EVALUATION AND PREDICTION OF ENERGY POTENTIAL OF LANDFILL MINED SOLID WASTE

by

RAKIB AHMED

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT ARLINGTON

July 2019

Acknowledgements

I would like to give a very big thanks and gratitude to my supervisor ‘’Dr Hossain’’ For his continuous support, outstanding guidance and inspiring life lessons. Without being his mentee, it would be never be possible to accomplish anything in my graduate life. I am also grateful to Dr. Sattler, Dr. Yu, and Brenda Haney for their valuable time among their busy schedules to be on my committee. I can’t express how I am thankful to all SWIS members for their unconditional support and help. My silent acknowledgements go to my parents who taught me to look into the world in a very simple way. I am grateful to my witty friends for the moment of laugh although my graduate life. Special thanks to my beloved wife Dr Shayla Haque Mishu for her endless moral support and motivation to achieve my goal.

July 15, 2019

Abstract

EVALUATION AND PREDICTION OF ENERGY POTENTIAL OF LANDFILL
MINED SOLID WASTE

Rakib Ahmed

The University of Texas at Arlington, 2019

Supervising Professor: MD. Sahadat Hossain

Landfilling is the most popular waste disposal system worldwide; however, with increasing scarcity of materials, increases in land values, and the presence of non-engineered landfill sites in both the developing and developed world, landfill mining has been the recipient of special interest in today's waste management practices. Therefore, the motivation of the current study was to evaluate the energy potential of mined landfill waste and develop a statistically significant mathematical model to predict its energy potential (calorific value). The current study was conducted by using the municipal solid waste (MSW) samples collected from the City of Denton landfill and the City of Irving landfill Texas. Mined waste was collected from conventional cell (cell 0) and ELR operated cell (cell 2) from City of Denton Landfill, and the calorific value of the collected MSW was investigated, using an oxygen bomb calorimeter. The fine/degraded fraction made up 48% of the mined waste at the City of Denton landfill. The average calorific value of mined waste was found to be 3586.97 Btu/lb. The calorific value was also determined for fresh MSW collected from the working phase of the landfill. Based on the results, 52% of the energy value is still available in the mined waste compared with the energy potential of fresh waste. Different parameters, such as depth, landfill operation, moisture content, volatile solid, age of waste, precipitation, and fine fraction were analyzed to understand the behavior of mined solid waste. It was observed that the fine fraction had a decreasing trend, and the volatile solid had an increasing trend with the increase of calorific value. Moisture content and depth of the landfill did not exhibit any significant correlation with the calorific value. Based on the degradation nature of the solid waste components, a universal energy index, based on the composition of the waste, was introduced and found to be a very good predictor the for calorific value of MSW. Proximate analysis (Volatile solid determination) and elemental analysis 2343 determined by a muffle furnace and an elemental analyzer, respectively. Carbon was found to be the most significant element for energy value.

Three simple linear regression (SLR) models, based on three different analyses (physical composition, proximate analysis, and elemental analysis), were developed to predict calorific value, using the statistical tool R. The physical model, which used the energy index, was validated with mined solid waste collected from the City of Irving landfill, and showed excellent agreement between the predicted calorific value and the measured calorific value of the MSW collected from the landfills. The model-based elemental analysis was in good agreement with the experimental values found in literature. Overall, this study will enhance the understanding of the physical characteristics and energy potential of landfill mined waste and will provide two universal mathematical models for better predictions of calorific value from any waste composition.

Table of Content

List of Figures

List of Tables

1 Chapter: Introduction

1.1 Background

The United States Environmental Protection Agency (EPA) has four waste management components, which are listed in order of preference: Source reduction, recycling, combustion with energy recovery, and disposal through landfilling in the waste management hierarchy. One of the approaches, however, may not be suitable for managing universal waste management problems around the world. In 2015, about 262 million tons of municipal solid waste (MSW) were generated in the US, among which 52.5% was sent to landfills, 34.7% was recycled, and 12.8% was combusted for energy recovery Landfills have long been considered the most economical waste management system, (Krook et al., 2012), but at present, the global increased competition for raw materials, which has destroyed natural reservoirs with valuable resources and increased environmental problems, is making the concept of material extraction from alternative sources a practical option (Kapur, 2006; Halada, 2009; and Krook et al., 2012). Finding suitable and available space is another major challenge for landfill operations, especially in densely populated urban areas (Zhao et al., 2007). Such issues change the current applicability of landfills as a final destination for waste, and make it important to form new perspectives of landfills. Therefore, landfill mining for material recovery and as a resource for energy provide a sustainable solution. Krook et al. (2012) defined landfill mining as "*a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground.*"

Although most of the mining research has been confined to conceptual discussions and pilot-scale studies of landfill mining projects, a limited number of studies have been conducted on the composition of excavated waste. Energy potential has been determined as a part of the chemical characteristics, along with waste composition in some studies. The experimental energy values, measured by an oxygen bomb calorimeter, were reported in previous studies: 1461.74-3740.33 Btu/lb., Italy, (Cossu et al.,1995); 2966.47-3396.39 Btu/lb., Fiborna Landfill, Sweden, (Hogland et al.,2003); 2579.54-5588.99 Btu/lb., Germany, (Brammer et al., 1995); 3084 Btu/lb., and Pennsylvania landfill, USA (Forster G,1995). Kaartinen et al. (2013) found the valorization potential of 40-45% (weight basis) by hand sorting, and approximately 30% (weight basis) by the mechanical sorting process. Quaghebeur et al. (2012) found the energy potential to be 23-50% (w/w) in the REMO landfill, in Belgium. Mined waste was used as part of a mixture of fuel and fresh waste in incinerators (Forster, 1994; Salerni, 1997). Salerni (1997) used a 50/50 mixture of mined waste and fresh waste, whereas Forster (1994) used a mixture of 1:4. Hence, different landfill sites have different valorization/energy potentials from both the perspectives of landfill mining potential and end use. Different factors, such as the landfill age, type of operation, weather and hydrological conditions, and the location of the landfill might affect the degradation and energy potential of stored waste inside the landfill (Prechthai et al., 2008).

In addition to the oxygen bomb calorimeter method, two other methods, elemental analysis and proximate analysis, were also used to assess the energy potential of mined solid waste. These methods addressed the important factors of energy potential, such as moisture content and volatile and fixed carbons (Shi et al., 2015). Carbon was found to be a major contributor of calorific value (Komillis et al., 2011).

The process of measuring the energy potential of MSW, followed by developing a prediction model, has been carried out, using fresh waste in different countries in the world like Malaysia (Kathirvale et al., 2003), Canada (Shi et al., 2015), Greece (Komilis et al., 2011), and Taiwan (Liu et al., 1996). The composition and heating value of fresh municipal solid waste was determined comprehensively in New York . (Chin and Franconeri, 1980). A high portion of the waste in the Rio Grande Valley in Texas is plastic and paper, which is a potential source of energy (Chang and Davilla, 2007). A prediction model based on the physical composition of fresh waste was developed for the Lower Rio Grande Valley.

1.2 Problem Statement

The energy potential of fresh municipal solid waste is important for waste-to-energy facilities, as it appears to be one of the important parameters in the design of incinerators (Shi et al., 2015). Due to the heterogeneity of solid waste, along with the climatic conditions and types of operation, MSW in closed landfills may not experience equal degradation levels (Hull et al., 2005). The number of active landfills decreased significantly in the early 1990’s due to the amendment of the Subtitle D landfill regulations of the Resource Conservation and Recovery Act (RCRA, 1991). Hence the closed landfills could become a potential source for energy that could be extracted through landfill mining.

Energy recovery from landfill mined waste, airspace recovery, and recycling from non-degraded waste are the three drivers for landfill mining; however, high-level contamination makes it difficult to use materials that are recycled from excavated waste (Hull et al., 2005; Quaghebeur et al., 2012). The energy potential depends on the age of the waste, type of landfill, meteorological conditions, environmental conditions (temperature and moisture content), and the degree of degradation that takes place over time inside the landfill (volatile solids) (Hull et al., 2005). The energy potential from mined waste was measured in landfills in Pennsylvania (Forster, 1995) and New Jersey (Hull et al., 2005). Hull et al. (2005) determined the energy potential of excavated waste, using a mathematical formula rather than the experimental method (calorimeter). Texas has more than 4000 closed landfills, according to the Texas Commission on Environmental Quality (TCEQ); therefore, a comprehensive study on a Texas landfill was deemed necessary to evaluate the energy potential for both fresh and mined landfill waste.

The waste composition of excavated material is the most studied work in landfill mining (Kaartinen et al., 2013, Cossu et al., 1995; Hogland et al., 2003; Hull et al., 2005; Quaghebeur et al., 2012). Due to heterogeneity of waste, an exploration or trend of energy from solid waste is still unexplored in the literature, hence a detailed and depth-wise study of waste composition from different boreholes, along with numerous physical and chemical characteristics, needs to be performed.

