height of 124 cm and diameter of 60 cm. The top portion of reactor is sealed air tight. The entire system is placed over a wooden pallet which is shifted to the insulation chamber for reaction. The leachate collection system was provided at the bottom. The CO_2 analyser was kept at the air outlet at bottom portion of the reactor. The temperature probes were fitted along the height of the reactor at 20 cm distance apart. The air supply was provided in a controlled manner through the digital gas mass flow controller which is supplied at the top region of the reactor matrix. The entire reactor unit has been placed inside the insulation chamber of dimensions 1.5 m × 1.5 m.

Table. 5.7.1 Composition of MSW substrate

Component	Particulars	Weight (kg)	Subtotal (kg)	Grand Total (kg)
Organic components	Raw food waste	15	61.2	**90.7**
	Cooked food waste	35		
	Fibers	1.2		
	Dried leaves	5		
	Fresh leaves	5		
Paper and Cardboard	News paper	8	13.5	
	Print Paper	1		
	Cardboard	3.5		
	Paper glass	1		
Plastics	Crushed bottles	1	7	
	Milk Covers	4		
	Plastic Covers	2		
Textiles	Cotton	5	9	
	Polyester	4		

The preparation of synthetic MSW is carried out as per the composition shown in Table.5.7.1. The initial moisture content of MSW is obtained as 55.74 %. The initial moisture content is less than that in the previous experiments, which may be due to the fact that extreme summer climatic conditions resulted in drying of the entire waste components. The initial weight of the filled reactor matrix was observed to be 79.5 kg, and the filled volume was 0.302 m^3.

The air was provided at a volumetric rate of 80 L/m through the top of the reactor and the exhaust air was taken through the reactor bottom. The corresponding specific air flow was 1.46 m^3/kg .day, which is higher than the previous experiments. The Leachate production is a major drawback of the reactors with down flow mode of aeration and inorder to overcome that higher specific air flow rate has been provided. The initial bulk density of the reactor matrix was 168.61 kg/m^3.

5.7.4 Results and Discussions

5.7.4.1 Weight Reduction

The weight of the reactor matrix has been measured using the electronic load cell. The entire reactor unit is placed over it and the readings were taken at every second which is transferred through the data acquisition system in to the monitor of computer. In this experiment the weight of the reactor matrix has been reduced from the initial value of 79.5 kg to final 45.8 kg in 12 days of reaction (Fig.5.7.2).

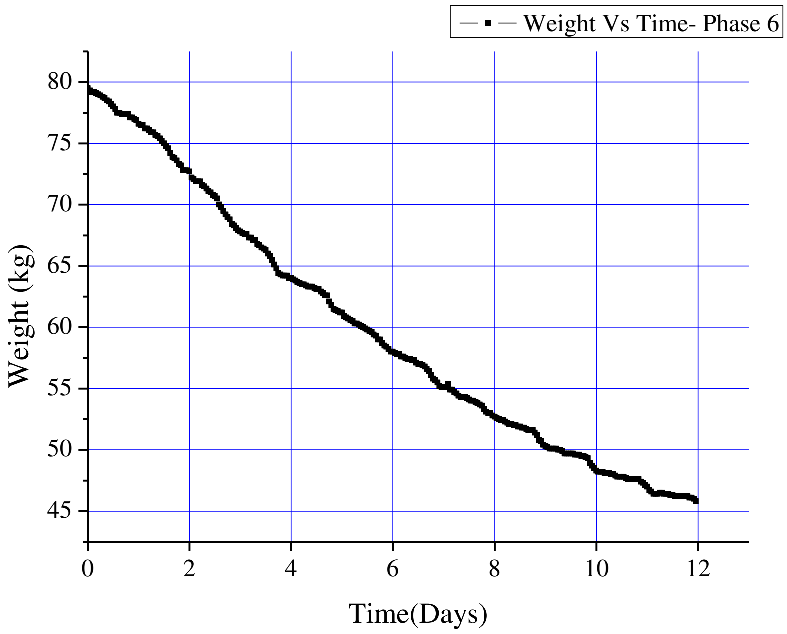


Fig. 5.7.2 Weight Reduction-Sixth Phase with Down Flow Mode of Aeration.

The total weight loss was 33.7 kg, which accounts for an average per day weight reduction of 2.86 kg/day. The down flow aeration at higher specific air flow rate in this experiment was more effective in terms of weight reduction with 42.39 % achieved in 12 days of reaction

5.7.4.2 Temperature Profile

Self heating sanitization of the product is one of the objectives of biodrying process. The self heating temperature peak achieved in the sixth phase was 47.7ºC during 12 days of biodrying process (Fig.5.7.3). The high specific air flow rate has resulted in cooling of the reactor matrix to some extent, which may be one of the reasons for low temperature development. It was observed that the down flow mode of aeration has resulted in more air short circuit zones inside the reactor matrix than the up flow mode of aeration.

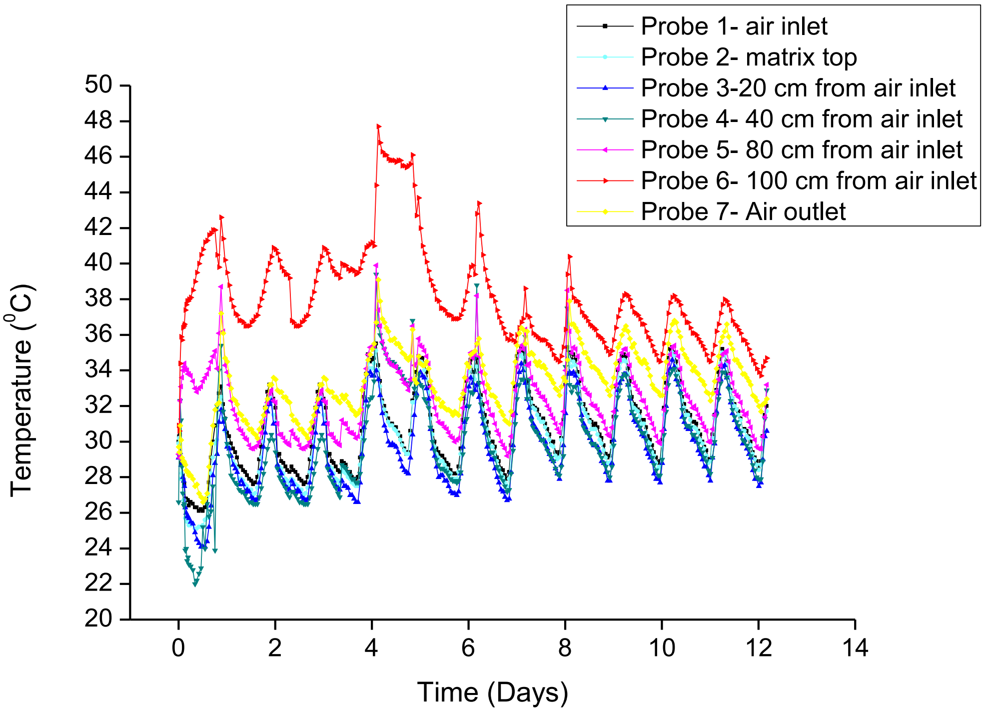


Fig. 5.7.3. Temperature Profile-Down Flow Mode of Aeration- Phase 6.

5.7.4.3 Moisture Profile

The moisture reduction is plotted against time as shown in Fig.5.7.4. The down flow aeration at a high rate has not helped to increase the uniformity of moisture distribution inside the reactor matrix. The standard deviation of moisture results varies in the range 1.6-14. The non-uniform moisture reduction, points out that air channelization as well as short circuits inside the reactor matrix. The moisture of the reactor matrix has been decreased form initial value of 55.74 % to final value of 32.63 %, i.e., the average moisture content has been reduced by 41.5 %. Though it is higher when compared to that at up flow aeration experiment at 40 L/m, the haphazard variation of moisture within the matrix is a drawback of the process.

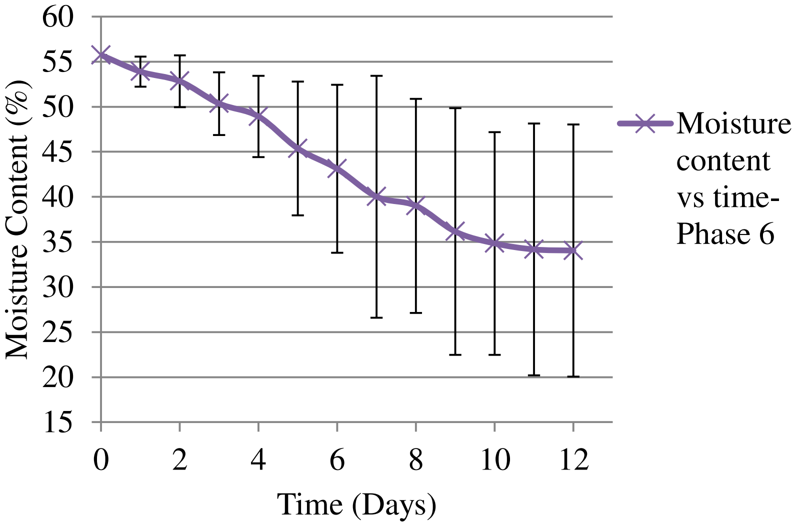


Fig.5.7.4 Average Moisture Profile- Phase 6- Down Flow Mode of Aeration.

5.7.4.4 Volume Reduction -Down Flow Mode of Aeration

The volume reduction in the process was found to be 34.57 %. The initial volume of 0.302 m^3 has been reduced in to 0.198 m^3 in 12 days (Fig.5.7.5).

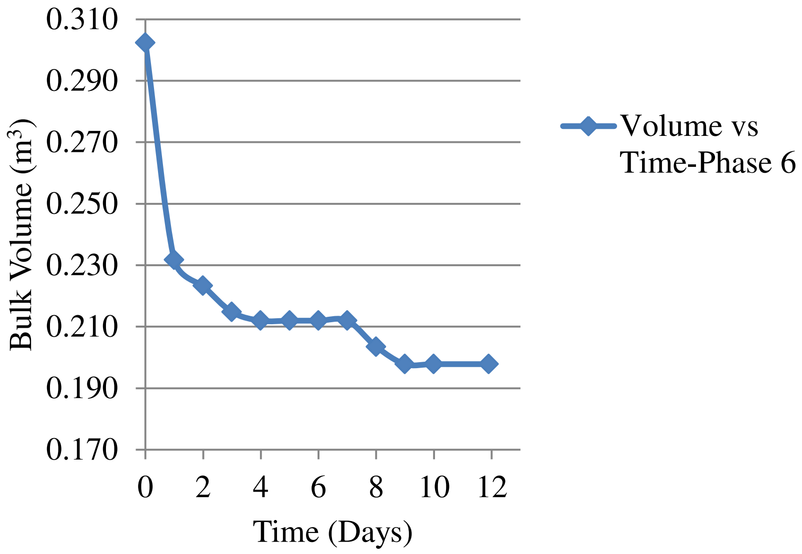


Fig. 5.7.5. Volume Reduction-Phase 6- Down Flow Mode of Aeration.

The pile height reduced from 1.07 m to 0.70 m and the volume reduction has been significant.

5.7.4.5 Bulk Density Profile

The in situ bulk density has been calculated as per equation 5.1. The initial bulk density of 168.8 kg/m^3 has been increased to 214.51 kg/m^3 in the first day of reaction and after that it started a decreasing trend. This shows lack of oxygen inside the reactor matrix after the initial settlement and that may be the reason for uneven drying. The bulk density went on decreasing after this and at the end of 12 days of reaction it was 174.56 kg/m^3. The bulk density increase at the end of reaction was only 3.41 % (Fig.5.7.6). This is entirely different from that obtained in the up flow biodrying process, where sufficient increase in bulk density has been occurred. The sixth phase of experiment has resulted in drying together with biodrying.

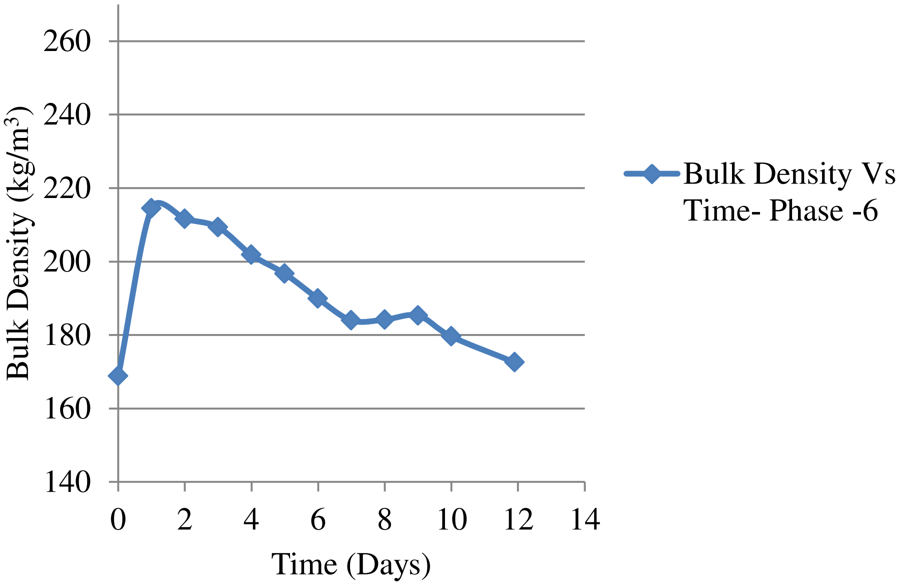


Fig.5.7.6. Bulk Density Profile-Phase 6 -Down flow mode of aeration.

5.7.4.6 Leachate Production

Leachate production was observed to be very less and mainly it occurred in the initial four days and it was negligible to measure.

5.7.5 Summary

In the sixth phase of experiment with down flow mode of aeration at a high specific flow rate of 1.46 m^3/kg.day, it was observed that along with the biodrying process, drying process also occurred at random locations inside the reactor matrix. Considering the overall weight reduction and moisture removal efficiency sixth phase is better than previous experiments with weight reduction of 42.39% and moisture reduction of 41.5% achieved in 12 days of reaction. The homogeneity of the biodried product is affected badly which is a drawback of the sixth phase of experiment. The heterogeneity of moisture value was very high due to the air channelization and short circuiting.

5.7.6 Limitations

The major limitation of the sixth experiment was the highly non-uniform moisture distribution of the biodried substrate. Also the temperature peak was not achieved which points out that the self heating was not utilized fully for drying purpose.

5.7.7 Future Recommendations

The improvement of the process for homogeneity of the product by mixing of the reactor matrix through an energy efficient way needs to be studied in future. The non-uniform drying is due to the fact that faster drying of the matrix has reduced the preferential flow in the lower part of the reactor. Inorder to overcome that the pilot scale reactor configuration can be provided with segmented air flow reducing downwards (Navaee-Ardeh et. al., 2006).