The calorific value (energy potential) of solid waste is measured accurately by using a calorimeter. Due to the complexity of the equipment and the need for skilled technicians (Kathirvale et al., 2003), proximate analysis is used widely as an alternative method for assessing the energy potential. However, it does not promise to always provide the correct calorific value (energy value) (Ozyuguran and Yaman, 2016); instead, it explains the quality of the overall combustion process (Avelar et al., 2016).

To overcome this problem, elemental analysis has been used to assess the energy potential of solid waste with greater accuracy, even though the widely used experimental elemental analysis values are not contemporary (Komillis et. al., 2011). Therefore, a comprehensive elemental analysis of mined waste was deemed necessary to evaluate the energy potential with greater accuracy.

Very few statistical analyses are performed on landfill-mined data. The most common prediction model for the calorific value currently being used was developed by Dulong (Kathiravale et al., 2003), but the model used data from coal, and may not predict municipal solid waste accurately (Shi et. al., 2015) because the prediction of energy potential of MSW is best suited in its own area (Kathirvale et al., 2003). Therefore, it is important to investigate comprehensive analyses of energy potential of landfill mined waste by different analytical methods, and develop a statistically sound prediction model to predict the energy potential of mined waste.

1.3 Objective of the study

The main objective of this research is to evaluate the energy potential of mined MSW from landfill. As a part of the study, different predictive model to evaluate the energy potential of mined MSW will also be developed. The specific tasks of the current study are outlined as:

1. To determine Waste composition and Physical Characteristics of fresh waste and mined waste
2. To evaluate of Energy Value of Municipal Solid waste by Oxygen Bomb Calorimeter
3. To evaluate of Thermochemical characteristics of mined solid waste by proximate analysis

4. To assess the elemental composition of Mined waste by Elemental Analysis
5. To develop mathematical model to predict energy potential of Mined solid waste.

1.4 Dissertation Framework

This dissertation is folded into six chapters as summarized below:

- Chapter 1 provides an introduction and indicates the problem statement and objectives of the study.
- Chapter 2 presents a literature review on physical & chemical characteristics of fresh & mined municipal solid waste, energy value of fresh & mined solid waste, elemental composition of solid waste and predictive empirical model of energy value.
- Chapter 3 describes the detail experimental procedures followed to collect and sort MSW samples, to measure energy value, elemental composition from the fresh and mined waste
- Chapter 4 presents the experimental results followed by the discussion on the results, and comparison of the results with existing literature.
- Chapter 5 presents three statistical modeling using simple linear regression analysis based on the physical composition, proximate & elemental analysis

- Chapter 6 summarizes the main conclusions from the current study and provides recommendations for future work.

2 Chapter: Literature Review

2.1 Landfill

A landfill is an engineering method of final disposal of waste into land that has layers of soil and waste. Krook et al., (2012) defined a landfill as a large area of land or an excavated site that was designed to receive wastes. Landfilling has been the common way to store waste at minimum cost in many regions of the world, including the United States. According to Danthurebandara (2015), a modern landfill is an engineered method for waste disposal into protected or specially constructed land surfaces, or in excavations into a land surface. The landfill location, design, operation, and monitoring are designed to ensure compliance with federal regulations (USEPA). Although the recycling rate of waste has increased significantly during past decades in United States, landfilling is still the most popular and most practiced waste management method. The US Air Quality Bureau (2010) defined a closed landfill as a landfill that stopped accepting municipal solid waste. At present, there are 97 Type 1 municipal solid waste landfills in Texas (TCEQ Report, 2018).

2.1.1 Classification of Landfill

According to the US Environmental Protection Agency (EPA), a modern landfill is a well-engineered facility that is designed for receiving specific types of wastes: municipal solid waste (MSW), construction and demolition debris (C&D), and hazardous waste. The landfills are classified according to the regulation principal of the Resource Conservation and Recovery Act (40 CFR Part 258 in Federal regulations 1991). Subtitle D landfills include the following.

- **Municipal solid waste landfills (MSWLFs)** that are specifically designed to receive household waste, as well as other types of nonhazardous wastes;
- **Bioreactor landfills** that are a type of MSWLF that operates to rapidly transform and degrade organic waste;
- **Industrial waste landfills** that are designed to collect commercial and institutional (i.e., industrial) waste, which is often a significant portion of solid waste, even in small cities and suburbs;
- **Construction and demolition (C&D)** debris landfills that are a type of industrial waste landfills that is designed exclusively for construction and demolition materials, which consist of the debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. C&D materials often contain bulky, heavy, materials, such as concrete, wood, metals, glass, and salvaged building components.
- **Coal combustion residual (CCR) landfills** that are industrial waste landfills that are used to manage and dispose of coal combustion residuals (CCRs or coal ash);

- **Hazardous waste landfills** that are used specifically for the disposal of hazardous waste. These landfills are not used for the disposal of solid waste.

2.2 Landfill mining

In most of the world, landfills have long been seen as the cheapest way to dispose of waste permanently (Krook et al., 2012). This dependence on landfilling has created a chain of long-term economic, social, and environmental impacts. Apart from material and energy wastage, landfill deposits generate methane emissions that are due to organic degradation (Mor et al., 2006; Sormunen et al., 2008) and contribute to local pollution, due to leaching of hazardous substances if not properly contained (Flyhammar, 1997). The lack of space is another constraint for landfill operations, especially in densely populated areas (Zhao et al., 2007). Over the years, most regions have accumulated a huge number of closed landfills that contain significant amounts of old materials, some of which are valuable (Lifset et al., 2002; Zhao et al., 2007). Present worldwide situations, such as rapidly increasing competition for materials, prices, depletion of valuable natural resources, and increasing environmental problems make resource recovery from different sources a pragmatic option (Kapur, 2006; Halada, 2009, Krook et al., 2012). Such possibilities challenge the practice of landfilling as a permanent destination for waste, and demand a new perspective. Landfill mining is primarily defined as a valuable material extraction and energy resource recovery strategy

(Krook et al., 2012). Cossu et al. (1996) defined it as "*the excavation and treatment of waste from an active or inactive landfill for one or more of the following purposes: conservation of landfill space, reduction in landfill area, elimination of a potential contamination source, mitigation of an existing contamination source, energy recovery from excavated waste, reuse of recovered materials, reduction in waste management system costs and site re-development.*" Krook et al. (2012) defined landfill mining as "*a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground."*

2.2.1 History of Landfill Mining

Savage et al. (1993) reported that landfill mining started in Tel Aviv, Israel in 1953 to explore ways to make fertilizer for orchards. It remained as the only reported landfill mining project for several decades (Krook et al., 2012). The US considered further mining projects as a strategy for regaining the airspace, due to the imminent concern of a shortage of landfill space (Kruse, 2015). The landfill project started in Naples, Florida (1986-1992) and Edinburgh, New York (1988), with both of the projects aimed at avoiding and reducing landfill closure costs (US-EPA, 1997). The project in Naples included a wide range of resource recovery strategies, along with the traditional concepts of landfill mining (Kruse, 2015):

- recover and reuse fine degraded material as a landfill daily cover,
- use excavated combustible waste in the waste-to-energy facility, and
- recover recyclable materials like metal and glass.

However, the project was only able to recover the cover materials, and the excavated material failed to qualify as a fuel for a waste-to-energy facility.

The first European pilot project of landfill mining was conducted in Germany in 1993 (Rettenberger et al., 1995) for the purpose of evaluating the technical and economic feasibility of such a project. Numerous mining projects started right after the pilot project, even though the purpose was to prevent hazard materials (Hölzle, 2010).

In 1994, Italy (Sardinia) and Sweden (Filbona) had their first landfill mining projects. The motive of the projects was to regain airspace for growing cities and prevent risks that occurred in the landfills. (Cossu et al., 1996) Despite numerous pilot projects around the world, mining projects did not gain popularity as commercial projects on a large scale until recently.

Many pilot applications have been reported in the literature, but full-scale projects are fewer, as the environmental legislation for them tends to be stricter, (Gaitanarou et al., 2014). The pilot projects are located mainly in Germany (Hogland 2002), the Netherlands (Van der Zee et al. 2004), and Finland (Kaartinen et al. 2013). Some pilot-scale projects in the United Kingdom (Hayward-Higham 2008) did not prosper, and were finally abandoned (Gaitanarou et al., 2014). Little information is available on the landfill mining projects. Numerous studies and LFM projects have been carried out worldwide, mainly in Asia. Most of them are located in India (Joseph et al. 2007; Hogland et al. 2004) and China (Zhao et al. 2007; Lou et al. 2009 cited in Gaitanarou et al., 2014), as their vast population has created issues related to landfilling (Gaitanarou et al., 2014). Landfill mining projects were implemented at the Non Khaem Landfill in Bangkok, Thailand, and at the Nanjido Landfill in Seoul, Korea (Strange 2008).

There are several reasons for adopting LFM, but nearly every project was motivated by the need to prevent pollution & hazardous conditions. Resource extraction from mined projects was a rare motivation in the past; however, it has become an important attraction recently (Kruse, 2015). Relocation of excavated waste without exploring resource recovery is prohibited in Germany by a law passed in 2015.