5.8 OVERALL ASSESSMENT OF SIX PHASES OF EXPERIMENTAL INVESTIGATIONS

5.8.1 General

The input as well as output parameters of five phases of experimental investigations were listed in Table.5.8.1. The detailed study of the individual parameters for first five phases of experiments has been carried out.

Table 5.8.1 Input vs Output Parameters for Five Phases

Study No	**Duration (Days)**	**Peak Temperature of Reactor matrix (^{0}C)**	**Weight(kg)**		**Moisture (%)**		**Volume (m^3)**		**Bulk Density (kg/m^3)**	
			Input	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**
1	33	59	109	72	61.25	48.5	0.39	0.18	173.3	263.9
2	15	59.9	124	75.8	65.5	43.9	0.39	0.22	189	231.3
3	15	65.5	167	109	62.45	43.5	0.46	0.28	220.2	267.7
4	11	58	172	136.9	66.4	57.1	0.56	0.31	182.8	264.1
5	11	50	180	106.8	60.06	36.74	0.56	0.35	198.9	222.8

5.8.2 Weight Reduction

The weight reduction achieved in five phases of investigations has been shown in Fig.5.8.1. It can be seen that the weight reduction has been considerably increased from 33.94% in the first phase of experiment to 39.2% in the second phase where the air saturation has been avoided by condensation prevention.

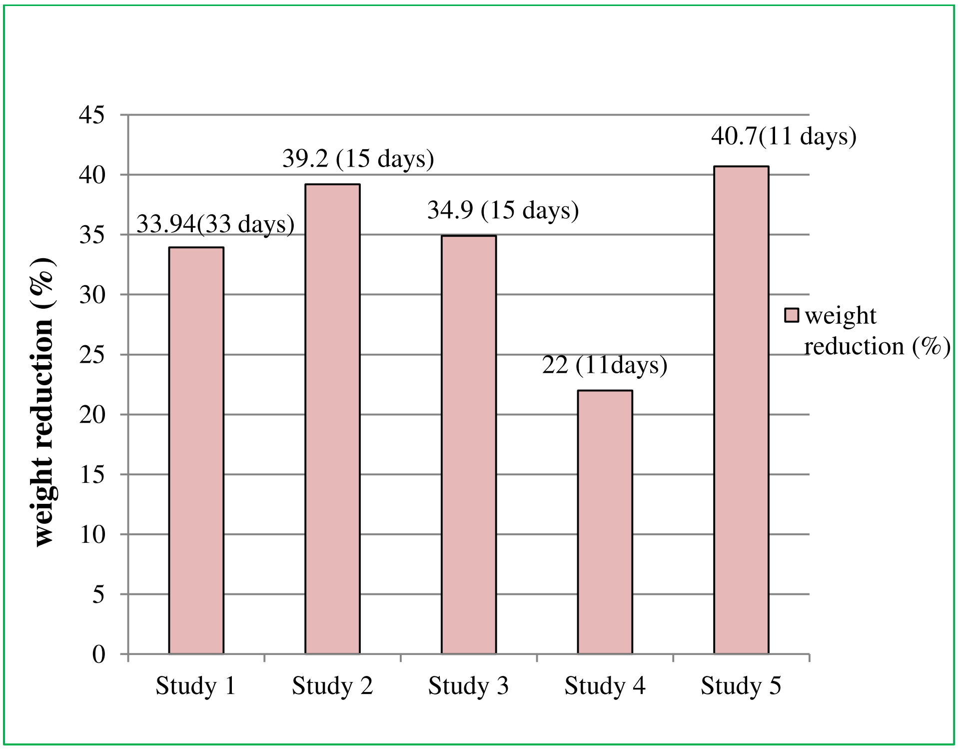


Fig.5.8.1 Weight Reduction Profile.

The process duration has been reduced from 33 to 15 days in the second phase of experiment which is a major achievement. The modified design with horizontal air flow system (HAF) was efficient in accelerating the biodrying reaction. The weight reduction in the third phase of experiment has been decreased slightly where the maximum self heating temperature rise up to 65 ºC has been achieved inside the reactor matrix. Therefore high thermophilic temperature in biodrying process is not necessary for weight reduction and efficient moisture reduction. On the other hand high range of temperature may be advantageous in view of disinfection and safety in handling and working conditions of the biodried output. Both these situations have to be considered to achieve the ideal process conditions in biodrying reaction.

Considering the fourth phase of experiment, it can be seen that the weight reduction has been considerably reduced to 22 %. In the fourth phase, the increased height of reactor matrix at loose packing will not contribute to biodrying process efficiency and there was no further improvement in self heating process. It is partly due to the air insufficiency and partly due to air channelisation inside the reactor matrix.In the fifth phase of experiment the volumetric air flow rate has been increased from 40L/m to 80L/m (specific air flow rate increased from 0.335m^3/kg.day to 0.640m^3/kg.day) that has to achieve a better weight reduction profile. The weight of reactor feed has been reduced by 40.7 % in 11 days of biodrying reaction.

5.8.3 Moisture Profile

Moisture reduction profiles for the five phases of experiments have been plotted as shown in Fig. 5.8.2. In the first phase of experiment the moisture reduction was 20.8% in 33 days of reaction, which is increased to 33 % in the second phase. The duration

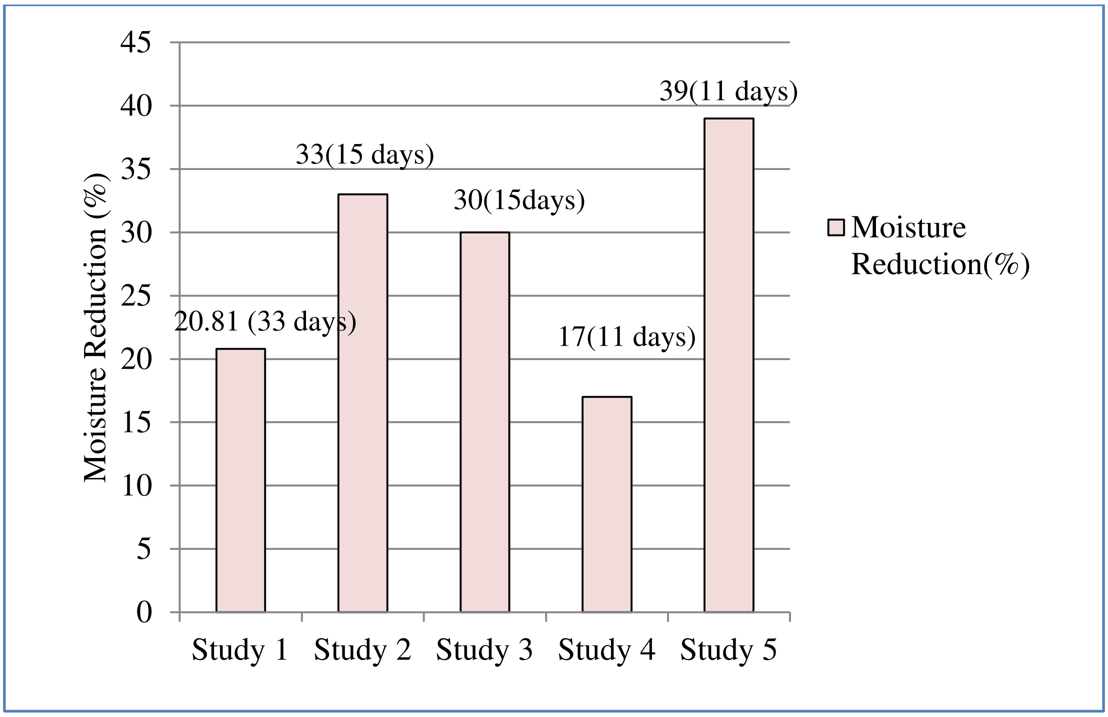


Fig.5.8.2 Moisture Profile.

of the second experiment was reduced to 15 days which is a major success of the modified design with horizontal air flow system(HAF) in the top region of the reactor. The third phase of experiment has also resulted in considerable moisture reduction of 30 %. The high self heating has not contributed more to moisture reduction. It is pointing out that biodegradation process is required just enough to evaporate the moisture and more degradation will not accelerate the biodrying reaction. In the fourth study the moisture reduction has shown a decreasing trend which is mainly due to the scarcity of air supply and air channelisation problems along the height of the reactor matrix.

The fifth experiment has been conducted to overcome the air scarcity by doubling the volumetric airflow rate from 40 L/m to 80 L/m (specific air flow rate increased from 0.335m^3/kg.day to 0.640m^3/kg.day). This fifth phase has achieved more uniform biodried product at high efficiency. The fifth phase has resulted in 39% moisture reduction in 11 days of biodrying reaction.

5.8.4 Volume Reduction

The volume reduction in biodrying reaction is advantageous in handling bulk of municipal solid waste. The first and fourth phases of experiments have the lower moisture reduction results while it has higher volume reduction (Fig.5.8.3).

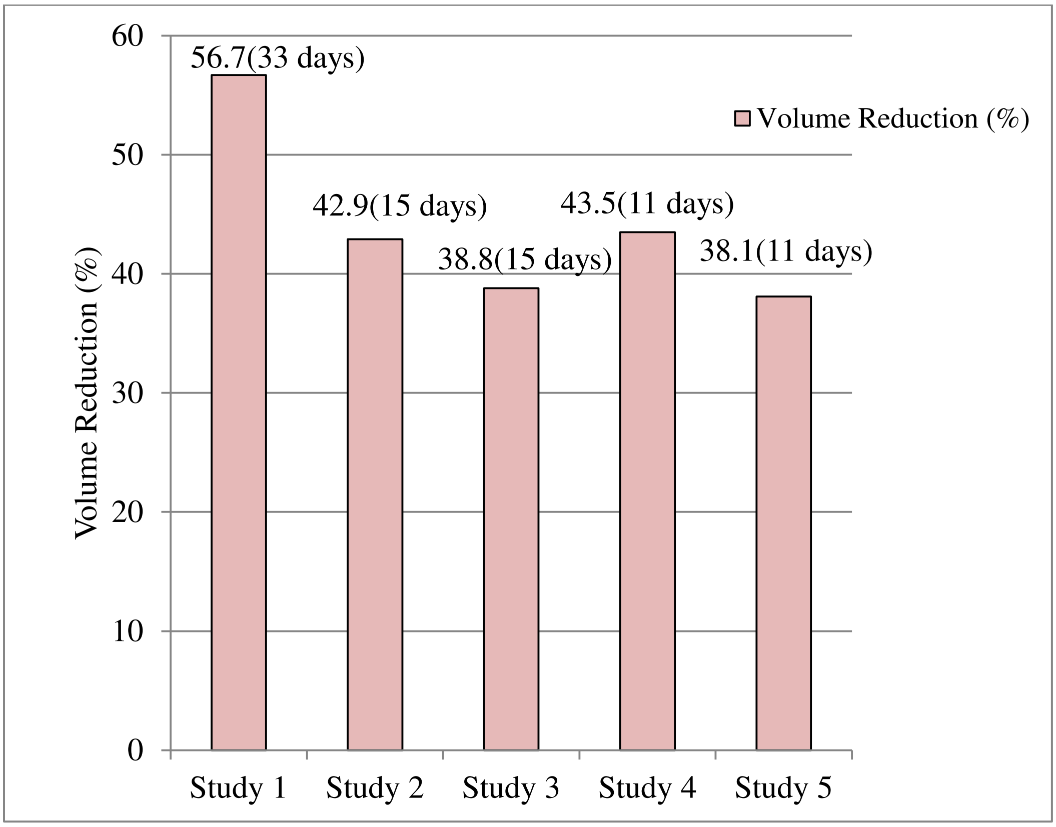


Fig.5.8.3 Volume Reduction.

The volume of the reactor fill was reduced by with 56.67 % in 33 days of reaction in the first experiment and 43.54 % reduction was achieved in the fourth experiment in 11 days of reaction. It was observed that faster drying process resulted in volume reduction; along with that the biological reaction shows a decreasing trend. The volume reduction in the second and third experiments was significant with 42.93 % and 38.84 %in 15 days of reaction. The fifth phase of experiment has achieved 38% volume reduction in 11 days of reaction.

5.8.5 Bulk Density

Bulk density increase is an important indication of the biological reaction in packed reactors. The bulk density increase in the present experiments also revealed the nature of reactions inside the matrix (Fig.5.8.4). The first phase of experiment has resulted in maximum bulk density increase of 52.3 % in 33 days of reaction.

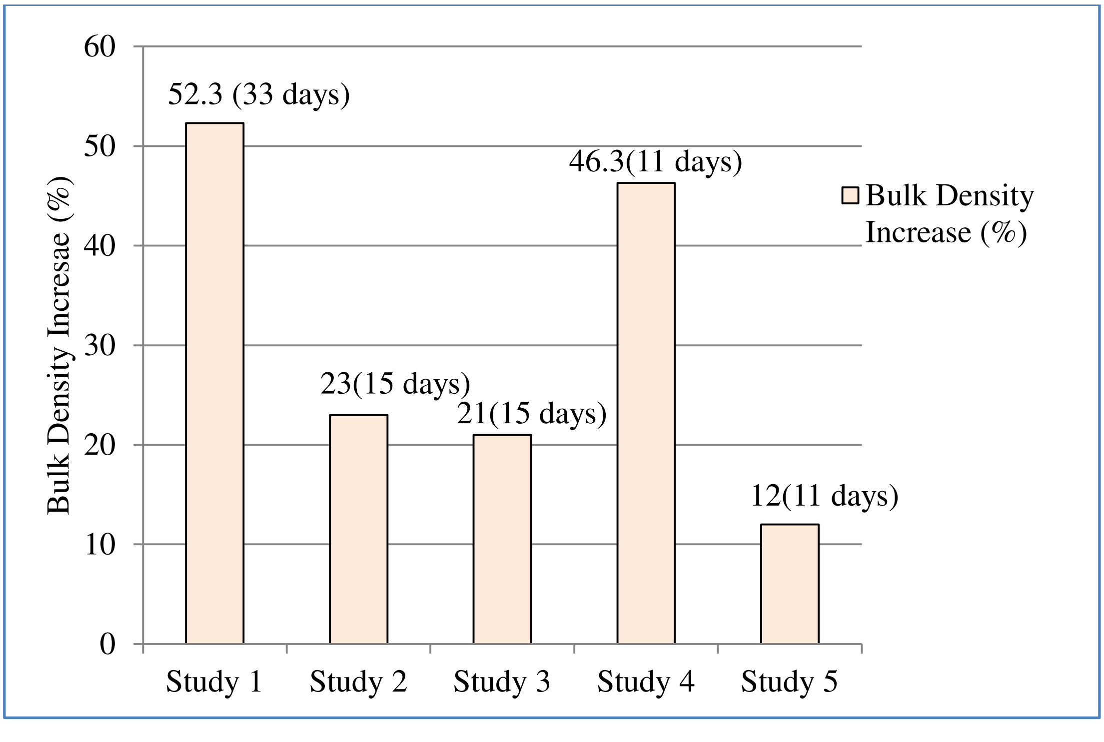


Fig.5.8.4. Bulk Density Profile.

The bulk density increase has drastically reduced to 23 % and 21% in the second and third phase of studies. These results point out that the accelerated rate of moisture reduction in these phases lead to moisture deficiency. The moisture deficiency has decelerated the biological reactions in the reactor matrix. In the fourth experiment again bulk density increase was prominent with 46.3% increase, which is mainly due to activation of degradation reaction and air scarcity. The fifth phase has resulted in bulk density increase of 12% in 11 days of reaction. In the fifth phase the accelerated moisture removal has affected the biological degradation reaction and hence bulk density increase was lesser while compared to other experiments.

5.8.6 Assessment of Sixth Phase of Study

The sixth phase of study with down flow mode of aeration at a high specific air flow rate of 1.46 m^3/kg.day has resulted in weight reduction of 42.39 % in 12 days of reaction. This phase of study has resulted in moisture reduction of 41.5% in 12 days of reaction. However the biological drying as well as air drying has occurred in the sixth phase, which is evident from the non- uniform moisture content of the output. In the sixth phase of experiment the volume has reduced by 34.57% in 12 days of reaction. The bulk density increase was very less with 3.41% increase achieved in 12 days of reaction. Bulk density increase was lower in the sixth phase because the air drying reaction occurred together with biodrying reaction. The weight reduction, moisture reduction, volume reduction and bulk density increase of sixth phase of study has been shown in fig. 5.8.5.

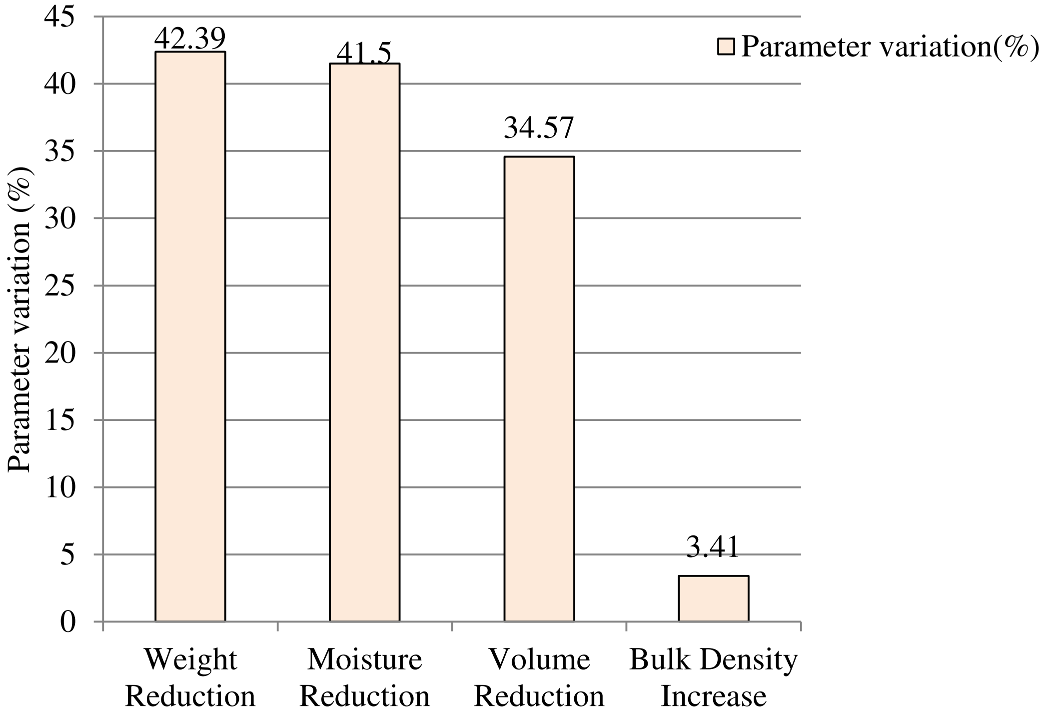


Fig.5.8.5 Assessment of Sixth Phase of Study.

5.8.7 Temperature Cumulation Index

Biodrying is a self heating process where the biological heat is used for drying purpose. In the case of highly ventilated process like biodrying, the self heating reaction can be delineated through the analysis of temperature cumulation index. The temperature cumulation index has been calculated for all the phases using mean matrix temperature(T_m) and temperature of air inlet (T_i) which is given by:

Temperature cumulation index (TCI) = $\sum(T_m - T_i).\Delta t$ ------------ (5.8.1)

Where Tm = mean matrix temperature (°C), Ti = temperature of air inlet (°C) and Δt = Time interval (day) [$\Delta t = 1$, for the present study].

The temperature cumulation index for all the phases during 11-15 day period has been plotted as shown in Fig. 5.8.6. In the first phase of experiment, the lower drying rate and presence of moisture content due to condensation reaction has accelerated the biological reaction. In the second study the heat accumulation was lesser than that in the first study during the period of 15 days. It is evident from the graph that the slope of the temperature accumulation index is very steep in the first and third phases of studies while compared to the other phases (Fig. 5.8.6).

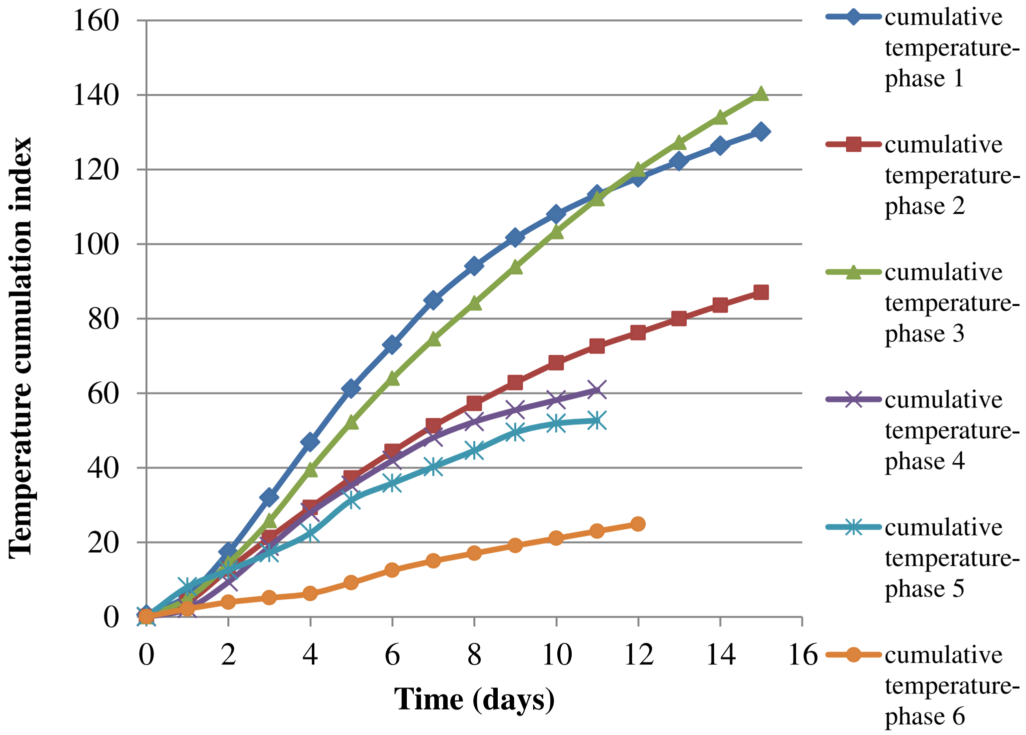


Fig.5.8.6 Temperature Cumulation Index in Six Phases of Biodrying Process.

This indicates the rate of heating with respect to time is very high in these phases while compared to the other ones. Considering the moisture reduction in biodrying process the fifth experiment was more effective. Therefore too steep and too flat nature of temperature cumulation index plot does not favour biodrying reaction. Therefore heat accumulation is positively affecting the moisture reduction in biodrying reaction in the initial process duration, while it is negatively affecting moisture reduction as reaction time increases.

It can be explained on the basis of convective evaporation process in biodrying reaction. Air convection may eventually dry the surface of the particle, reaching the hygroscopic limit, resulting in less water to evaporate. For further drying, the bound moisture has to migrate from the particle interior to its surface, which is governed by heat dissipating diffusion mechanisms (Roy et. al., 2006). Therefore not only the heat accumulation reaction but also the heat dissipation plays a major role in accelerating biodrying mechanism. The rate of air flow, initial temperature rise, and the duration of biodrying reaction together constitute better heat dissipating diffusion mechanism.

5.8.8 Mass Balance Analysis in Biodrying

The mass balance calculations were carried out in two ways. Firstly the weight loss and moisture loss based mass balance study has been carried out. Secondly the CO_2 emission loss based mass balance analysis has been done and both the results have been compared to analyze the biodrying process in detail.

5.8.8.1 Moisture Reduction Basis

Mass balance for the designed biodrying processes is calculated by the following equations

The water losses at time t (W^t_{loss}, kg) are calculated by:

$$W^t_{loss} = (WM_0 \times w_0) - (WM_t \times w_t) \text{--------------------------------} (5.1)$$

Where WM_0 (kg) and WM_t (kg) are the wet materials at the initial time and time t, respectively, w_0 (%) and w_t (%) are water contents at initial time and time t, respectively.

Table.5.8.2 Mass Balance Calculations

Expt No.	Initial weight (kg)	Final weight (kg)	Weight Loss (kg)	Initial moisture content (%)	Final moisture content (%)	Initial Water (kg)	Final Water (kg)	Water Loss (kg)	Net Emission Loss (kg)
1	109.00	72.00	37.00	61.25	48.50	66.76	34.92	31.84	5.16
2	124.00	75.40	48.60	65.50	43.90	81.22	33.10	48.12	0.48
3	167.00	109.00	58.00	62.45	43.50	104.29	47.42	56.88	1.12
4	172.00	135.00	37.00	66.40	57.20	114.21	77.22	36.99	0.01
5	180.00	106.80	73.20	60.06	36.74	108.11	39.24	68.87	4.33
6	79.50	45.80	33.70	55.74	32.60	44.31	14.93	29.38	4.32

Net emission losses at time t (E_{loss}, kg) are given by,

$$E_{loss} = WM_0 - WM_t - W^t_{loss} - LO^t_{loss} \text{---------------------------------------} (5.2)$$

Where LO^t_{loss} is leachate weight, which is negligible in the present study. The mass balance calculations were enlisted in Table.5.8.2.

5.8.8.2 CO_2 Emission Loss Based Mass Balance Analysis

The mass balance analysis has also been carried out by using the data achieved through CO_2 analyser. The details were enlisted in Table 5.8.3.

Table.5.8.3 Measured Emission Loss

Experiment No.	**CO_2 (%) Average**	**CO_2 (kg)**	**Emission loss(kg)**	**Net emission due to other gases**
1	0.758	4.98	5.16	0.18
2	0.075	0.48	0.48	0
3	0.125	0.821	1.12	0.299
4	0.0145	0.01	0.095	0.085
5	0.325	4.27	4.33	0.06
6	0.257	3.38	4.32	0.94

The mass balance calculations helped to explore the difference between the biodrying processes in the different phases of experiments. In the first phase of experiment the net emission loss is higher where the process duration was the longest (Table.5.8.2 and Table.5.8.3). Therefore degradation reactions are more active as time progress in biodrying process, especially when the rate of moisture reduction is not enough to decelerate biological reaction.

In the second phase of experiment moisture reduction was faster due to elimination of condensation in top region of the biodrying reactor. This resulted in reducing the experiment duration from 33 days in the first experiment to 15 days in the second phase. Active drying in short period was observed with reduction in CO_2 production. In the third experiment emission loss was higher than that of second one where the increased volume of the matrix has resulted in active degradation reaction at some points inside the reactor matrix. During the fourth phase of experiment the emission loss has decreased and the moisture reduction has shown a decreasing trend. This is mainly due the air scarcity which gave rise to zones of anaerobic condition inside the reactor matrix. The present investigations revealed that an optimum balance of aerobic and anaerobic conditions inside the reactor matrix is an essential requirement for efficient biodrying reaction. The sixth phase was effective in terms of drying reaction, but the biological heat utilisation was lesser. The high rate of air circulation cooled the heated air. Therefore along with the biodrying reaction air drying process has also occurred.

CHAPTER 6

CALORIFIC VALUE OF RAW VS BIODRIED SUBSTRATE

6.1. INTRODUCTION

Waste to energy (WTE) technologies have the potential to reduce the volume of the original waste by 90%, depending on the composition by recovering the energy (Wang, 2009; Kathiravale, 2003). Recovering energy from municipal solid waste is feasible by a means of a number of energy generation processes like incineration, pyrolysis, gasification etc. The design and operation of all the energy systems of municipal solid waste are largely influenced by the heating value of MSW. Mixed MSW has a heating value of about one third of the calorific value of coal (8-12 MJ/kg for MSW and 25-30 for MJ/kg for coal) (International Energy Agency, IEA 2003, Municipal solid waste and its role in sustainability). The net energy yield depends upon the density, composition and relative percentage of moisture of the waste (Fobil, 2005). Therefore moisture reduction in biodrying process and the resulting energy value increase is required to assess the end use possibilities of biodried output. The lower calorific value of municipal solid waste can be calculated based on a number of available modelling equations, which is described in the following section.

6.1.1 Proximate Analysis

Proximate analysis method for calculating the lower calorific value of municipal solid waste is used by a number of researchers. The available modelling equations are given below.

$$LHV = 45V - 6W \text{ ----------------------------- } (6.1) \quad \textit{(JNMSWF,1991)}$$

$$LHV = 44.75V - 5.85W + 21.2 \text{ ------------- } (6.2) \quad \textit{(JNMSWF,1991)}$$

Where LHV: lower heating value (kcal/kg)

Where V-volatile solids (%)

W- Moisture content (%)

6.1.2 Physical Composition Analysis

Physical composition method of energy assessment is widely used for calculating energy value of heterogeneous municipal solid waste. The available modelling equations based on physical composition are given below.