A public support scheme in Bavaria, Germany explored the exploration of closed landfills and stored material. These policies and incentives expedited the interest in landfill mining activities in 2007 and 2008 (Bockreis and Knapp, 2011).

The following are some of the reasons for adopting LFM (Reno Sam, 2009):

- Life extension of a landfill by increasing the storage capacity,
- Reduction of the source of contamination and pollution,
- Prevention of pollution and mitigation of existing sources of contamination,

- Recovery of resources by recycling and energy
- Reduction of landfill closure cost
- Redevelopment of the existing site.

LFM has been revolutionized to the point where resource recovery is the primary goal of mining, and has been redefined as enhanced landfill mining (ELFM). According to Jones et al., (2013), "*In our novel ELFM vision, the goal is not to stabilise the materials but rather to valorize the various waste streams either as material or as energy*." ELFM has gained popularity in Flanders, Belgium, where research and pilot studies led to a series of publications (Geysen et al., 2009; Jones et al. 2012; Bosmans et al., 2013; Quaghebeur, et al., 2013; Van Passel et al., 2013).

2.2.2 Landfill Mining Initiative in USA

In the US, the interest in landfill mining increased suddenly during the 1990's, due to stricter environmental regulations, which put the active landfills in a tough situation. If they closed down, they had to comply with the regulations on final close/post closure and long-term monitoring of pollutants (Spencer, 1990; Richard et al., 1996a; 1996b). Landfilling was still the most popular and economic waste disposal system in the country, but the strict environmental requirements and public opposition made it more difficult to develop a new landfill. The excavation of landfills, along with the recovery of excavated waste, was identified as an effective strategy for solving the scarcity of landfill airspace. Eventually, the requirements and costs of post-closure were postponed for landfills that were almost at capacity (Dickinson, 1995; Reeves and Murray, 1997). Moreover, there was a potential source of additional revenue from recovered material.

The scenario was similar in Europe and Asia, as those regions had an urgent need for landfill airspace due to rapid urbanization, and the old landfills were hampering the urban city development. Therefore, the overall interest in landfill mining was growing at that time (Cossu et al., 1996; Hogland et al., 1996).

Around the beginning of the new millennium (2000), research on landfill mining suddenly decreased, and only erratic efforts were reported in scientific literature. This could have been the reason for the economic recession. The world realized that there were more sophisticated waste treatment options and highly effective recycling programs, and the advancement of these options diverted some of the attention from landfill mining. One of the findings from the 1990's landfill mining projects affected the whole mining movement, however. The excavated waste did not contain high quality and uncontaminated recyclable materials for the recycle market (Savage et al., 1993; Krogmann and Qu, 1997), which eventually prevented landfills from regaining lost ground, and reinitiated the need for final closure. The inability to sell the excavated materials caused new waste management problems in terms of revenue. Hull et al. (2005) argued that landfill mining is only economically viable under certain conditions: as an alternative option for remediation, preferably co-financed with clean-up funds; for removal of deposits hampering urban development; for extraction of supplementary waste fuel in order to secure full working loads at waste incinerators; or for creating new landfill space by using existing sites and infrastructures, thereby also facilitating the permitting process (Krook et al., 2012).

2.3 Physical Characteristics of Landfill mined waste

According to the US EPA, municipal solid waste (MSW) is collected by community sanitation services. It is denoted as trash or garbage, which is discarded every day after use, such as, food residuals, clothing, newspapers, bottles, paint, product packaging, furniture, appliances, grass clippings, and batteries generated from households, institutions like schools, hospitals, and businesses. The MSW can be waste components of different categories, including paper products, glass, metal, plastics, rubber and leather, textiles, wood, food wastes, yard trimmings, and miscellaneous inorganic wastes (Alam. Z., 2016). Municipal solid waste which was disposed of earlier is defined as landfilled waste. The characteristics of landfilled wastes depend on the location, community, type of landfill, depth of filling, age of waste, moisture content, etc. Many studies have been conducted to determine the waste characteristics of MSW because it is difficult to determine them, due to the following reasons given by Samir (2011) and Manassero et.al (1997).

- It is difficult to obtain a representative sample of a large quantity in the in-situ condition.
- There is no manual that provides guidelines for sampling procedures of waste materials.
- The properties of waste materials fluctuate because of their heterogeneity.
- The training program and education of the landfill operating officials may not be adequate for dealing with crucial situations scientifically.
- Solid waste is heterogeneous by nature, and varies significantly in different geographical locations.

2.3.1 Mined Waste Composition

The physical composition of solid waste determines (on a weight basis) the types and percentages of the waste components present in the total waste stream. A waste composition study is the single most important tool for a waste management operation, and the various procedures that can be used to determine the waste composition are listed below.

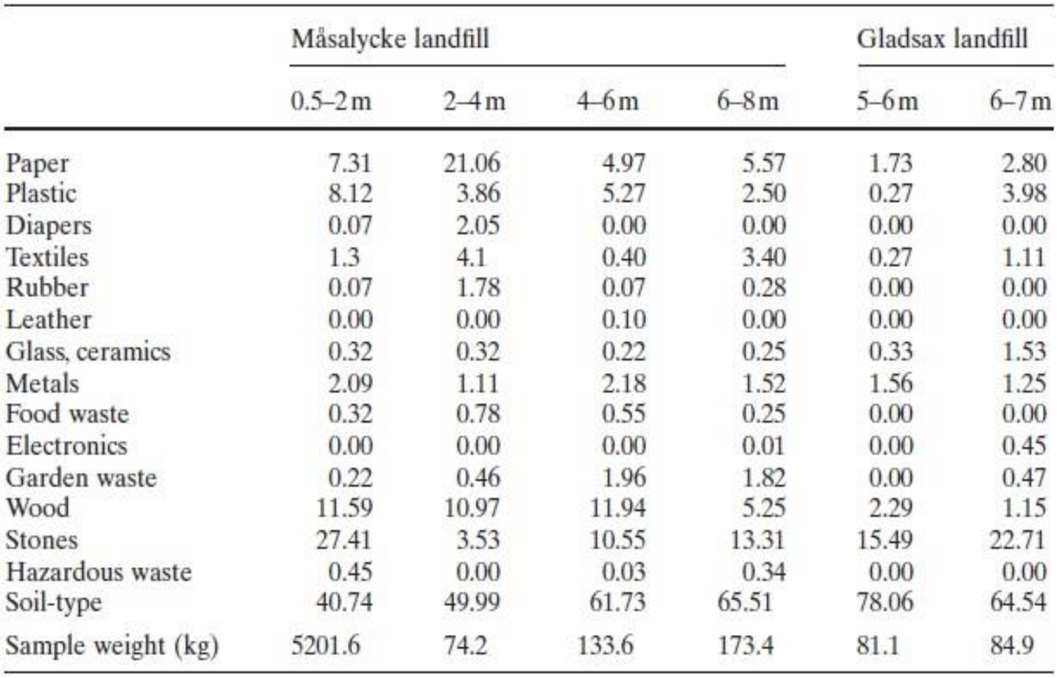
- **Input Method** - The physical composition can be estimated by using the published national level data.
- **Hand Sorting**
- **Photogrammetry Method** - The waste composition is determined by analyzing a photograph of the representative portion.

Mined waste compositions have been reported in literature around the world. Some of them are summarized below.

Hogland et al. (2004) determined the physical and chemical properties of excavated waste in Sweden. The age of the excavated waste was 17-22 years and 23-25 years, respectively. The composition was determined at four different depths in the Masalycke landfill and two depths in the Gladsax landfill (Table 2-1).

Gomes et al. (2005) conducted a study to characterize the buried waste in the San Tirso landfill in Portugal. Three different sections were selected for evaluating three different ages. Section A was still in operation, but Sections B and C were closed. The excavated waste from Section C was from an old dumpsite. The waste of Section B was disposed of between 1998 and 1999.

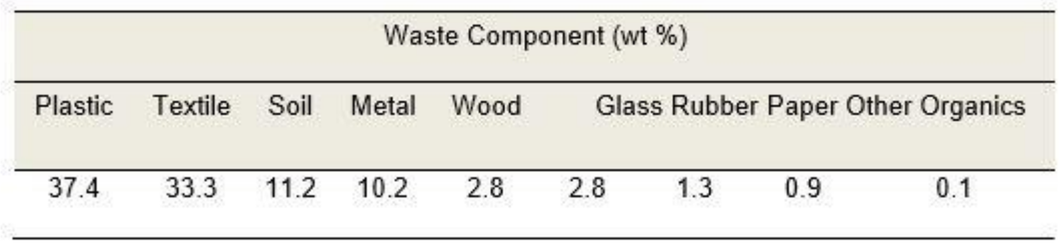
Table 2-1 Weight composition (%) of unsorted waste excavated from different depths (Hogland et al., 2004)



	Måsalycke landfill				Gladsax landfill	
	0.5–2 m	2–4 m	4–6 m	6–8 m	5–6 m	6–7 m
Paper	7.31	21.06	4.97	5.57	1.73	2.80
Plastic	8.12	3.86	5.27	2.50	0.27	3.98
Diapers	0.07	2.05	0.00	0.00	0.00	0.00
Textiles	1.3	4.1	0.40	3.40	0.27	1.11
Rubber	0.07	1.78	0.07	0.28	0.00	0.00
Leather	0.00	0.00	0.10	0.00	0.00	0.00
Glass, ceramics	0.32	0.32	0.22	0.25	0.33	1.53
Metals	2.09	1.11	2.18	1.52	1.56	1.25
Food waste	0.32	0.78	0.55	0.25	0.00	0.00
Electronics	0.00	0.00	0.00	0.01	0.00	0.45
Garden waste	0.22	0.46	1.96	1.82	0.00	0.47
Wood	11.59	10.97	11.94	5.25	2.29	1.15
Stones	27.41	3.53	10.55	13.31	15.49	22.71
Hazardous waste	0.45	0.00	0.03	0.34	0.00	0.00
Soil-type	40.74	49.99	61.73	65.51	78.06	64.54
Sample weight (kg)	5201.6	74.2	133.6	173.4	81.1	84.9

Physical and chemical characteristics of the excavated waste were determined, including classification of wastes, determination volumetric weight, moisture content and organic content. The strength parameter (shear strength) and compressibility characteristics were also determined. The field monitoring program included determination of the displacement, deformation, porewater pressure, and horizontal pressure. Table 2.2 indicates the mined waste composition of profile B (closed zone) collected from 1998-1999.

Table 2-2 Waste component from San Tirso landfill, Portugal (Gomes et al., 2005)



Waste Component (wt %)								
Plastic	Textile	Soil	Metal	Wood	Glass	Rubber	Paper	Other Organics
37.4	33.3	11.2	10.2	2.8	2.8	1.3	0.9	0.1

Gabr and Valero (1994) determined the geo-environmental properties of two different landfills. The excavated waste from both of the landfills was about fifty years old. The samples were collected, using an auger rig and fresh samples were collected from the surface. Table 2.3 shows the composition of the both type of waste.

Table 2-3 Composition between fresh and mined waste (Gabr and Valero, 1994)

	Percentage of total weight (Dry Basis)	
Category	Fresh Waste	Aged Waste
Paper	29	0
Plastic	7	13
Food Waste	23	0
Wood	10	9
Textiles	5	23
Metal	1	10
Glass and Ceramic	8	10
Ash	17	19
Miscellaneous	0	14

Suthatip et al. (2006) evaluated the biodegradability of food, wood, and paper, as well as the excavated MSW samples that were approximately 20 years old. The physical composition of the excavated waste is presented in Figure 2.1.

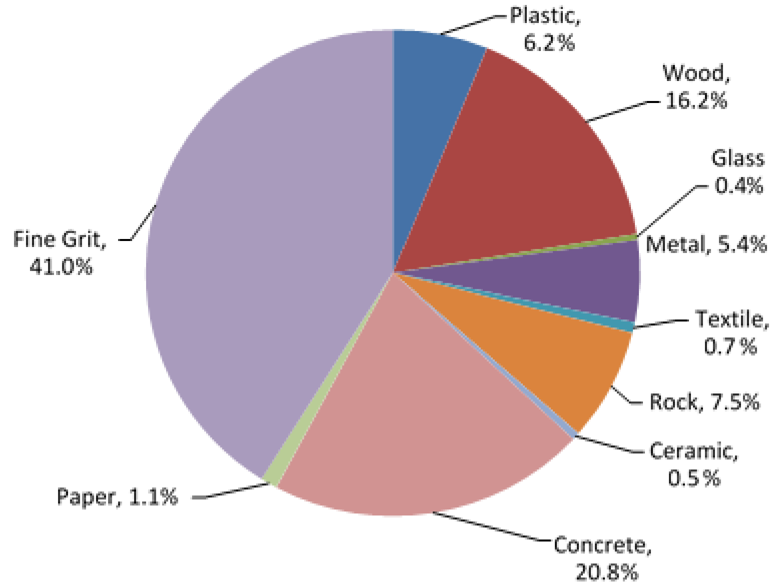
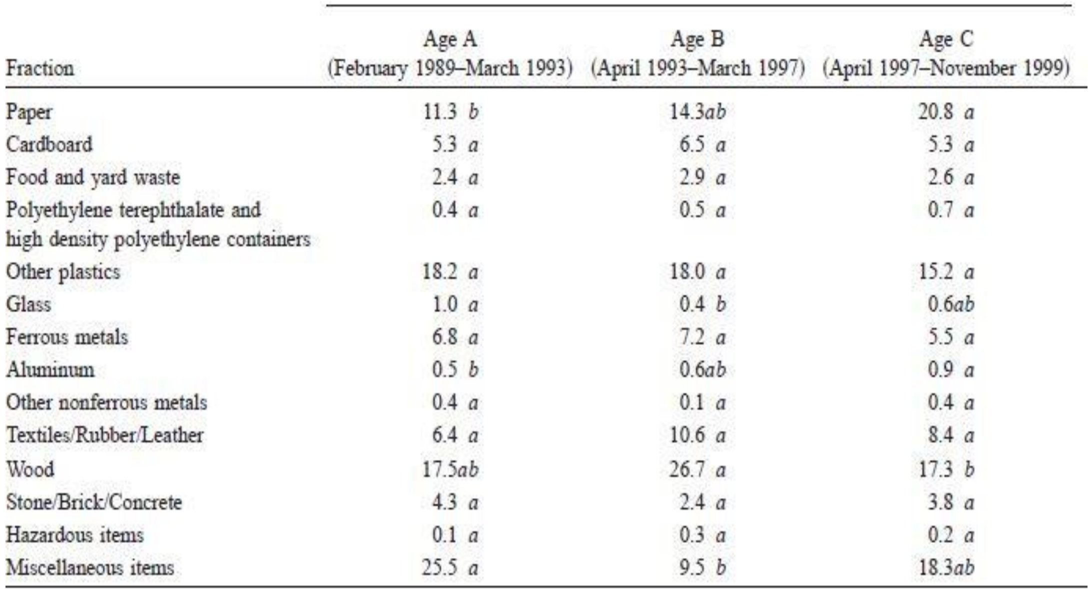


Figure 2-1 Excavated waste composition from a Japanese landfill (Suthatip et al., 2006)

Hull et al., (2005) conducted a thorough research on waste composition and characteristics of mined materials recovered from a New Jersey landfill that was operated from 1989-1999. The mean composition of the materials is shown in Table 2.4.

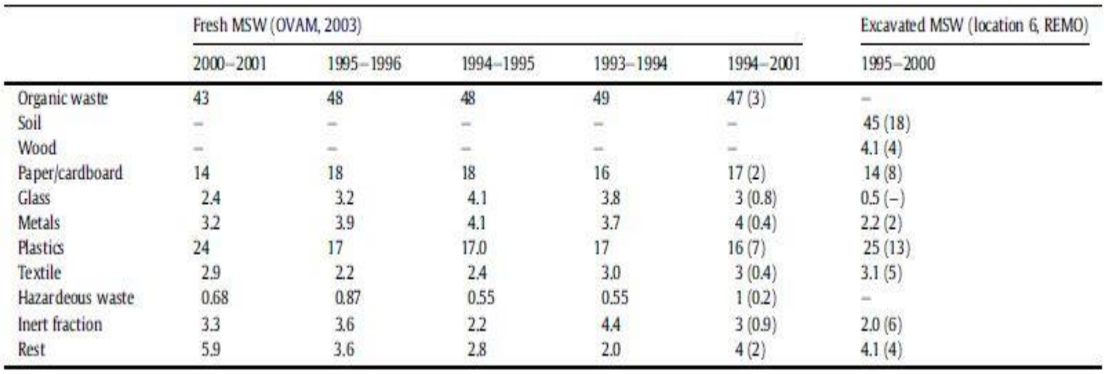
Table 2-4 Mined waste composition from a New Jersey landfill, USA (Hull et al., 2005)



Fraction	Age A (February 1989–March 1993)	Age B (April 1993–March 1997)	Age C (April 1997–November 1999)
Paper	11.3 *b*	14.3*ab*	20.8 *a*
Cardboard	5.3 *a*	6.5 *a*	5.3 *a*
Food and yard waste	2.4 *a*	2.9 *a*	2.6 *a*
Polyethylene terephthalate and high density polyethylene containers	0.4 *a*	0.5 *a*	0.7 *a*
Other plastics	18.2 *a*	18.0 *a*	15.2 *a*
Glass	1.0 *a*	0.4 *b*	0.6*ab*
Ferrous metals	6.8 *a*	7.2 *a*	5.5 *a*
Aluminum	0.5 *b*	0.6*ab*	0.9 *a*
Other nonferrous metals	0.4 *a*	0.1 *a*	0.4 *a*
Textiles/Rubber/Leather	6.4 *a*	10.6 *a*	8.4 *a*
Wood	17.5*ab*	26.7 *a*	17.3 *b*
Stone/Brick/Concrete	4.3 *a*	2.4 *a*	3.8 *a*
Hazardous items	0.1 *a*	0.3 *a*	0.2 *a*
Miscellaneous items	25.5 *a*	9.5 *b*	18.3*ab*