Modelling Equation- 1

$$LHV = [88.2P_{pl} + 40.5(P_{fo} + P_{pa})]\left(\frac{100-W}{W}\right) - 6W \text{ ------------- } (6.3)\ \textit{[JNMSWF,1991]}$$

Modelling Equation- 2

$$LHV = (38.52P_{pa} + 92.09P_{pl} + 49.24P_{te} + 38.34P_{wo} + 37.55P_{fo} + 64.07\ P_{mi})\left(\frac{100-W}{W}\right) - 6W \text{ --- } (6.4) \quad \textit{[Lin 2000]}$$

Where LHV: lower heating value (kcal/kg)

P_{pl}: Plastics (wt %), P_{fo} : food waste (wt %), P_{pa} : paper and card board (wt %)

W: moisture content (%), P_{te} : textiles (wt %)

P_{wo} : wood (wt %), P_{mi} : miscellaneous component (wt %)

In the present study equations based on physical composition is used (equations 6.3 and 6.4) for energy calculations of raw & biodried MSW. The composition of the mixed municipal solid waste substrate as well as the moisture content before and after the process for five phases of experiments has been listed in Table.6.1.

Table 6.1 Composition of Different Components of Mixed Municipal Solid Waste

Expt No.	Organic components		Paper		Plastics		Textiles		Initial Moisture content (%)	Final Moisture content (%)
	Weight (kg)	P_{fo}%	Weight (kg)	P_{pa}%	Weight (kg)	P_{pl}%	Weight (kg)	P_{te}%		
1	78.40	70.00	13.44	12.00	10.08	9.00	10.0800	9.00	61.25	48.50
2	91.98	73.00	12.60	10.00	8.82	7.00	12.6000	10.00	65.50	43.90
3	124.56	72.00	19.03	11.00	13.84	8.00	15.5700	9.00	62.45	43.50
4	151.90	70.00	26.04	12.00	21.70	10.00	17.3600	8.00	66.40	57.20
5	125.40	66.00	32.30	17.00	14.25	7.50	18.0500	9.50	60.06	36.74

The lower heating value of the mixed municipal solid waste before and after the biodrying process is calculated using two modelling equations 6.3 & 6.4. The table 6.2 shows lower heat value of MSW in five phases of study.

Table.6.2 Lower Heat Value of MSW- Comparison of Five Phases of Biodrying Process.

Expt No.	Process Duration	Lower Heat Value in kcal/kg			
		Modelling Equation-1		Modelling Equation-2	
		Raw MSW	Biodried MSW	Raw MSW	Biodried MSW
1	33	2235.74	3874.74	2392.58	4152.43
2	15	1263.51	4588.54	1383.99	4938.97
3	15	2070.77	4998.56	2215.14	5311.62
4	11	1728.42	2801.73	1830.92	2954.65
5	11	2314.94	6538.73	2493.56	7012.77

The average heating value obtained from the two modelling equations for raw as well as biodried Municipal solid waste has been expressed in kJ/kg as shown in Table. 6.3. The calorific value of raw municipal solid waste varies from7446 kJ/kg to 10059.38 kJ/kg. The incineration of MSW with low calorific value encounters a range of problems including difficulty in ignition, unsteady and unstable combustion flame, incomplete combustion of the waste, and increased formation of air pollutants.

Supplementary fuel, which would significantly increase the operating cost, is often necessary for incineration of such high moisture, low energy content waste (Cheng et. al.,2007; Cheng and Hu, 2009; Nie, 2008; Cheng and Hu 2010).

Table. 6.3 Average Lower Heat Value of Mixed MSW in kJ/kg- Comparison of Five Phases of Studies Before and After Biodrying Process

Expt No.	**Lower Calorific Value (kJ/kg)**	
	Raw MSW Before Biodrying	**Biodried MSW**
1	9682.45	16792.84
2	5538.58	19931.55
3	8966.12	21568.90
4	7446.14	12042.34
5	10059.38	28349.73

In this scenario the biodried substrate is useful for energy production since its calorific value has increased. Graphical Representation of Calorific value of MSW Substrate Before and After the Biodrying Process for five phases of study varies from 12.04 MJ/kg to 28.35 MJ/kg as represented in Fig.6.1.

The biodrying process of municipal solid waste with high moisture content has reported an increase of lower heating value up to 2 times the initial value in previous study of Shao et.al., 2010. The maximum calorific value of 28349.73 kJ/kg obtained in fifth phase of study was 2.8 times the initial calorific value of 10059.38 kJ/kg. The calorific value of raw as well as biodried substrate in the sixth phase of study has been shown in Table.6.4

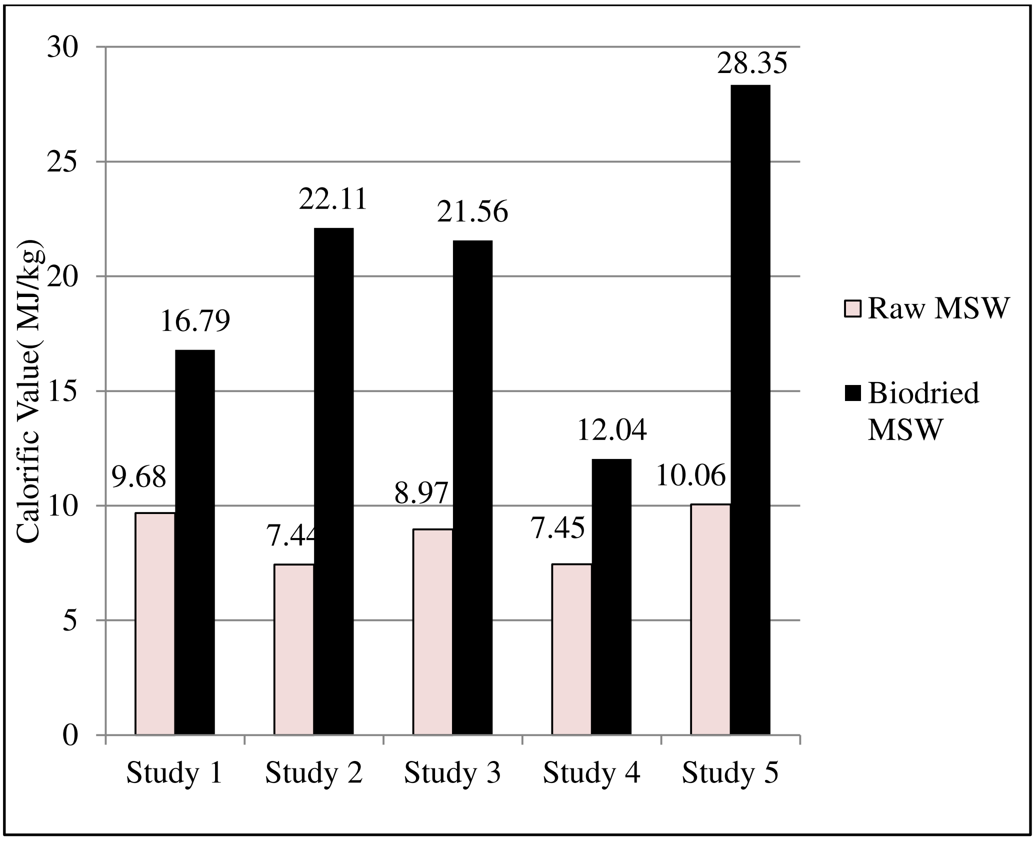


Fig.6.1 Graphical Representation of Calorific value of MSW Substrate Before and After the Biodrying Process

Table 6.4 The Calorific Value of Raw and Biodried MSW-Phase 6

EXPT NO.	**Lower Calorific Value (kJ/kg)**	
	Raw MSW	**Biodried MSW**
6	12331.43	33138.27

It was observed that the calorific value of raw substrate was higher in the sixth phase with a value of 12331.43 kJ/kg. The biodrying process along with the drying process in the sixth phase has facilitated higher moisture reduction but its distribution was non-homogeneous.

The energy value of biodried output has been compared with that specified in existing RDF standards as shown in Table. 6.5. It can be observed that the energy value of biodried output has increased upto the RDF standards in the present investigations. It is promising for the application of biodried output for energy producing applications.

Table.6.5 Existing Data on MSW and RDF Comparison

Main properties of renewable fuels	**MSW**	**RDF**
Gross calorific value (kJ/kg of waste)	10,159.8	18,280.8
Gross calorific value (kJ/kg of dry waste)	18,973.1	23,444.6
Gross calorific value (kJ/kg of dry-ash free waste)	26,518.9	26,948.7
Low calorific value (kJ/kg of waste)	8325.9	16,660.7
Low calorific value (kJ/kg of dry waste)	17,677.1	22,061.2
Low calorific value (kJ/kg of dry-ash free Waste)	24,990.2	25,409.9
Moisture (%)	46.46	22.07
Non-combustible material (% wt dry basis)	15.23	10.10
Specific weight (kg/m^3)	208.0	130.8

(Montejo et al., 2011.)

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 SUMMARY

Municipal solid waste is a readily available resource, which can be used for renewable energy production. The major hindrance towards the use of energy producing applications of municipal solid waste is the high moisture content and low calorific value. The search for a technology which will convert the raw MSW in to an energy enriched material as well as the need of technologies for mixed municipal solid waste treatment has led to ‘Biodrying Process’ as a sustainable option.

The main objective of the present study was the development of biodrying technology as a sustainable method for municipal solid waste management. The novel features of the biodrying reactor are vertical tubular design with up-flow mode of aeration, continuous process monitoring with data acquisition system, an innovative design of horizontal air flow system for condensation prevention, provision of temperature probes for continuous monitoring along the reactor matrix, a unique design of bottom chamber for optimum air circulation inside the reactor matrix and provision for easier unloading of the biodried material etc. Better performance was brought into the system through a series of improvisations wherein the performance of various elements of the configuration was investigated independently and for maximum efficiency.

The investigation studies on the pilot scale biodrying reactor have been conducted in six phases. In the first phase of study, the specific air flow rate of 0.528 m^3/kg.day was provided and process monitoring has been carried out for 33 days. The major limitation of first study was that moisture removal efficiency in the biodrying process has been affected due to exhaust air saturation. The biodrying reactor unit has been modified with Horizontal Air Flow system (HAF) in the second phase for prevention of condensation. This study has resulted in better drying efficiency in short duration of 15 days at a specific air flow rate of 0.460 m^3/kg.day.

In the third phase, the effect of variation in specific air flow rate and increased reactor matrix height on biodrying reaction has been studied. Self heating temperature was better in this phase with a peak value of 65°C achieved in this phase. The increase in non-homogeneity of the biodried output was the major limitation of this study. The fourth phase has conducted to study the effect of further increase in reactor fill and the effect of substrate packing on the biodrying process. The loose packing of substrate was provided here while compared to previous study. The peak self heating temperature of 58°C was observed in this phase, which is lesser that in the previous study.

In the fifth phase, the effect of increase in specific air flow rate has been studied. The volumetric air flow rate has doubled to 80 L/m and fully filled reactor has been used in this study. The self heating was lesser with a peak value of 50ºC recorded in this phase of study. The sixth phase of study has conducted to study the effect of down flow mode of aeration. The final stage of the research included the study of energy value assessment of the biodried product. It was observed that the calorific value of raw municipal solid waste has increased in all the six phases of studies.

7.2 CONCLUSIONS

Studies on the developed biodrying reactor have shown that it can be effectively used for mixed municipal solid waste management. From this study, the following major conclusions can be made:

➢ Characterisation Study

The characterisation study has revealed that the typical municipal solid waste of the study area has an average moisture content of 61% and volatile solids content of 90 %. It indicates that the MSW substrate selected for the present investigation is having optimum conditions for active biodrying reaction.

➢ Feasibility of Biodrying process in the Developed Reactor- Phase 1

The first phase of study has facilitated active biodrying reactions at the bottom region of reactor matrix and biodegradation reaction at the top region of reactor matrix. It was due to the condensation of evaporated water back into the reactor top region. Weight reduction of 33.94 % , moisture reduction of 20.81%, Bulk density increase of 52 % and volume reduction of 56.5 % has been achieved in 33 days of biodrying reaction. The maximum temperature of 59.5°C has been attained by the reactor matrix in this phase.

- **Effect of Modified Reactor with Horizontal Air Flow System on Biodrying Process – Phase 2**

In the second phase of study, the modified reactor with horizontal air flow (HAF) system was successful with complete elimination of condensation reaction at the top region of reactor matrix. Better process efficiency with a weight reduction of 39 % and a moisture reduction of 33 % has been achieved in 15 days of reaction, at a specific air flow rate of 0.460 m^3/kg.day. Also bulk density increase of 24 % and volume reduction of 43 % has been achieved in the same duration. Peak temperature of 59.9°C has been developed inside the reactor matrix and the self heating process was prominent along the time axis in this phase. The major achievement in this phase is that the process efficiency obtained in shorter duration period of 15 days

- **Effect of Specific Air Flow Rate and Increased Reactor Matrix Height on Biodrying Process – Phase 3**

The increased reactor matrix height and a lower specific air flow rate of 0.350 m^3/kg.day has resulted in increased self heating temperature with a peak value of 65.5°C inside the reactor matrix. In this phase, weight reduction of 35 %, moisture reduction of 30 %, bulk density increase of 21 % and volume reduction of 39 % has been achieved in 15 days of biodrying reaction. The moisture reduction has not increased, though high temperature heating occurred, which is mainly due to the formation of localized zones of biodegradation inside the reactor matrix.

➢ Combined Effect of Substrate Packing and Rector Matrix Height on the Biodrying Process –Phase 4

Weight reduction of 20.4 % and moisture reduction of 17 % has been achieved in 11 days of biodrying reaction at a specific air flow rate of 0.345 m^3/kg.day in the fourth phase of study. The air scarcity in biodrying reactor has lead to biodegradation reaction more than biodrying reaction. Therefore, the volume has been reduced to 43.5% and the bulk density has been increased to 46.3 % in 11 days of biodrying reaction which is more than the previous studies. The peak value of self heating temperature has reduced to 58.1 °C, which is lesser than that in the previous study. The loosely packed reactor feed has not reduced the heterogeneity of the product and rather it resulted in air channelisation and short circuiting.

➢ Effect of Increase in Air flow Rate on Biodrying Process- Phase 5

In the fifth phase weight reduction of 41 %, moisture reduction of 39 %, volume reduction of 38 % and bulk density increase of 12 % has been achieved after 11 days of operation. The moisture reduction has been increased by 2.3 times that of fourth phase, when the air flow rate was doubled under the selected experimental conditions This study was most successful in terms of biodrying process efficiency and uniformity of the biodried product

➢ Effect of Down Flow Mode of Aeration on Biodrying Process- Phase 6

The sixth phase with down flow mode of aeration at a high rate of 1.45 m^3/kg.day was effective with weight reduction of 42.39 %, moisture reduction of 41.5 % and volume reduction of 34.57 % in 12 days of reaction. The moisture distribution was highly heterogeneous inside the reactor matrix, which is pointing out non-homogeneous biodrying reaction inside the reactor matrix. The higher rate of specific air flow has cooled down the reactor matrix and hence the self heating temperature was lesser with a peak value of 47.7 ºC. The bulk density increase was 3.41 % which is very less while compared to other phases of experiments. This point out that air drying has also occurred along with the biodrying in the sixth phase of study.