Quaghebeur et al., (2012) evaluated the valorization potential of excavated waste from the REMO landfill in Belgium. The waste was deposited from 1980-2000. Table 2-5 indicates the mean composition of the fresh waste collected from the Flemish region of Belgium (1993-2001) and excavated waste of the REMO landfill. No trend was observed in the waste composition with increasing depths of the landfills

Table 2-5 Mean composition of fresh waste collected from flemish region of Belgium (1993-2001) (Quaghebeur et al., 2012)



	Fresh MSW (OVAM, 2003)					Excavated MSW (location 6, REMO)
	2000–2001	1995–1996	1994–1995	1993–1994	1994–2001	1995–2000
Organic waste	43	48	48	49	47 (3)	–
Soil	–	–	–	–	–	45 (18)
Wood	–	–	–	–	–	4.1 (4)
Paper/cardboard	14	18	18	16	17 (2)	14 (8)
Glass	2.4	3.2	4.1	3.8	3 (0.8)	0.5 (–)
Metals	3.2	3.9	4.1	3.7	4 (0.4)	2.2 (2)
Plastics	24	17	17.0	17	16 (7)	25 (13)
Textile	2.9	2.2	2.4	3.0	3 (0.4)	3.1 (5)
Hazardeous waste	0.68	0.87	0.55	0.55	1 (0.2)	–
Inert fraction	3.3	3.6	2.2	4.4	3 (0.9)	2.0 (6)
Rest	5.9	3.6	2.8	2.0	4 (2)	4.1 (4)

Quaghebeur et al., (2012) also compared the mined waste composition with other landfill mining studies shown in Table 2-6

Table 2-6 Comparison of mined waste composition from different landfills (Quaghebeur et al., 2012)

Country (age) Reference Number of samples (N)	Thailand (3–5 years old) Prechthai et al. (2008)	Sweden (17–25 year old) Hogland et al. (2004)	Belgium (14–29 years old) This study
	12	6	23
Glass	6.5	0.5 (1)	1.3 (0.8)
Inert fraction (stone)	3.3	16 (9)	10 (6)
Metal	6.4	1.6 (0.4)	2.8 (1)
Textile	7.6	1.8 (2)	6.8 (6)
Wood	8	7.2 (5)	6.7 (5)
Paper/cardboard	3.3	7.2 (7)	7.5 (6)
Plastic/rubber/foam	31	4.4 (3)	17 (10)
Soil	34	60 (13)	44 (12)

Forster (1995) conducted a comprehensive study of a landfill reclamation project in Pennsylvania’s Lancaster County Solid Waste Management Authority (LCSWMA), where the excavated waste was from one to five years old. Combustible materials, such as such as paper, cloth, wood, cardboard, household refuse, plastics, roofing, and insulation were found to amount to approximately

67% of the total waste (Figure 2-2). Noncombustible material, such as soil and rocks amounted to about 30%, and the remaining 3% was metal, aluminum, and steel.

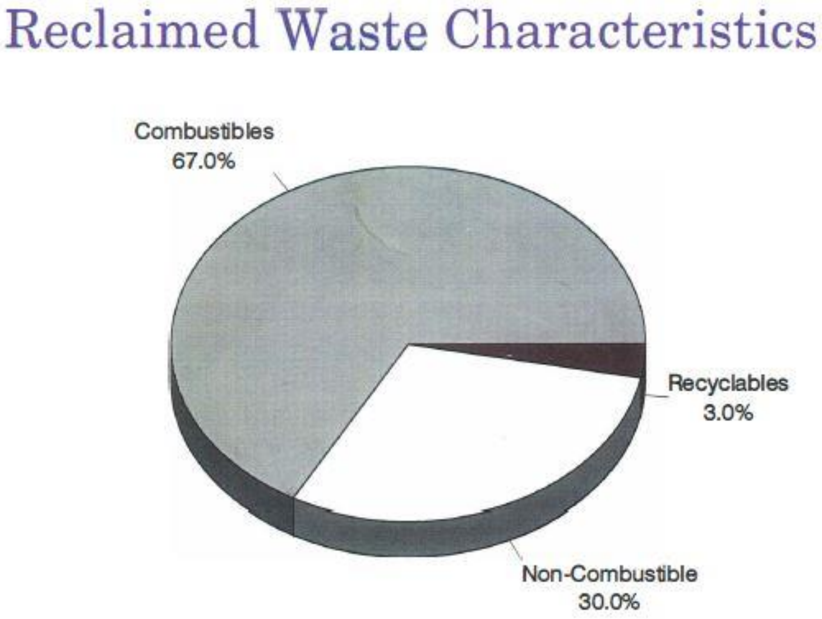


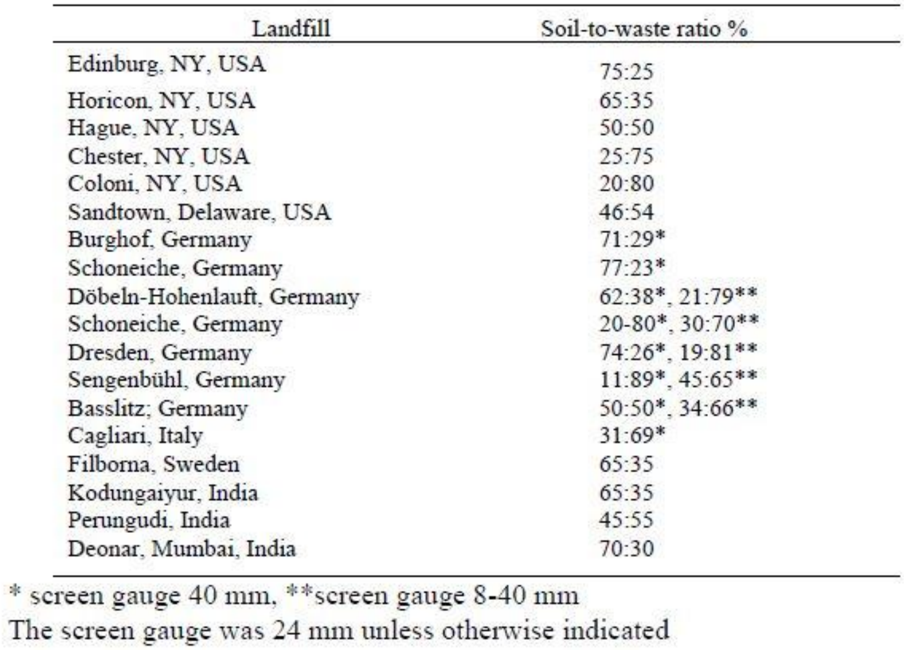
Figure 2-2 Composition of recovered waste from Lancaster County landfill (Forster, 1995)

2.3.2 Fine Material

Krook et al., (2012) indicated that the fine/degraded materials comprised between 50 – 60% of the weight of the excavated waste, but according to the literature, other researchers are not in agreement about the size of the fine materials.

Hull et al., (2005) identified the fine fraction as < 25.4 mm, whereas Quaghebeur et al., (2012), Kaartinen et al., (2013) and Hogland et al., (2003) defined the fine fraction as <10 mm, <20 mm, and <18 mm, respectively. Kurian et al., 2003 compiled a soil-to-waste ratio, based on various mining projects shown in Table 2-7, in which the soil was degraded fine particles.

Table 2-7 Soil (degraded fine particle) to waste ratio from different mining project. (Kurian et al., 2003)



Landfill	Soil-to-waste ratio %
Edinburg, NY, USA	75:25
Horicon, NY, USA	65:35
Hague, NY, USA	50:50
Chester, NY, USA	25:75
Coloni, NY, USA	20:80
Sandtown, Delaware, USA	46:54
Burghof, Germany	71:29*
Schoneiche, Germany	77:23*
Döbeln-Hohenlauft, Germany	62:38*, 21:79**
Schoneiche, Germany	20-80*, 30:70**
Dresden, Germany	74:26*, 19:81**
Sengenbühl, Germany	11:89*, 45:65**
Basslitz; Germany	50:50*, 34:66**
Cagliari, Italy	31:69*
Filborna, Sweden	65:35
Kodungaiyur, India	65:35
Perungudi, India	45:55
Deonar, Mumbai, India	70:30

* screen gauge 40 mm, **screen gauge 8-40 mm

The screen gauge was 24 mm unless otherwise indicated

2.3.3 Moisture Content

Moisture content indicates the environmental conditions in landfills. It is the first item on the checklist for processing the excavated waste. Biological or thermal treatment highly depends on moisture content. There are some interrelated factors that affect the moisture, such as waste composition, waste fraction type, physical and chemical properties, climatic conditions, method of landfill operation, leachate and gas collection, and water consumption due to biological processes (Qian et al. 2002).

Hull et al., (2005) reported the average moisture content of the excavated waste of the New Jersey landfill as 28.3% by weight, with individual ranges from 18.8% to 41.6%. The average moisture content of the mined waste in this project supported the previous literature for conventional landfills of similar age: 24% (Bäumler et al. 2001), 21.9% (Zornberg et al. 1999), 23.9% (Zanetti et al. 1997), and 35.3% (Ham et al. 1993)

Excavated material absorbs more water from infiltration of rainfall and from organic materials, such as food and yard wastes. Therefore, mined waste tends to have a higher moisture content, and is in the 40-70% range of moisture recommended for optimum microbial activity in landfills (Barlaz et al. 1990).

According to Hogland et al., (2003) mixed unsorted waste has almost constant values of moisture at a different depth in the Måsalycke Landfill in Sweden. The moisture content of the mixed, unsorted waste was found to be 29 - 30% at 0.6 - 7m depth. Quaghebeur et al., (2012) found that the average moisture content of the mined waste collected in one location at the REMO landfill was between 48% - 66% and was observed fluctuating during the excavation due to the impervious layers in the landfill. Some layers were found saturated with water, while some layers were unusually dry. Due to the heterogeneity of the waste, the water balance scenario inside landfills vary significantly. Moisture profiles inside the waste must be taken into consideration before evaluating the valorization and treatment of mined waste.

Hull et al., (2005) found that the moisture content of the excavated waste can be predicted by the moisture content of the fine fraction, as shown in Figure 2-3. No correlation was observed between the moisture content and depth in the landfill, except for some individual gas extraction well borings.

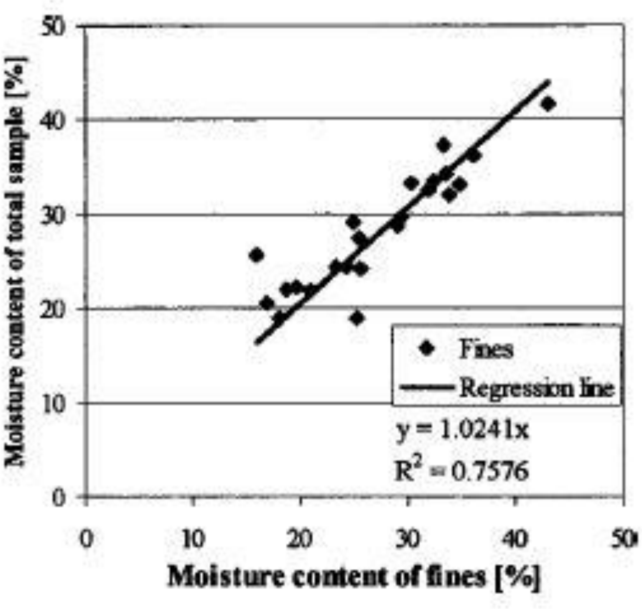


Figure 2-3 Effect of fine fraction on moisture content of total sample (Hull et al., 2005)

An excavated waste composition study from San Tirso landfill was reported in Gomes et al. (2005) They determined the moisture content as 61% on surface, (fresh waste) and increased to 117% at 11m depth (3-year old waste).

Decomposed waste has a higher percentage of fines, resulting in higher moisture content of the total mixed waste.

According to Landva & Clark, (1990), the moisture content has a positive correlation with organic content. The moisture content was found up to 120% (dry weight) and 65% (wet weight).

Gabr and Valero (1995) conducted a comparative study between fresh and landfilled samples. The average moisture content was determined to be 20% on a dry weight basis for fresh waste, whereas it was found to be from 60% to 150% on a dry weight basis for mined waste. There was not any significant correlation between depth of waste and moisture content.

Xiang-rong et al. (2002) revealed a decreasing trend of moisture content with increasing depth. The average moisture content was found 30%.

Hossain et al. (2008) reported the increase of moisture content from 55% to 64.7% for a simulated ELR landfill after complete degradation.

Carboo et al. (2005) conducted a detailed study, including physico-chemical analyses of municipal solid waste, in the Accra metropolis of Ghana. The collection efficiency was found to be only 55% of the total generation. The sampling location was selected in three different zones, based on the income level and density of the population of the residents. Zone A had a high income population with low density, Zone B had a middle income population with medium density, and Zone C had a low income population with high density. Ten households in each zone was randomly selected for sample collection every other day, for two months. Moisture content is one of the most important parameters to measure when assessing valorization potential. It will take longer time for waste burn.The moisture contents from different zones are presented in Figure 2-4

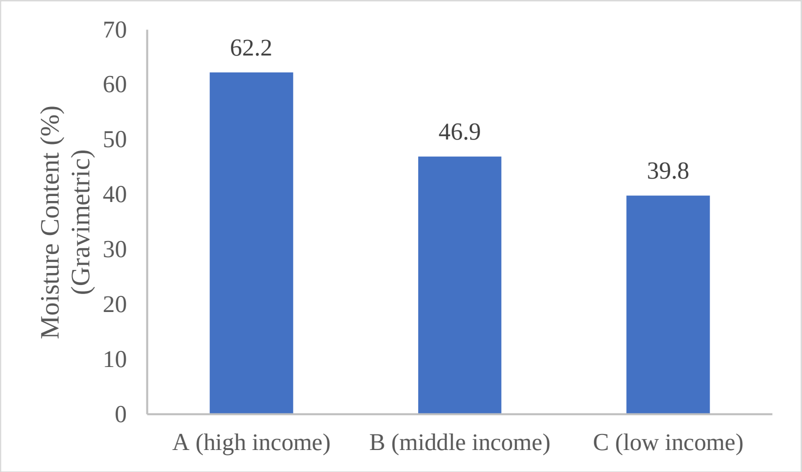


Figure 2-4 Moisture content of fresh waste in the Accra, Ghana (Carboo et al., 2005)

The data showed that the moisture content decreases with the income of the region. High-income areas residents are more likely to dispose of waste that contains energy-rich bonds, including paper, which primarily consists of an H-bond that is attracted to water and results in higher water content in higher energy rich bond compounds. The waste becomes heterogeneous in the low income zone, resulting in a decrease of bond energy.

2.3.4 Unit Weight/Bulk Density

The unit weight of solid waste depends on the size of the waste particles in the landfill. If the waste particles are finer, the unit weight becomes higher due to the smaller void space. The particles' size becomes smaller with the degradation, resulting in an increase in the unit weight.

Landva & Clark (1990) conducted a thorough study on the classification of municipal solid waste. According to their study, the in situ unit weight of MSW was from 6.8 to 16.2 KN/m3. The unit weight of the cover soil was separated from the MSW, and was measured separately.

Zhu Xiang-rong et al. (2002) measured the geotechnical behavior of the 13-year old mined waste from the Tianziling landfill, in China. The study found that the compressibility of the solid waste was high. The increase in normal stress, filling depth and time resulted in higher shear strength of solid waste. The density of MSW was found from 8 KN/m3 to 16.8 KN/m3.

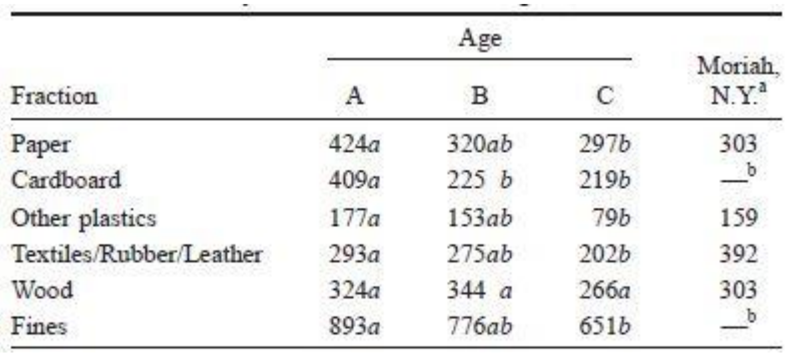
Hossain et al. (2010) determined that the dynamic properties of MSW in a bioreactor landfill, considering degradation, volatile organic content, methane yield, and pH, could be used to assess the state of the degradation. The geotechnical properties of waste were determined, using the remolded sample from the bioreactor landfill. The fine materials were 10% of the total waste after the first stage, which eventually increased to 39% at the end of the fourth stage. The unit weight increased with the degradation, from 8.5-9.1 KN/m3 in Phase I to 10.7-11.2 KN/m3 for Phase IV.

Chen et al. (2009) conducted a thorough study of the compressibility of waste from the Qizhishan landfill in Suzhou, China The study discovered the inaccuracy of the settlement prediction model, using the single compressibility value. The fill age and embedding depth of the MSW were the compressibility-measuring parameters. A total of 31 borehole samples were collected by drilling. Based on the test results, the compressible components of the MSW decreased with the fill age, resulting in a decreased void ratio with depth. On the other hand, incompressible components increased with the fill age. The unit weight, from 5 to 15 KN/m3, gradually increased with the increase of depth.

Chiemchaisri et al. (2007) found the density of the waste as 240 kg/m3 at the top of the landfill; it increased to 1260 kg/m3 at the bottom.

The bulk density of excavated waste is rarely reported in literature. Hull et al., (2005) found that the bulk density of the excavated waste from New Jersey (Table 2-8) was similar to the bulk density from the Moriah landfill in New York (Reis 1995).