➢ Potential of High Calorific Value of Biodried MSW for Energy Production

The calorific value of the biodried municipal solid waste has been increased from 10.06 MJ/kg to 28.35 MJ/kg in the fifth phase of study. This is an increase of 2.8 times the calorific value of raw MSW which is beneficial for energy producing applications. The energy enriched biodried material can be easily transported, stored, sorted and can be used as fuel in waste to energy plants. The biodried municipal solid waste is the suitable renewable fuel for incineration plants with energy recovery in the form of heat and electricity.

This research findings has established that biodrying can serve as an innovative technology in the field of treatment of municipal solid waste which is a major challenge to environmental engineers.

7.3 LIMITATIONS OF THE STUDY

The major limitation of the study was the heterogeneous nature of biodried output. The predominance of biodegradation over the biodrying in some localized zones of reactor has caused non homogeneous biodried output. The moisture distribution along the reactor matrix was not uniform mainly due to temperature gradient formation observed in biodrying process. The temperature rise was not uniform in horizontal as well as in vertical direction along the reactor matrix due to the static reactor used for biodrying process. Also the loosely packed reactor has resulted in air channelisation and short circuiting.

7.4 SCOPE FOR FURTHER STUDIES

- **Feasibility Study for Further Process Improvement of the Biodrying Reactor**

Temperature gradation has been observed inside the reactor matrix, which requires further studies to get homogeneous output and uniform self heating inside the biodrying reactor matrix. The provision of mixing devices to achieve uniform mixing inside the reactor for better biodrying process efficiency has to be studied. The mixing can also be carried out in rotary type reactors, which needs further studies. Also the effect of mode of aeration on the biodrying process has to be studied in detail to delineate further process variations.

➢ The Feasibility Studies for the End Use Application of Biodried Output

- **Suitability of Biodried MSW as a Renewable Energy Source**

The use of biodried substrate as a raw material for incinerators with heat recovery has to be studied. The potential of biodried material for use as a biofuel in gasification plants for energy production needs further investigations. The renewable energy of the biodried material for production of refuse derived fuel has to be studied which can replace or reduce the use of fossil fuel consumption in various industries like cement industry, brick industry etc.

- **Utilization of Biodried MSW for Production of Sustainable Construction Materials**

The potential use of biodried MSW as a raw material, filler, and additive in developing construction material like bricks, hollow bricks, solid bricks, pavement blocks and tiles has to be studied.

REFERENCES

1. **Adani, F., Baido, D., Calaterra, E.** and **Genevini, P**. (2002). The influence of biomass temperature on biostabilization-biodrying of municipal solid waste. *Bioresource Technology* **83**, 173-179.

2. **Adani, F., Tambone, F.** and **Gotti, A**. (2004). Biostabilization of municipal solid waste. *Waste Management* **24**, 775-783.

3. **American Society of Mechanaical Engineers** (2008). Waste-to-Energy: A Renewable Energy Source from Municipal Solid Waste; White Paper Submitted to Congreaa; New York, NY.

4. **Appel, H,R., Fu, Y,C., Friedman, S, P., Yavorsky, M.** and **Wender, I.** (1971). Converting organic wastes to oil, *US Bureau of Mines Report of Investigation*, No. 7560.

5. **Archer, E., Baddeley, A., Klein, A., Schwager, J.** and **Whiting, K.,** (2005). Mechanical-Biological Treatment: A Guide for Decision Makers".CD-ROM,V1, March 2005, Juniper Consultancy Services U.K.

6. **Arena, U.** (2012). Process and technological aspects of municipal solid waste gasification: a review, *Waste Management*, **32**, 625–639.

7. **Asnani P.U.** (2006). Solid Waste Management. *Indian Infrastructure Report* 2006. Oxford 708 university press, New Delhi, India.

8. **ASTM D 3173-87** (1996). Standards test method for moisture in the analysis of sample of coal and coke, in gaseous fuels; coke. Section 5, *Annual book of ASTM standards*.

9. **ASTM D 3175- 89** (2011). Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke.

10. **Ayari, F., Hamdi, H., Jedidi, N., Gharbi, R.** and **Kossai, R**. (2010). Heavy metal distribution in soil and plant in municipal solid waste compost amended plots. *Int. J. Environ. Sci. Tech.*, **7** (3), 465-472, Summer 2010 ISSN: 1735-1472.

11. **Babcock and Wilcox** (1992). Steam Its Generation and Use, 40th edition, The Babcock and Wilcox Company, USA.

12. **Bach, P.D., Nalasaki, K., Shoda, M.** and **Kubota, H.** (1987). Thermal balance in composting operations. *Journal of Fermentation Technology*, **65** (2), 199-209.

13. **Bailey, J.E.** and **Ollis, D, F**. *Biochemical Engineering Fundamentals*. McGraw-Hill International Editions Inc., Singapore, 1986.

14. **Barducci, G.** (1990). Gasification of wastes and refuse-derived fuel: leading edge technology for energy and the environment, *Proceedings of Energy from Biomass Contractors Meeting,* Florence, Italy, 20–22 November 1990, 1990, pp. 347–371.

15. **Barducci, G**. (1992). The RDF gasifier of Florentine area (Gréve in Chianti Italy), *The First Italian–Brazilian Symposium on Sanitary and Environmental Engineering.*

16. **Barducci, P.,** and **Neri, G.** (1997). An IGCC plant in Italy for power generation from biomass, *Bioelettrica Internal Report*.

17. **Bartha, B.,** and **Brummack, J.** (2007). Investigations on the separability of dynamically dried municipal solid waste. In: Kuehle-Weidemeir, M. (Ed.), *International Symposium MBT* 2007, Hanover, Germany 22–24 May 2007, pp. 350–360.

18. **Bartha, B.K.** and **Brummack, J.** (2006). Development of a control strategy for biotechnological processes in waste treatment. *In: Kühle-Weidemeier, M. (Hrsg.): Waste Research Days,. Göttingen: Cuvillier*,

19. **Bartha, B.K., Brummack, J.** and **Kloden, W** (2002). Control of a reactor for the treatment of waste with biogenic components. Final report on the DBU project 14736, Dresden University of Technology.

20. **Bartha, B.K.** (2008). "Development of a Control Strategy for the Treatment of Biological Waste in a Dynamic Reactor", Ph.D.Thesis, Technische Universitat Dresden, Dresden, p. 265.

21. **Baykara, S,Z.,** and **Bilgen, E**. (1981). A feasibility study on solar gasification of Albertan coal, *Alternative Energy Sources IV*, 6, Ann Arbor Sci, New York.

22. **Belgiorno, V., De, G,F., Della, R,C.,** and **Napoli, R,M,A**. (2003). Energy from gasification of solid wastes, *Waste Management* **23**, 1–15.

23. **Beukering, P.V., Sekher, M., Gerlagh, R.** and **Kumar, V.** (1999). Analyzing urban solid waste in developing countries: a perspective on

Bangalore, India, Working Paper No. 24. Collaborative Research in the Economics of Environment and Development (CREED), London

24. **Bhide, A.D.** and **Shekdar, A.V.** (1998). Solid waste management in Indian urban centers. International Solid Waste Association Times (ISWA) (1), 26–28.

25. **Bilgin, M. and Tulun, S**. (2015). Biodrying for municipal solid waste: Volume and weight reduction. *Environmental Technology* (United Kingdom), **36**(13), 1691-1697.

26. **Braber, K**. (1995). Anaerobic digestion of municipal solid waste: a modern waste disposal option on the verge of breakthrough. *Biomass Bioenerg*. **9** (1–5), 365–376.

27. **Bramryd, T.** and **Binder, M**. (2001). Environmental impacts of landfill bioreactor cells in comparison to former landfill techniques. *Water, Air, and Soil Pollution* **129**, 289–303.

28. **Brorson, T.** and **Larson, G**. (1999). Environmental Management — How to Implement an Environmental Management System within a Company or Other Organization, *EMSAB, Stockholm.*

29. **Bureau, C. J., Disdier, C.A., Gauroy, C.** and **Treguer, D.** (2010). A quantitative assess of the determinants of the net energy value of biofuels. *Energy Policy*,**38**,2282-2290.

30. **Cai, L., Gao, D., Chen, T., Liu, H., Zheng, G.** and **Yang, Q.** (2012). Moisture variation associated with water input and evaporation during sewage sludge biodrying. *Bioresource Technology*, **117**, 13-19.

31. **Calcaterra, E., Baldi, M.** and **Adani, F.** (2000). An innovative technology for municipal solid waste energy recovery. In: CIPA (Ed.), CIPA- *Centro di Ingegneria per la Protezione dell' Ambien*te. CIPA, Milano, Italy, pp.123-135.

32. **Yunus, A, Çengel.,** and **Michael, A. Boles.** A. *Thermodynamics: An Engineering Approach*. McGraw-Hill Education. ISBN 0-07-121688-X, 2015.

33. **Center of Excellence (CoE) on Solid Waste & Waste Water Management, Strategy & Framework for MSW Management.** *Centre for Environment and Development, Thiruvananthapuram,* November2010. (Availableathttp://www.cedindia.org/wp-content/uploads/2010/11/strategy-1.pdf. accessed 10.10.11).

34. **Central Pollution Control Board (CPCB)** (1999). '*Status of solid waste generation, collection, treatment and disposal in metro cities'*. Central Pollution Control Board, Delhi.

35. **Central Pollution Control Board (CPCB)** (2004). "*Management of Municipal Solid Waste"-Ministry of Environment and Forest*, New Delhi, India.

36. **Central Public Health and Environmental Engineering Organisation (CPHEEO)** (2000). *"Manual on Municipal Solid Waste Management*", Central Public Health and Environmental Engineering Organisation, Ministry of Urban Development, New Delhi.

37. **Chattopadhyay, S., Dutta, A.,** and **Ray, S.** (2007). Existing municipal solid waste management of Kolkata-Deficiencies and solutions. *Journal of IAEM*, **34** (3), 161-167.

38. **Cheng , H., Zhang, Y., Meng, A.** and **Li, Q.** (2007). Municipal solid waste fueled power generation in China: A case study of waste-to-energy in Changchun city. *Environ. Sci, Technol.* **41**, 7509-7515.

39. **Cheng, H.** and **Hu, Y.** (2010). Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. Bioresource Technology, **101**, 3816-3824.

40. **Cheng, H., Hu,Y.** and **Zhao, J.** (2009). Meeting China's water shortage crisis: current practices and challenges. Environ.Sci. Technol. **43**, 240-244.

41. **Cheng, H., Zhang, Y., Meng, A.** and **Li, Q.** (2007). Municipal solid waste fueled power generation in China: A case study of waste-to- energy in Changchun city. Environ. Sci. Technol. **41**, 7509-7515.

42. **Cherubini, F., Bargigli, S.** and **Ulgiati, S**. (2009). Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration, *Energy* **34**, 2116–2123.

43. **Choi , H.L., Richard, T.L.** and **Ahn, H.K.** (2001). Composting high moisture materials: biodrying poultry manure in a sequentially fed reactor. *Compost Sci. Util.* **9**, 303-311.

44. **Cimpan, C., Maul, A., Jansen, M., Pretz, T.** and **Wenzel, H**. (2015). Central sorting and recovery of MSW recyclable materials: A review of technological state-of-the art, cases, practice and implications for materials recycling. *Journal of Environmental Management*, **156**, 181-199.

45. **Cocarta, D,M., Rada, E,C., Ragazzi, M,A., Badea, T.** and **Apostol, A.** (2009). Contribution for a correct vision of health impact from municipal solid waste treatments, *Environmental Technology* **30** (2009) 963–968.

46. **Daniel, A,L.** and **Dilip, R, A**. (1990). Relative contributions of greenhouse gas emissions to global warming. *Nature*, **344**, 529-531.

47. **Daskalopoulos, E., Badr, O.** and **Probert, S.D.,** 1997.“Economic and Environmental Evaluations of WasteTreatment and Disposal Technologies for Municipal Solid Waste”.*Applied Energy*, Vol. **58**, No. 4, pp. 209-255.

48. **Debicka, M., and Zygadlo, M.,** (2017). Full-scale biodrying process of municipal solid waste, E3S Web of Conferences 17, 00018.

49. **Defra**. 2011c. Recycling of Catering and food waste – Evidence Project Final Report. London: Defra.

50. **Demirbas A**. (2011). Waste management, waste resource facilities and waste conversion processes. *Energy Convers Manage* 52(2):1280–7. http://dx.doi.org/10.1016/j.enconman.2010.09.025.

51. **Denison, R, A.** (1996). Environmental lifee-cycle comparison of recycling, landfilling and incineration: a review of recent studies. *Annu. Rev. Energ. Environ,***21**, 191-237.

52. **Diaz, L,F., Savage, G,M., Eggerth, L,L.** and **Golueke, C, G**. (1996). Solid Waste Management for Economically Developing Countries, *ISWA*, Copenhagen.

53. **DiBlasi, C.** (2000). Dynamic behaviour of stratified downdraft gasifier, *Chemical Engineering Science* **55**, 2931–2944.

54. **Di Maria, F., Benavoli, M.** and **Zoppitelli, M**. (2008). Thermodynamic analysis of the energy recovery from the aerobic bioconversion of solid urban waste organic fraction. *Waste Management,* **28**, 805-812.

55. **Directive, 2007/76/EC** of the European Parliament and of the Council of 4 December 2000 on the incineration of waste.

56. **Domingo, J,L.** and **Nadal, M.** (2009). Domestic waste composting facilities: A Review of human health risks. *Environment International*, **35**, 382-389.

57. **Dong-Qing, Z.,Pin-Jing, He.** and **Li-Ming, Shao** (2008). "Sorting Efficiency and Combustion Properties of Municipal Solid Waste during Biodrying", *Waste Management'*,Vol.**29**, Issue 11, Pp.2816-2823.

58. **Earle, J.F.K., Chynoweth, D.P.** and **Nordstedt, R.A**. (1995). Anaerobic bioconversion: biogasification of municipal solid waste. *Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences*, University of Florida. Bulletin 267.

59. **Edelmann, W., Baier, U.** and **Engeli, H**. (2005). Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes. *Water Sci. Technol.* **52** (1–2), 203–208.

60. **Edelmann, W.** and **Engeli, H.** (1993). Combined digestion and composting of organic industrial and municipal wastes in Switzerland. *Water Sci. Technol.* **27** (2), 169– 182.

61. **Edelmann, W., Schleiss, K.** and **Joss, A.** (2000). Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes. *Water Sci. Technol.* **41** (3), 263–273.