Table 2-8 Comparison of bulk density between New Jersey and Moriah landfill Hull et al., (2005)



Fraction	Age			Moriah, N.Y.[a]
	A	B	C	
Paper	424*a*	320*ab*	297*b*	303
Cardboard	409*a*	225 *b*	219*b*	—[b]
Other plastics	177*a*	153*ab*	79*b*	159
Textiles/Rubber/Leather	293*a*	275*ab*	202*b*	392
Wood	324*a*	344 *a*	266*a*	303
Fines	893*a*	776*ab*	651*b*	—[b]

Moreover, (Hull et al., 2005) determined that the bulk density of the fine fraction of excavated materials ranged between 370 and 1,206 kg/m3, with a median of 742 kg/m3, which was lower than the values of previous landfill reclamation studies (Forster 1994; Reis 1995). The basic difference between Hull's study and other cited studies was the use of the waste characterization method. This study considered hand sorting, whereas other studies used a trommel screen to sort the fine fractions. This might be the cause of the discrepancy in the bulk density of the fine fraction of excavated waste.

2.3.5 Temperature

There is very limited research regarding the temperature of excavated waste. Hull et al, (2005) determined the temperature of excavated waste from the New Jersey landfill. At a depth of 3.1 m, a temperature of 22.2 °C was recorded for a sample; at the greater depth of 27.4 m, 68.3 °C was recorded. With the increase of 1 m, the temperature increased 1 °C (Figure 2-5). This finding is supported by other research (Zornberg et al. 1999, Attal et al. 1992, and Gurijala and Sulfita 1993).

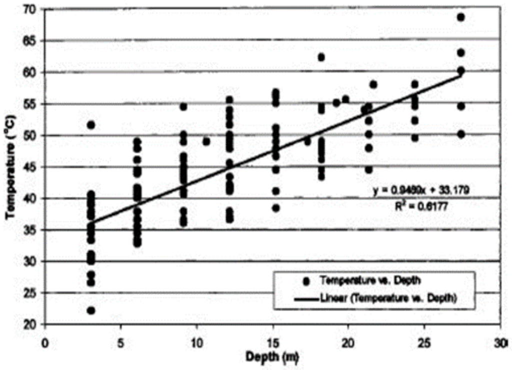


Figure 2-5 Temperature of excavated waste from New Jersey landfill (Hull et al.,2005)

Zanetti et al. (1997) and Attal et al. (1992) discovered a depth, at the top of the landfill, where the temperatures started decreasing due the heat loss to the subsoil. The temperature profile inside the landfill was modeled by El-Fadel (1991).

2.4 Energy from Municipal Solid waste

Thermochemical and biochemical processes produce energy from biomass/solid waste (Vargas-Moreno et al., 2012). During biochemical conversion, the entire process undergoes aerobic or anaerobic conditions. Microorganisms break the solid waste particles into smaller molecules under aerobic or anaerobic conditions, using minimal energy input. This process is suitable for biodegradable waste, but is slower than the thermochemical process. (Shi et al., 2015)

In the thermochemical conversion, waste undergoes a destructive process that consumes a lot of energy. Easier continuous operation, less need for water, and a short production cycle make the thermochemical conversion more efficient than the biochemical process. There are three broad types of thermochemical conversion:

- Incineration,
- Pyrolysis & Torre faction, and
- Gasification (Shi et al., 2015).

The determination of the energy content or calorific value (CV) of the solid waste is very important for evaluating the feasibility of energy recovery (Abu-Qudais and Abu-Qdais, 1999). The heating value, or calorific value, defines the fuel’s energy capacity (Shi et al., 2015).

2.4.1 Calorific Value

According to Majumder et al., 2008. ‘’*Calorific value is defined as the amount of heat evolved when a unit weight of the coal/MSW is burnt completely and the combustion products cooled to a standard temperature of 298◦K.”* In literature, different units, such as Btu/lb., KJ/kg, and kcal/kg are used to report the energy content.

There are two types of calorific value:

- Net heating value/lower heating value (LHV), and

- Gross heating value/higher heating value (HHV).

‘’The lower heating value is obtained when the water evaporated from the combustion remains as steam and does not condense back to liquid water after combustion’’ (Komilis, 2013). The lower heating value (LHV) is a function of the higher heating value (HHV) and the moisture content. ‘’*HHV is obtained when the evaporated water condenses back to liquid water’’* (Komilis, 2013). Therefore, the value of the higher heating value is always greater than the value of the lower heating value (LHV). The latent heat of water is roughly equivalent to the difference between the LHV and HHV. Experimentally, the higher heating value (HHV) is usually measured by a bomb calorimeter. There are numerous mathematical models available that calculate the calorific value.

The “Methodology for Allocating Municipal Solid Waste to Biogenic and Non-Biogenic Energy” by the US Department of Energy determined the calorific value of different waste compositions. Table 2-9 shows the values of different components.

Table 2-9 Calorific value of different components (Lariviere, 2007)

Waste Component	**Btu/lb**
PET(Plastic)	10250
HDPE(Plastic)	19000
PVC(Plastic)	8250
LDPE/LLDPE(Plastic)	12050

Polypropylene (Plastic)	19000
Polystyrene (Plastic)	17800
Other (Plastic)	10250
Rubber	13450
Leather	7200
Textile	6900
Wood	5000
Food	2600
Yard Trimming	3000
Newspaper	8000
Cardboard	8250
Mixed Paper	3350

2.4.2 Factors affecting Calorific Value of Excavated Waste

2.4.2.1 Waste Composition

Waste composition plays a vital role in determining the energy potential of mined waste. Excavated waste that has an increased proportion of high energy content, like plastic and wood, is equivalent to raw waste in terms of fuel capacity. (Hull et al., 2005).

Hogland et al., 2003 concluded that it is possible to incinerate the excavated fraction without additional fuel, as the fractions >50 mm consist mainly of paper, wood, and plastic.

2.4.2.2 Storage time of the excavated waste

Due to the heterogeneity of waste, the standard deviation of any individual fraction is high. Some fractions keep changing over time, with or without maintaining a significant trend. These changes can be explained by the decomposition of the waste over time, which subsequently affects the calorific value of the excavated waste. The initial composition of fresh waste affects the storage of the waste, and resulting from differences in waste management procedures, change of consumer behavior during a specific period or concerning legislation (Quaghebeur et al., 2013).Forster (1995) conducted a comprehensive study on landfill mining in Pennsylvania and developed a graph that correlates the calorific value of the waste with the age of the waste (Figure 2-6).

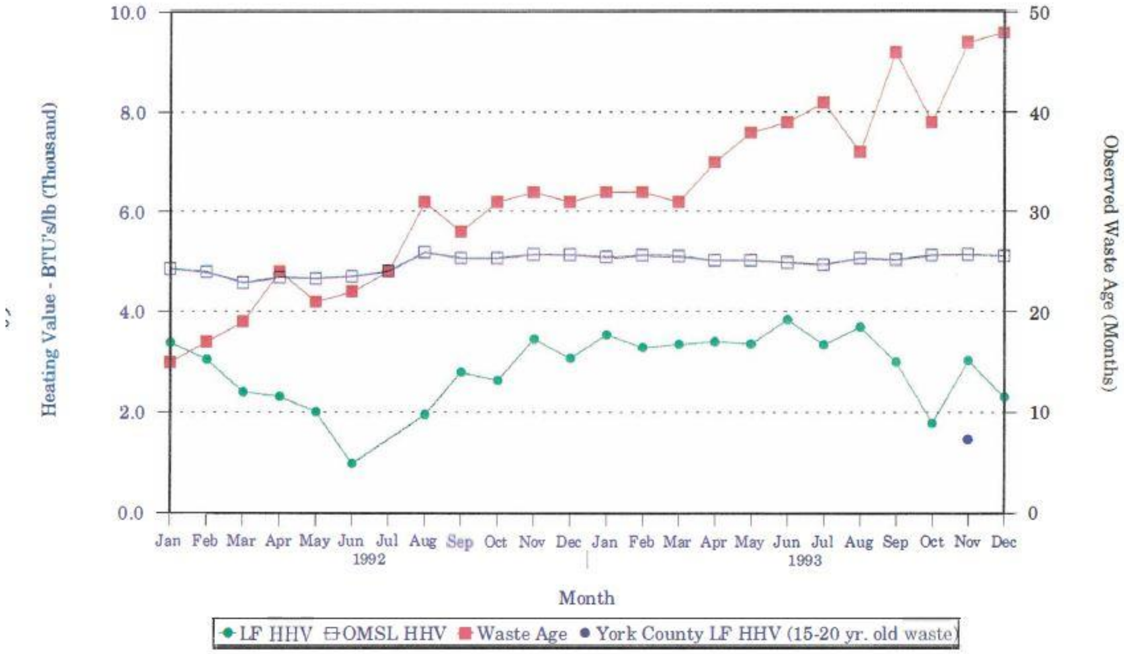


Figure 2-6 Correlation between calorific value and age of the waste (Forster, 1995)

2.4.2.3 Moisture Content

Excavated material absorbs more water from precipitation, infiltration and organic materials, such as food and wood wastes. Therefore, it tends to have a higher moisture content from the time of disposal (Hull et al., 2005). Majumder et al. (2008) reported that moisture has a negative effect on the calorific value. Chang and Davilla (2007) implied the benefit of an incineration having low moisture content and slightly higher paper content. Drying is one of the procedures that increases the calorific value. Kommilis et al. (2012) emphasized that the lower moisture content results in a higher calorific value.