62. **Ekinci, K., Keener, H.M.** and **Akbolat, D**. (2006). Effects of feedstock, airflow rate, and recirculation ratio on performance of composting systems with air recirculation. *Bioresour. Technol.***97**, 922-932.

63. **Elango, D., Pulikesi, M., Baskaralingam, P., Ramamurthi, V.** and **Sivanesan, S**. (2007). Production of biogas from municipal solid waste with domestic sewage, *Journal of Hazardous Material*s **141**, 301–304.

64. **Energy Information Administration (EIA)** (2007). Methodology for Allocating Municipal Solid Waste to Biogenic and Non-Biogenic Energy; Office of Coal, *Nuclear, Electric and Alternate Fuels*, U.S. Department of Energy: Washington, Dc.

65. **Eriksen, G., Coale, F.** and **Bollero, G**. (1999). Soil nitrogen dynamics and maize production in municipal solid waste amended soil. *Agron. J.* **91**, 1009–1016.

66. **Esmaeili, M, B., Karbassi, A, R., Baghvand, A., Saeedi, M.** and **Pejman**, A, H. (2010). Potential of natural bed soil in adsorption of heavy metals in industrial waste landfill. *Int.J. Environ. Sci. Tech.,* **7** (3), 545-552, Summer 2010 ISSN: 1735-1472.

67. **Falkovich, G**. *Fluid Mechanics, a short course for physicists.* Cambridge University Press, 2011, ISBN 978-1-107-00575-4.

68. **Finnveden G, Johansson J, Lind P** and **Moberg A (2005)**. Life cycle assessment of energy from solid waste – part 1: general methodology and results. *J Clean Prod*, **13** (3):213–29.

69. **Finstein, M,S., Miller, F,C.** and **Strom, P.F.** (1986). Waste treatment composting as a controlled system. *Biotechnology*, **8**, 363-398.

70. **Flamme, S.** (2006). "The Biogenic Content in Substitute Fuels. *Mineral Process*, **47**, 40-45.

71. **Fobil, J, N., Carboo, D.** and **Armah, N, A**. (2005). Evaluation of municipal solid waste (MSW) for utilisation in energy production in developing countries. *Int. J. Environmental Technology and Management*, **5**, 76- 87.

72. **Foo, T.S.** (1997). Recycling of domestic waste: early experiences in Singapore. *Habitat International* **21**, 277-289.

73. **Di Maria., F., Postrioti, L., Micale. C., Sordi, A.** and **Marconi, M**. (2014). Energy recovery from low temperature heat produced during aerobic biological treatment. *Energy Procedia*, **45**, 81-90.

74. **Frei, K.M., Cameron, D., Jasmin, S.** and **Stuart, P.R.** (2006). Novel sludge drying process for cost-effective on-site sludge management. *Pulp and Paper Canada*, **107** (4), 47-53.

75. **Frei, K.M., Stuart, P.R.** and **Cameron, D**. (2004b). "Novel drying process using forced aeration through a porous biomass matrix". *Dry. Technol.* **22**, 1191–1215.

76. **Fricke, K., Santen, H.** and **Wallmann, R**. (2005). Comparison of selected aerobic and anaerobic procedures for MSW treatment. *Waste Manage*. **25**, 799–810.

77. **Garcia, C., Hernandez, T.** and **Costa, F**. (1991). Study on water extract of sewage sludge composts, *Soil Sci. Plant Nutr.*, **37** (3), 399-408.

78. **Garg, A., Smith, R., Hill, D., Longhurst, P,J., Pollard, S,J,T.** and **Simms, J**. (2009). An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste. *Waste Manage.* **29**, 2289-2297.

79. **Genon, G.** and **Brizio, E.** (2008). Perspectives and limits for cement kilns as a destination for RDF. *Waste management*, **28**, 2375-8235.

80. **Ginkal, Van, J.T., Raats, C, P, A., Haneghem** and **Van, I, A**. (1999). Bulk density and porosity distributions in a compost pile. *Netherlands Journal of Agricultural science*, **47**, 105-121.

81. **Gottas, Harold, B.** (1956). Composting- Sanitary Disposal and Reclamation of Organic Wastes .*World Health Organization,Monogrpah Series* Number 31, Geneva, p.81.

82. **Guardia, A.D., Petiot, C.** and **Rogeau, D**. (2008). Influence of aeration rate and biodegradability fractionation on composting kinetics. *Waste Manage*. **28**, 73-84.

83. **Handbook of fundamentals** (1967). American Society of Heating, Refrigerating and Air-conditioning Engineers, New York.

84. **Hansen, T., Bhander, G., Christensen, T., Bruun, S.** and **Jensen, L.** (2006). Life cycle of environmental impacts of application of processed organic municipal solid waste on agricultural land (EASEWASTE). *Waste Manag*. Res. **124**, 153–166.

85. **Hargreaves, J.C. , Adl, M.S.,** and **Warman, P.R** . (2008). A review of the use of composted municipal solid waste in agriculture, *Agric. Ecosyst. Environ*. **123**,1–14.

86. **Hartmann, H.** and **Ahring, B.K.** (2006). Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview. *Water Sci. Technol*. **53** (8), 7–22.

87. **Haug, R, T**. (1993). The Practical Handbook of Composting Engineering, Chap.2, 10, Lewis Pub.

88. **He, X., Traina, S.** and **Logan, T**. (1992). Chemical properties of municipal solid waste compost. *J. Environ. Qual*. **21**, 318–329.

89. **Herhof GmbH** (2008). Reference Plants. Available at: http://www.herhof.com/en/business-divisions/stabilat/reference-plants.html.

90. **High Powered Expert Committee** (2011). *Report on Indian Urban Infrastructure and Services*, Ministry of Urban Development.Government of India.

91. **Hoffmann, B.** (2005). New possibilities and limitations for the processing of waste from human settlements. Neue moglichkeiten der aufberei tung von siedlungsabfallen und ihre Grenzen. Aufbereitungs- Tech./ *Mineral Process*. **46**, 8-19.

92. **Hoornweg, D.** and **Bhada-Tata, P**. "*What a waste: A global review of solid waste management*".The World Bank, Washington, DC, 2012. https://openknowledge.worldbank.org/handle/10986/17388.

93. **Hsu, J, H.** and **Lo, S, L.,** (1999). Recycling of separated pig manure: characterisation of maturity and chemical fractionation of elements during composting. *Water Sci. Technol.*, **40**, 121-127.

94. **Huet, J., Druilhe, C., Tremier, A., Benoist, J, C.** and **Debenest, G**. (2012). The impact of compaction, moisture content, particle size and type of bulking agent on initial physical properties of sludge-bulking agent mixtures before composting. Bioresource Technology, vol.**114**,pp.428-436.

95. **International Energy Agency IEA** (2003). Municipal Solid Waste and its Role in Sustainability: A position paper. In: Bioenergy (ed.) www.ieabioenergy.com/media/ 40_IEAPositionPaper MSW.pdf

96. **Iglesias-Jimenez, E.** and **Alvarez, C.** (1993). Apparent availability of nitrogen in composted municipal refuse. *Biol. Fert. Soils* **16**, 313–318.

97. **Incropera, Frank., P. DeWitt** and **David P**. Fundamentals of Heat and Mass Transfer (3rd ed.). John Wiley & Sons, 1990. p. 28. ISBN 0-471-51729-1.

98. **International Organisation of Supreme audit institutions (INTOSAI)** (2002). Towards auditing waste management. Report of INTOSAI Working Group on Environmental Auditing, INTOSAI, Norway

99. **Iqbal, M. K., Shafiq, T.** and **Ahmed, K.** (2010). "Characterisation of bulking agents and its effects on physical properties of compost. *Bioresource. Technol.* **101**, 1913-1919.

100. **IS 5194** (2002). Indian standard method for determination of Nitrogen - Kjeldahl method.

101. **Jakobsen, S**. (1995). Aerobic decomposition of organic wastes 2. Value of compost as fertilizer. *Resour. Conserv. Recy*. **13**, 57–71.

102. **James I. Chang, Y.** and **J.Chen** (2010). "Effects of bulking agents on food waste composting". *Bioresource Technology*, vol.**101**, pp.5917-5924.

103. **Jewell, W.J., Dondero, N.C., van Soest, P.J., Cummings, R.T., Vegara, W.W.** and **Linkenheil, R**. (1984). "High Temperature Stabilization and Moisture Removal from Animal Wastes for By-Product Recovery", Final

Report for the Cooperative State Research Service, SEA/CR 616-15-168, USDA, Washington, DC, USA, p. 169.

104. **JNMSWF** (1991). Design Guide for the Facility of Solid Waste Disposal, Tokyo. Japan National Municipal Solid Waste Foundation.

105. **Johnke, B**. Current situation of waste incineration and energy recovery in Germany in: V.I. Grover, V.K. Grover, W. Hogland (Eds.), Recovering Energy from Waste: Various Aspects, Science Publishers, 2002, Plymouth, UK, pp. 195–2000.

106. **Kara, M., Gunay, E., Tabak, Y. and Yildiz, S**. (2009). Perspectives for pilot scale study of RDF in Istanbul, Turkey. *Waste Management*, **29**, 2976-2982.

107. **Kara, M.** (2012). Environmental and economic advantages associated with the use of RDF in cement kilns. *Resources, Conservation and Recycling*, **68**, 21-28.

108. **Kathiravale, S., Abu., M. P., Yunus, M. M. and Abd-Kadir, K.Z.** (2003). Energy potential from municipal solid waste in Malaysia. *Renewable Energy*, **29**, 559-567.

109. **Katyal, S.** (2007). Effect of carbonization temperature on combustion reactivity of bagasse char, *Energy Sources* Part A, **29**, 1477–1485.

110. **Keener. H. M., Elwell. D, L., Das, K.** and **Hansen, R, C.** (1998). Specifying design/operating of composting system using pilot scale data. *Applied Engineering in Agriculture*, **13**, 767-772.

111. **Knoblauch, A**. (2001). Investigation of industrial composting processes with focus on sanitation of bio-waste. Dissertation, Dresden University of Technology.

112. **Korobitsyn, M, A., Jellema, P.** and **Hirs, G,G**. (1999). Possibilities for gas turbine and waste incinerator integration, *Energy* **24**, 783–793.

113. **Krogmann, U.** Composting. Bonn: Economica, 1994.

114. **Kroll, K**. Dryer and drying process. Berlin, Heidelberg, Springer, 1978.

115. **Kerala State Urban Development Programme (KSUDP)** (2006). Solid waste management of Kollam, Kochi, Thrissur and Kozhikkode Corporations of Kerala. Dft. Detailed Project Report. Local Self Government Department, Government of Kerala & Asian Development Bank (Personal communication)

116. **Lardinios, I.** and **Van de Klundert, A**. (1997). 'Integrated sustainable waste management', Paper for the Programme Policy Meeting Urban Waste Expertise Programme, April, pp.1–6.

117. **Lastella G, Testa C, Cornacchia G, Notornicola M, Voltasio F** and **Sharma V, K**. (2002) Anaerobic digestion of semi-solid organic waste: biogas production and its purification. *Energy Convers Manage*, **43**(1):63–75.

118. **Liliana, K., Zawdzka, A.** and **Ledakowicz, S.** (2010). "Autothermal Drying of Sewage Sludge and Organic Fraction of Municipal Solid Waste in Batch Bioreactor",A thesis work.

119. **Lin, C, H**. Model to evaluate lower heat value of solid waste in Taiwan. Tung Nan Institute of Technology, Taipei, Taiwan, ROC, 2000.

120. **Ling Zhao, Wei-Mei Gu, Pin-Jing He** and **Li-Ming Shao** (2010). Effect of air-flow rate and turning frequency on bio-drying of dewatered sludge. *Water Research*, **44**, 6144-6152.

121. **Ling Zhao, Wei-Mei Gu, Pin-Jing He** and **Li-Ming Shao** (2011). "Biodegradation potential of bulking agents used in sludge bio-drying and their contribution to bio-generated heat". *Water Research* vol.**45**, pp.2322-2330.

122. **Lopes, W.S., Leite, V.D.** and **Prasad, S**. (2004). Influence of inoculum on performance of anaerobic reactors for treating municipal solid waste. *Bioresour. Technol*. **94**,261-266.

123. **Lu, Cai, Ding Gao., Tong-Bin Chen., Hong-Tao Liu., Guo-Di Zheng.** and **Qi-Wei, Yang.** (2012). Moisture variation associated with water input and evaporation during sewage sludge bio-drying. *Bioresource Technolog*y, **11**, 13-19.

124. **Lu, Y.J., Wu, X. W.** and **Guo, J.F.** (2009). Characteristics of municipal solid waste and sewage sludge co-composting. *Waste Manage.* **29**,1152-1157.

125. **Magrinho, A.** and **Semiao, V.** (2008). On the effect of MSW moisture content on meeting target recycling rates. *Waste Management*, **28** (2), 310-317.

126. **Mason, I.G.** (2006). Mathematical modelling of the composting process: A review. Waste Management **26**, 3-21.

127. **Meissl, K.** and **Smidt, E.** (2007). High quality composts from anaerobic digestion residues. *Biocycle* **48** (3), 55–58.

128. **Ministry of Environment and Forests (MoEF)** (2000). The Gazatte of India. Municipal Solid Waste (Management and Handling) Rules, New Delhi, India.

129. **Mohaibes, M.** and **Heinonen-Tanski, H**. (2004). Aerobic thermophilic treatment of farm slurry and food wastes. *Bioresour. Technol.* **95**, 245–254.

130. **Mohajer,A., Tremier,A., Barrington,S., Martinez,J., Teglia, C.** and **Carone, M.** (2009). "Microbial oxygen uptake in sludge as influenced by compost physical parameters. *Waste Management* .vol.**29**, 2257- 2264.

131. **Mohammed, M., Ozbay, I., Karademir, A., Isleyen, M.,** (2017). Pre-treatment and utilization of food waste as energy source by bio-drying process. Energy Procedia, 128, 100-107.

132. **Mohan, D., Pittman, J, C, U** and **Steele, P, H**. (2006). Pyrolysis of wood/biomass for bio-oil: a critical review, *Energy & Fuels* **20** (2006) 848–889.

133. **Mohn, J., Szidat, S., Fellner, J., Rechberger, H., Quartier, R., Buchmann, B.** and **Emmenegger, L**. (2008). Determination of biogenic and fossil CO_2 emitted by waste incineration based on $^{14}CO_2$ and mass balances. *Bioresour. Technol.*, **99**, 6471–6479.

134. **Montejo, C. Costa, P. Ramos, M.** and **del Carmen Marquez**. Analysis and comparison of municipal solid waste and reject fraction as fuels for incineration plants. *Applied Thermal Engineering*, 2011, doi: 10.1016/j.applthermaleng.2011.03.041.

135. **Morris, M**. Electricity production from solid waste fuels using advanced gasification technology, Swana's Waste con. 1998/ISWA World Congress, North Carolina, USA.

136. **Mueller, A.C.** Heat exchangers in Handbook of Heat Transfer,W.M. Rohsenow and J.P.Hartnett, eds., McGraw-Hill, New York, 1973,Chapter 18.

137. **Murphy, J, D.** and **McKeogh, E.** (2006). The benefits of integrated treatment of wastes for the production of energy. *Energy* **31**, 294–310.

138. **Navaee- Ardeh, S., Bertrand, F.** and **Stuart, P.R.** (2010). Key variables analysis of a novel continuous biodrying process for drying mixed sludge. *Bioresour. Technol.***101**, 3379-3387.

139. **Navaee-Ardeh, S., Bertrand, F.** and **Stuart, P**. (2006). Emerging biodrying technology for the drying of pulp and paper mixed sludges. *Drying Technology*, **24**, 863-878.

140. **Negoi, R, M., Ragazzi, M., Apostol, T., Rada, E, C.** and **Marculescu, C.** (2009). Biodrying of Romanian municipal solid waste: An analysis of its viability. *U.P.B. Sci.Bull.*,Series C, **71**(4), 2009.

141. **Neklyudov, A.D., Fedotov, G.N.** and **Ivankin, A.N.** (2006). Aerobic processing of organic waste into composts. *Appl. Biochem. Microbiol.* **42** (4), 341–353.

142. **Nellist M.E.** and **Brook, R.C.** "Drying Wheat by Continuous Ventilation with Unheated Air in a Favourable Location". AFRC Institute of Engineering Research, Silsole, 1987, UK.p.18.

143. **Nellist, M.E., Lamond, W.J., Pringle, R.T.** and **Burfort, D**. "Storage and Drying of Comminuted Forest Residues".. AFRC Sisloe Research Institute, Silsoe, 1993, UK. p.82.

144. **Nie, Y**. (2008). Development and prospects of municipal solid waste(MSW) incineration in China, Front. *Environ*. *Sci.Eng*. China **2**, 1-7.

145. **Ofori-Boateng, C., Lee, K.T.** and **Mensah, M.** (2013). The prospects of electricity generation from municipal solid waste (MSW) in Ghana: A better waste management option. *Fuel processing Technology*, **110**, 94-102.

146. **Ogawa, H.** (2000). Sustainable solid waste management in developing countries. In: 7th ISWA International Congress and Exhibition. World helath Organization. Kuala Lumpur, Malayisa. Online: http://www.soc.titech.ac.jp/uem/waste/swmfogawal.htm (29 July).

147. **Otoma, S., Mori, Y., Terazono, A., Aso, T.** and **Sameshima, R.** (1997). Estimation of energy recovery and reduction of CO2 emissions in municipal solid power generation, *Resources, Conservation and Recycling,* 20, 95–117.

148. **Otten, L**. (2001). Wet–dry composting of organic municipal solid waste: current status in Canada. *Can. J. Civil Eng*. **28** (Suppl. 1), 124–130.

149. **Paar, S**. (2000). The Dombelüftungsverfahren. Dissertation, Dresden University of Technology.

150. **Pappu, A., Saxena, M.** and **Asokar, S.R**. (2007). Solid Waste Generation inIndia and Their Recycling Potential in Building Materials. Journal of Building and Environment **42** (6), 2311–2324.

151. **Patumsawad, S.** and **Cliffe, K. R**. (2002). Experimental study on fluidised bed combustion of high moisture municipal solid waste. *Energy Convers Manage,* **43**(17):2329–40.

152. **Peuker, U.A.** and **Stahl, W**. (2002) Through flow drying of preheated heaps Drying phase during mechanical-thermal dehumidification process. Chemie-Ingenieur-Technik, **74,** No. 3, pp. 350-355.

153. **Pimsler, R**. (2004). Building recycling: Sustainable reuse of existing structures, *New Life Journal*, April-May2004.

154. **Pinjing, H., Jiafu, T., Dongqing, Z., Yang, Z.** and **Liming, S**. (2010). Release of Volatile Organic Compounds during Bio-drying of Municipal Solid Waste, *Journal of Environmental Sciences*, vol. 22(5),pp.752–759.

155. **Poggi-Varaldo, H.M., Gómez-Cisneros, E., Fernández-Villagómez, G., Esparza-García, F.** and **Rinderknecht-Seijas, N.** (1999). Aerobic post-composting of digestates from anaerobic digestion of paper mill sludge and the organic fraction of municipal wastes. In: Mata-Alvarez, J., Tilche, A., Cecchi, F. (Eds.), Proceedings of the Second International Symposium on Anaerobic Digestion of Solid Wastes, 15th– 18th June, vol. 1. Barcelona, Spain, pp. 258–265.

156. **Prescott, L,M., Harley, J,P.** and **Klein, D,A**. Microbiology, second ed., W.C. Communications Inc., USA, 1993.

157. **Rada, E, C., Franzinelli, A., Taiss, M., Ragazzi, M., Panaitescu, V.** and **Apostol, T**. (2007a). Lower heating value dynamics during municipal solid waste bio-drying. *Environmental Technology,* **28**, 463-469.

158. **Rada, E, C., Ragazzi, M., Panaitescu, V.** and **Apostol, T. (**2005). An example of collaboration for a technology transfer: municipal solid waste biodrying. In: Maragherita di Pula, S. (Ed.), Proceedings Sardinia 2005. Tenth International Waste Management and Landfill Symposium. Cagliari, Itly, 3-7 October, Paper 044.

159. **Rada, E, C., Venturi, M., Ragazzi, M., Apostol, T., Stan, C.** and **Marculescu, C**. (2010). Bio-drying role in changeable scenarios of Romanian MSW management. *Waste Biomass Valor'*, **01**, 271-279.

160. **Rada, E,C., Ragazzi, M. and Badea, A.** (2012). MSW bio-drying: design criteria from a 10 years research, *UPB Scientific Bulletin*, Series D: Mechanical Engineering, **74**, 209–216.

161. **Ragazzi, M.** and **Rada, E, C.** (2012). Multi-step approach for comparing the local air pollution contributions of conventional and innovative MSW thermo-chemical treatments. *Chemosphere* **89**, 694–701.

162. **Ramachandra, T, V.** and **Bachamanda, S.** (2007). Environmental audit of Municipal Solid Waste Management. *Int. J. Environmental Technology and Management*, Vol. **7**, Nos.3/4,369-389.

163. **Ramachandra, T.V**. Management of Municipal Solid Waste, Capital Publishing Company, New Delhi, 2006.

164. **Ramachandra, T.V.** and **Varghese, S.K. (2**003). Exploring possibilities of achieving sustainability in solid waste management, *Indian Journal of Environmental Health*, Vol. **45**, No. 4, pp.255–264.

165. **Ravindranath, N, H.** (1993). Biomass gasification: environmentally sound technology for decentralized power generation, a case study from India, *Biomass and Bioenergy* **4**, 49–60.

166. **Richard, T.L., Hamelers, H, V, M., Veeken, A.** and **Silva, T**. (2002). Moisture Relationships in Composting Processes. *Compost Science & Utilization,* Vol.**10**,(4), 286-302.

167. **Roca-Pérez L, Martínez, C.** and **Marcilla, P**. (2009). Composting rice straw with sewage sludge and compost effects on the soil-plant system. J.Chemosphere, **75**(6):781-787.

168. **Rogoff, M**. (2013). 'Sustainable materials management': a new international solid waste paradign. *Waste Manage. Re*s. **31**, 1187-1189.

169. **Roy, G., Jasmine, S.** and **Stuart, P.R**. (2006). Technical modeling of a batch biodrying reactor for pulp and paper mill sludge. In: 17th CHISA International Congress of Chemical and Process Engineering, Prague, Czech Republic.

170. **Ruth, L, A.** (1998). Energy from municipal solid waste: a comparison with coal combustion technology, *Progress in Energy and Combustion Science* **24**, 545–564.

171. **Schlegel, H.G.** General Microbiology. Stuttgart, New York: Thieme, 1992.

172. **Shah, R.K**. Heat Exchangers in Encyclopedia of Energy Technology and the Environment, A.Bisionand S.G.Bootseds., Wiley, New York, 1994, pp.1651-1670.

173. **Shah, R.K**. Classification of heat exchangers in Heat Exchangers: Thermal-Hydraulic Fundamentals and Design, S.Kakac,A.E. Bergles,and F.Mayinger,eds., Hemisphere Publishing, Wasington, Dc, 1981, pp.9-46.

174. **Shah, R.K**. Compact Heat exchanger Technology and applications in Heat Exchanger Engineering ,Vol.2,Compact Heat Exchangers: Techniques for Size Reduction, E.A. Foumeny and P.J. Heggs.eds., Ellis Horwood, London, 1991a, pp.1-29.

175. **Shah, R.K.** Industrial heat exchangers- functions and types in Industrial Heat Exchangers ,J.M. Buchlin, ed., Lecture Series No.1991-04,von Karman Institute for Fluid Dynamics, Belgium, 1991b.

176. **Shanks (2007).** The intelligent Transfer Station. A Method for the Treatment of Municipal Solid Waste. Shanks Sistema Eco-deco, UK p.6.

177. **Shao, L,M., Xiao H., Yang, N., Fang, J,J., Lu, U, F.** and **Pin-Jing, H.** (2012). Biodrying of municipal solid waste under different ventilation modes: drying efficiency and aqueous pollution. *Waste Management & Research* **30**(12) 1272–1280

178. **Shao, L-M.,Ma, Z-H.,Zhang, H., Zhang, D-Q.** and **He, P-J.** (2010). Bio-drying and size sorting of municipal solid waste with high water content for improving energy recovery.,Waste Management, Volume 30,Pages 1165-1170.

179. **Sharholy., Mufeed, Kafeel, Ahmad., Gauhar, Mahmood** and **Trivedi, R.C**. (2008). "Municipal solid waste management in Indian cities – A review". *Waste Management* **28**, 459–467.

180. **Sharma, S.** and **Shah, K. W**. (2005). "Generation and Disposal of Solid Waste in Hoshangabad". In: Book of Proceedings of the Second International Congress of Chemistry and Environment, Indore, India, pp.749-751.

181. **Shekdar, A.V.** (1999). "Municipal Solid Waste Management –the Indian Perspective, *Journal of Indian Association for Environmental Management* **26**(2), 100-108.

182. **Shekdar, A.V., Krishnaswamy, K.N., Tikekar, V.G.** and **Bhide, A.D.** (1992). "Indian Urban Solid Waste Management Systems –Jaded Systems in need of resource augmentation. *Journal of Waste Management* **12**(4), 379-387.

183. **Shen, Y., Ren, L., Li,G., Chen, T.** and **Guo, R**. (2011). Influence of aeration on CH_4, N_2O and NH_3 emissions during aerobic composting of a chicken manure and high C/N waste mixture. *Waste Management*, **31**, 33-38.

184. **Silusar, N.** and **Armisheva, G**. (2013). Energy resources recovery on municipal solid waste disposal. Sinks a Vital Element of Modern Waste Management, 2nd International Conference of Final sinks.16-18 may2013, Finland.

185. **Skourides, I., Theophilou, C., Loizides, M., Hood, P.** and **Smith, S.R.** (2006). "Optimisation of advanced technology for production of consistent auxiliary fuels from biodegradable municipal waste for industrial purposes". In: Waste 2006 –Sustainable Waste and Resource Management. Stratford-upon-Avon, UK, 19–21September 2006, Paper 2B-14.40.

186. **Slack, R.J., Gronow, J.R.,** and **Voulvoulis, N**. (2005). Household hazardous waste in municipal landfills: contaminants in leachate - Review. *Science of the Total Environment*, vol.**337**, pp.119 – 137.

187. **Somsai , K., Tondee, T.** and **Kerdsuwan , S**. (2016). Effect of air flow on moisture removal of rotator biodrying reactors. Jurnal Teknologi (Sciences and Engineering), **78**, 5-6,57-63.

188. **Somsai, K., Tondee, T., Kerdsuwan, S.,** (2017). Effect of Recirculation on Moisture Removal Efficiency in Combined Hydrolytic- Aerobic Rotary Bio-Drying Process. MATEC Web of conferences, 108,,02007..

189. **Sozen, A., Gulseven, Z.** and **Arcaklioglu E.** (2007). Forecasting based on sectoral energy consumption of GHGS in turkey and mitigation policies. *Energy Policy* **35**(12), 6491-6505.

190. **Staber, W., Flamme, S.** and **Fellner, J**. (2008). Methods for determining the biomass content of waste, *Waste Manage. Res*. **26**, pp.78–87.

191. **Sugni, M., Calcaterra, E.** and **Adani, F**. (2005). Biostabilization – biodrying of municipal solid waste by inverting air-flow. *Bioresource Technology*, **96** (2005) 1331-1337.

192. **Tambone, F., Scalgia, B., Scotti, S.** and **Aadani, F.** (2011). "Effects of biodrying process on municipal solid waste properties". *Bioresource Technology* **102** (2011) 7443-7450.

193. **Tan, S.T., Lee, C.T., Hashim, H., Ho, W.S.** and **Lim, J.S.** (2014). Optimal process network for municipal solid waste management in Iskandar Malaysia. *J.CleanProd*, **71**:48–58.

194. **Tan, S,T., Ho, W,S., Hashim, H., Lee, C,T., Taib, M, R. and Ho, C, S.** (2015). Energy, economic and environmental (3E) analysis of waste-to-energy (WTE) strategies for municipal solid waste (MSW) management in Malaysia. *Energy Conversion and Management*, **102**,111-120.

195. **Tchnobanoglous, G., Theisen, H.** and **Vigil, S.A**. Integrated solid waste management: engineering principles and management issues. Nek York: McGraw-Hill, 1993.

196. **The Japan Institute of Energy**. The Asian Biomass Handbook: a guidebook for biomass production and utilization; 2008.

197. **Themelis, N J.** (2003). An overview of the global waste-to-energy industry. *Waste manage. World* **3**, 40-47.

198. **Themelis, N, J.** and **Kim ,Y,H.** (2002). Material and energy balance in a large-scale aerobic bioconversion cell. *Waste Management & Research*, **20**, 234-242.

199. **Themelis, N.J**. (2003). An overview of the global waste-to-energy industry. *Waste Management World* (July–August), 40–47.

200. **Thipse, S.S., Sheng, C., Booty, M, R., Magee, R,S.** and **Dreizin, E,L**. (2001). Synthetic fuel for imitation of municipal solid waste in experimental studies of waste incineration. *Chemosphere*, **44**, 1071-1077.

201. **Toledo, P.G., Davis, H.T.** and **Scriven, L.E.** (1995). Hyper dispersive Flow Liquid Thin Films in Fractal Porous Media. *Colloids Surf.***104**:73.

202. **Tsai, W,T.** and **Chou, Y,H**. (2006). An overview of renewable energy utilization from municipal solid waste (MSW) incineration in Taiwan, *Renewable & Sustainable Energy Reviews*, **10**, 491–502.

203. **Turan, N.G.** and **Ergun, O.N.** (2008). The effects of aeration modifications on municipal solid waste composting. *Fresenius Environmental Bulletin*, **17**, 778-785.

204. **U.S. Environmental Protection Agency** (2006a). Electricity from Municipal Solid Waste, http:// www.epa.gov/cleanenergy/muni.htm.

205. **UNEP** (1994). Landfill for hazardous industrial wastes: a training manual. Training Report No. 17, UNEP.

206. **United Nations Environment Programme** (1996). International Source Book on Environmentally Sound Technologies for Municipal Solid Waste Management. United Nations Environment Programme,Osaka/Shiga.

207. **USEPA** (2011). Municipal Solid Waste in the United States: 2011 Facts and Figures. United States Environmental Protection Agency, Office for Solid Waste, Washington DC.

208. **Varma, A**. (2006). A technical report on 'Status of Municipal Solid Waste Generation in Kerala and their Characteristics' Suchitwa Mission, Government of Kerala.

209. **Velis, C., Longhurst, P., Drew, G, H., Smith, R.** and **Pollard, S, J, T**. (2009). Biodrying for mechanical-biological treatment of wastes: A review of process science and engineering. *Bioresource Technology*, **10**0, 2747-2761.

210. **Velis, C., Wagland, S., Longhurst, P., Robson, B., Sinfield, K., Wise S.,** and **Pollard, S.** (2013). Solid Recovered Fuel: Materials flow analysis and fuel property development during the mechanical processing of biodried waste, *Environmental Science & Technology*, **47**, 2957- 2965.

211. **Venkatraman, K. and Ashwath, N**. (2009). Phytocapping: Importance of Tree Selection and Soil Thickness. *Water Air Soil Pollut: Focus* **9**:421–430.

212. **Vesilind, P, A**. (1994). The role of water in sludge dewatering. *Water Environment Research,* **66**, 4-11.

213. **Vladimir, K.** and **Tatiana, T.** (2011). Mixed Municipal Waste Management in the Czech Republic from the point of view of the LCA Method".*Int.J.LifeCycleAssess*, Vol.**16**, pp.113-124.

214. **Walkley, A.** and **Black, I, A.** (1934). An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil science*, **37**, 29-38.

215. **Wang, L., Gang, H., Gong, X.** and **Bao, L**. (2009). Emission reductions potential for energy from municipal solid waste incineration in Chongqing. *Renewable Energy*, **34**, 2074–2079.

216. **Weitz, K., Barlaz, M., Ranjitjan, R., Brill, D., Thomeloe, S.** and **Ham, R**., (1999). Life cycle management of municipal solid waste. Int.J LCA **4**,195-201.

217. **Weitz, K,A., Thorneloe, S,A., Nishtala, S,R.** and **Yarkosky, S.** (2002). The impact of municipal solid waste management on greenhouse gas emissions in the United States, *Journal of the Air & Waste Management Association*, **52**,1000–1011.

218. **Wiemer, K. and Kern, M**. 'Mechanical–Biological Treatment of Residual Waste Based on the Dry Stabilate Method'.M.I.C. Baeza-Verlag, Witzenhausen,Germany, 1995.

219. **Williams, R, H.,** and **Larson, E, D.** Advanced gasification-based biomass power generation, in: B.J. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams (Eds.), Renewables for Fuels and Electricity, Island Press, Washington, D.C., 1992, pp. 729–786.

220. **Wilson, D, C**. (2007). Development drivers for waste management, *Waste Management & Research*, **25**, 198–207.

221. **Wimmer, W., Ostad-Ahmad-Ghorabi, H., Pamminger, R.** and **Huber, M.** (2008). "Product innovation through eco design". *Int. J. Sustainable Design*, Vol. **1**, No. 1, pp.75–92.

222. **Wolf, K, H**. Kinetics in bioprocess engineering. Hamburg: Behr.,1991.

223. **Wolkowski, R**. (2003). Nitrogen management considerations for land spreading municipal solid waste compost. *J. Environ. Qual.* **32**, 1844–1850.

224. **Won, Yang., Hyung-sik, Nam.,** and **Sangmin, Choi.(2007)**. "Improvement of operating conditions in waste incinerators using engineering tools". *Waste Management* vol. **27** pp.604–613.

225. **WRAP,** 2011a. New estimates for household food and drink waste in the UK. Banbury, UK: Waste & Resources Action Programme.

226. **WRAP**, (2011b). Recovering Value from MRFs. Waste and Resources Action Programme (WRAP), Banbury, Oxon,UK.

227. **Wright P**. (2002). "Biodrying dairy manure."In:International Symposium on Composting and Utilisation.Colombus,OH,USA,6-8 May 2002,pp.996-1007.

228. **Yasuhara, A., Amano, Y.** and **Shibamoto, T.** (2010). Investigation of the self-heating and spontaneous ignition of refuse-derived fuel (RDF) during storage. *Waste Management*, **30**(7), 1161-1164.

229. **Yin, C.Y.** (2011). "Prediction of higher heating values of biomass from proximate and ultimate analyses''. *Fuel*, **90**: 1128-1132.

230. **Yuan, J., Zhang, D.,Li, Y., Li,J.,Luwo, W.,Zhang, H.,Wang, G., LiG.,**(2018). Effects of the aeration pattern, aeration rate,and turning frequency on municipal solid waste biodrying performance.J Environ Manage, July15, 218, pp416-424.

231. **Zaman, A. U**. (2010). "Comparative study of municipal solid waste treatment technologies using life cycle assessment method", *Int. J. Environ. Sci. Tech*., **7** (2), 225-234, Spring 2010**.**

232. **Zawadzka, A., Krzystek, L.,** and **Ledakowicz, S**. (2010). "Autothermal biodrying of municipal solid waste with high moisture content". *Chemical Papers* **64** (2) 265–268.

233. **Zawadzka, A., Liliana Krzystek,** and **Stanislaw Ledakowicz** (2009). "Autothermal Drying of Organic Fraction of Municipal Solid Waste".'*Environmental Protection Engineering*', Vol.**35**, No.3, pp.123-134.

234. **Zerbock, O** . Urban solid waste management: waste reduction in developing nations, Written for the Requirements of CE 5993 Field Engineering in the Developing World, Michigan Technological University, 2003.

235. **Zhang, B., Dixon, N.** and **El-Hamalawi, A**. (2010). Development and evaluation of a phase relationship for MSW. Proceedings of the ICE-Waste and Resource Management, **163**(2),pp. 67-75.

236. **Zhang, D, Q., He, P, J., Jin, T, F.** and **Shao, L, M**. (2008). Bio-drying of municipal solid waste with high water content by aeration procedures regulation and inoculation. *Bioresource Technology*, **99**, 8796-8802.

237. **Zhang, Dongqing, He , Pinjing_, Shao Liming, Jin Taifeng** and **Han Jingyao** (2008). Biodrying of municipal solid waste with high water

content by combined hydrolytic- aerobic technology. *Journal of Environmental Sciences* **20**, 1534–1540.

238. **Zhang, D-Q., He, P-J.** and **Shao L-M.** (2009). Sorting efficiency and combustion properties of municipal solid waste during bio-drying. *Waste Management*, **29**(11), 2816-2823.

239. **Zhang, H.Y., Gu, J., Wang, G,Q., Hao, L.W.** and **Wu, X.O**. (2014). Influence of aeration modes on aerobic bio-drying of municipal solid waste (MSW). *Advanced Materials Research*, 2014 (1010-1012), 934-938.

240. **Zhang, M., Heaney, D., Henriquez, B., Solberg, E.** and **Bittner, E**. (2006). A four year study on influence of biosolids/ MSW co-compost application in less productive soils in Alberta: nutrient dynamics. *Compost Sci. Util*. **14** (1), 68–80.

241. **Zhang, Y., Li, W.W., Zeng, G.M., Tang,L, Feng, C,L., Huang, D, L.** and **Li, Y,P.** (2009). Novel neural network-based prediction model for quantifying hydroquinone in compost with biosensor measurements. *Environmental Engineering Science*, **26**, 1063-1070.

242. **Zhao, L., Gu, Wei-Mei., He, Pin-Jing.,** and **Shao, Li-Ming**. (2010). Effect of air-flow rate and turning frequency on bio-drying of dewatered sludge. *Water Research*, Vol **44**, issue 20, 6144-6152.

243. **Zhao, W., Huppes, G.** and **Voet, E.** (2011). Eco-efficiency of greenhouse gas emissions mitigation of municipal solid waste management: A case study of Tianjin, China.*Waste managemnt*, **31**(6)pp 1407-1415.

ANNEXURE-I

AIR SUPPLY SYSTEM IN BIODRYING PROCESS

Air Compressor

Storage Tank

Digital Gas Mass Flow Controller

ANNEXURE- II

DIFFERENT STAGES IN CONVERSION OF RAW MSW TO BIODRIED MSW


Waste storage


Waste Proportioning


Waste Mixing


Filling the Biodrying Reactor


Biodried Output

LIST OF PUBLICATIONS BASED ON THIS THESIS

REFEREED JOURNALS

1. Asha P. Tom., Renu Pawels., Ajit Haridas., 2016. Biodrying process: A sustainable technology for treatment of municipal solid waste with high moisture content. Waste Management, 49, 64-72.

2. Asha P. Tom., Ajit Haridas., Renu Pawels., 2016. Biodrying Process Efficiency:- Significance of Reactor Matrix Height. Procedia Technology, 25, 130-137.

3. Renu Pawels, Asha P.Tom, 2013.Assessment of technological options for solid waste treatment in Kerala. International Journal of Scientific and research publications, Volume 3, Issue 8, August 2013, ISSN 2250-3153.

4. Asha P. Tom, Ajit Haridas, Renu Pawels, 2017. Exploration of biodrying process for mixed municipal solid waste management, Journal of Solid Waste Technology and Management (Accepted for publication).

CONFERENCES

International

1. Asha, P. Tom, Ajit Haridas, Renu Pawels. Exploration of biodrying process for mixed municipal solid waste management. Presented in the 32nd International Conference on Solid Waste Technology and Management, March19-22, 2017, Philadelphia, U.S.A.

2. Asha P Tom, Ajit Haridas, Renu Pawels, 2016. Biodrying Process Efficiency:-Significance of Reactor Matrix Height, Global Colloquium in Recent Advancement and Effectual Researches in Engineering, Science and Technology (RAEREST 2016), April 22-24, 2016.

3. Asha, P. Tom, Renu Pawels, Ajit Haridas, 2015. Biodrying process - A sustainable technology for municipal solid waste management. Proceedings of the International Conference on Recent Advances in Civil Engineering, January 2016.

4. Asha, P. Tom, Renu Pawels, Ajit Haridas, 2015. Biodrying process-Assessment of three case studies in Pilot Scale Reactor, Proceedings of the international conference ‘New Horizons in Biotechnology, 2015, November 21-23.

5. Asha P.Tom, Renu Pawels. “Solid Waste treatment Technologies-Challenges and Opportunities of Kerala”, Asian conference on Civil, Material & Environmental Science (ACCMES -142 -2013), Tokyo, Page: 343-351

6. Asha P Tom, Renu Pawels, Ajit Haridas, 2017.Biodrying process variations based on air flow regulation strategy. Proceedings of the international conference Global Waste management, Hyderabad, 1474-1483.

National

1. Asha, P. Tom, Renu Pawels, Ajit Haridas, 2016. Development of Sustainable Solid Waste Management Technology for Kerala. Proceedings of the 28th Kerala Science congress, January 2016, 748-761.

2. Asha, P. Tom, Renu Pawels, 2010. Assessment of Solid Waste Management Technologies. Proceedings of the National Conference on Recent Advances in Civil Engineering, RACE 2010.

ASHA P TOM
Periakottil House,
Vazhakulam P. O
Muvattupuzha,
Ernakulam Dist
Kerala-686670
Ph: 04852260624
Mob: 9744910087
ashaptom@gmail.com

Civil Engineer with 10 years of experience in research project, teaching, design and construction field.

Personal

Name : Asha P Tom
Date of Birth : 02-05-1981
Sex : Female
Father : P.A.Thomman
Permanent Address : Periakottil house,
Vazhakulam P.O.,
Muvattupuzha,
Ernakulam Dist., Kerala-686670

Experience

1. **KSCSTE Project co-investigator at a joint project of CSIR, NIIST and Cochin University of Science and Technology**

   Duration : May 2013- Dec31 2016

   Post Held : Research scholar and Co-investigator in Kerala State Council for Science, Technology and Environment (KSCSTE) funded project

2. **Holy Kings College of Engineering & Technology, Muvattupuzha.**

   Duration : From September 2011- April 2013

   Post Held : Associate Professor in Civil Engineering

   Subjects handled : Engineering Mechanics
   Surveying, Basic Civil Engineering.

3. **Ilahia College of Engineering & Technology, Muvattupuzha.**

Duration : From December 2009- August2011

Post Held : Lecturer in Civil Engineering

Subjects handled : Engineering Mechanics
Environmental Impact Assessment, Environmental Engineering (Theory and Practical), Surveying.

4. **Lecturer in Civil Engineering**

Institution: SCMS School of Engineering, Angamaly.

Duration : From October 2008- September 2009

Post Held : Lecturer in Civil Engineering

Subjects handled : Surveying-I, Survey Lab, Civil Engineering Drawing, EIA studies, Environmental Engineering (Theory& Practical).

5. **Larsen and Toubro Constructions, Chennai, Tamil Nadu**

Duration : From December 2006- April 2008

Post Held : Senior Design Engineer

Nature of Work : Design of Water Supply/Treatment plant systems.

Duties : Design of Pipelines and Pump houses, treatment plant Components, Surge analysis, Route selection and alignment of Pipelines-Both for tendering as well as execution.

6. **Sobha Developers Pvt.Ltd. Bangalore**

Duration : From November 2003-November2004

Post Held : Site Engineer

Nature of work : Project Quantity Surveyor

Duties : Estimation, Costing, Billing, site office management, material handling.

Education

PhD (Pursuing)

M.Tech (Environmental Engineering) from College of Engineering, Trivandrum, Kerala University with 8.75 CGPA (2004-2006)

B.Tech Civil Engineering from M.A.College of Engineering M.G.University with 80.4 % aggregate (1999-2003)

Software Knowledge

Primavera-6, GIS, Auto CAD.