2.4.2.4 Volatile Solid

Organic matter is one of the important properties in waste, and is directly related to degradation and energy values. Organic fractions (paper, plastic, food, food waste, and textiles) are supposed to be degraded according to age and soil type, but degradation does not take in this way in an anaerobic condition (landfill). Five to ten percent (5-10%) of cellulose is degraded in nature under anaerobic conditions (Bosmans et. al., 2014). Volatile solids assess the potential degradability of excavated waste from a landfill, and subsequently indicate the energy potential of the mined waste.

2.4.2.5 Rain fall

Forster (1995) indicated the continuous daily observation of the moisture content and the age of the waste throughout 1992 and 1993. Monthly rainfall was also tracked at the landfill, and no significant correlation was found between the HHV of mined waste and rainfall at the time of waste excavation. There was no effect of rainfall on the HHV of the mined waste at the time that the waste was initially landfilled. These relationships are plotted in Figures 2-7 and 2-8.

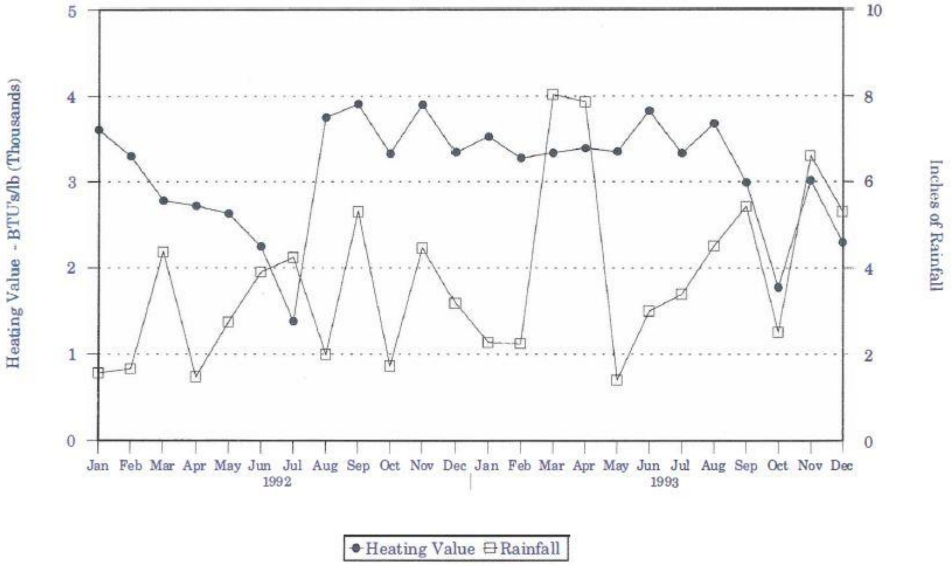


Figure 2-7 Effect of rainfall on calorific value (Forster, 1995)

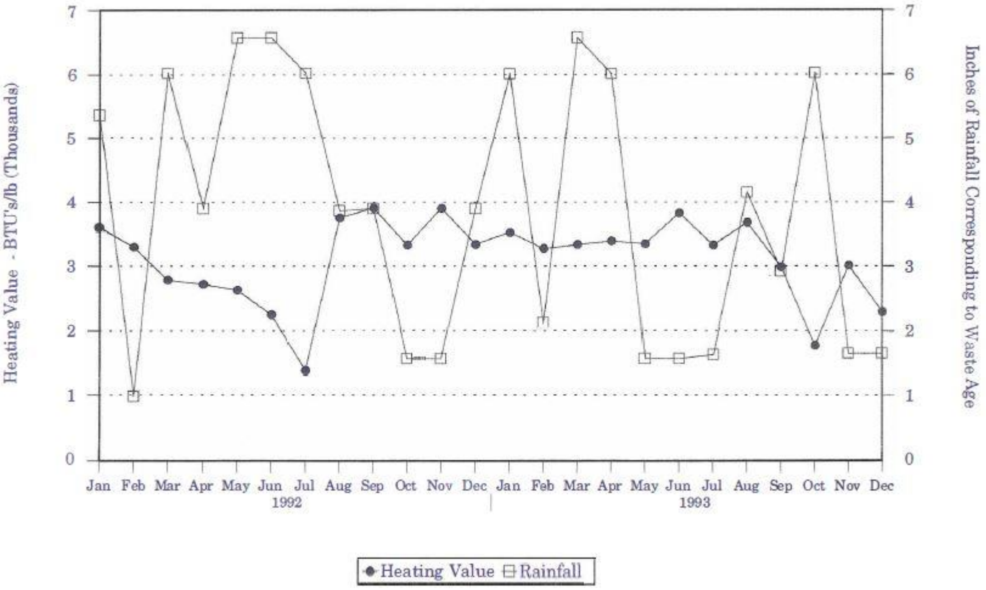


Figure 2-8 Effect of rainfall (during excavation) on calorific value (Forster, 1995)

2.5 Energy potential from Fresh Municipal Solid waste

Incineration is commonly used to treat municipal solid wastes (MSW), as the recovery of energy and reduction of volume and mass are the main goals of incineration. This waste management system is preferred where there is a lack of space and the land value is high (Komillis et al., 2013).

According to directive 2008/98/EC (European Parliament. Council of the European Union, 2008), Disposal and energy recovery is two alternate options from MSW incineration. Energy recovery completely depends on the efficiency of the incinerator. R 1 formula is a popular way to measure energy efficiency of the incinerator. Calorific value is an input parameter in R1 formula

Although measurement by a calorimeter is always preferred, a rapid assessment is needed to gain an idea of energy content and the self-sustained combustibility of the waste stream. These calculation determines the economic feasibility of the incineration project. For example, the absence of combustible material reduces overall energy efficiency of the incineration plant, because of the use of an external fuel (a parameter that is accounted for in the R1 formula) (Komilis et al., 2013). The calorific values (higher heating values/gross heating values) of mixed waste and individual components of waste around the world are listed in Table 2-10, with proper reference.

Table 2-10 Calorific value of fresh municipal solid waste in the literature

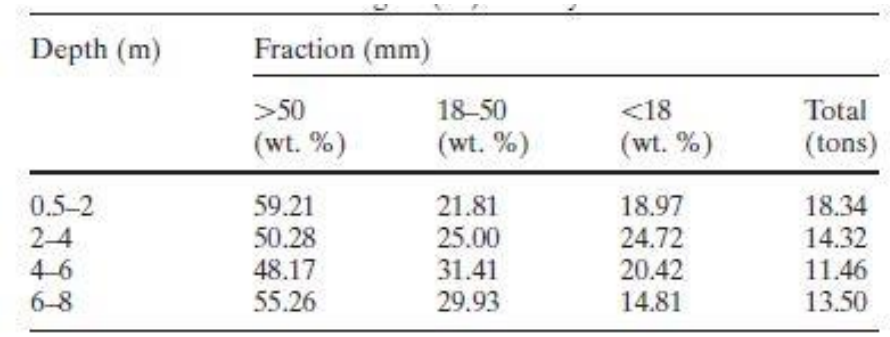
Waste Type	**Average Calorific value (Btu)**	**Location**	**Reference**
Mixed MSW	4941.293	Jordan	Abu-Qudais and Abu-Qdais,1999
Paper and cardboard	4982.666	Jordan	Abu-Qudais and Abu-Qdais,1999
Food Waste	1966.084	Jordan	Abu-Qudais and Abu-Qdais,1999
Plastic	11983.58	Jordan	Abu-Qudais and Abu-Qdais,1999
Mixed Waste	3433.902	Pakistan	Korai et al.,2015
Mixed Waste	2698.194-4676.87	China	Chunming et al.,2013
Mixed Waste	5159.07	Tanzania	Omanri et al.,2014
Mixed Waste	7407.5666	Nigeria	Amber et al.,2012
Paper and cardboard	6018.92	Italy	Giugliano et.al. (2008).
Wood	7738.61	Italy	Giugliano et.al. (2008).
Plastic	11607.9	Italy	Giugliano et.al. (2008).
Organic Fraction	3009.46	Italy	Giugliano et.al. (2008).
Fine	859.845	Italy	Giu gliano et.al. (2008).
Paper and cardboard	3869.3	Taiwan	Chang et al. (2008).
Wood	3869.3	Taiwan	Chang et al. (2008).
Plastic	9458.3	Taiwan	Chang et al. (2008).
Textile	4299.23	Taiwan	Chang et al. (2008).
Organic Fraction	859.845	Taiwan	Chang et al. (2008).
Leather and Rubber	6018.92	Taiwan	Chang et al. (2008).
Paper and cardboard	2149.61	Spain	Montejo et al. (2011).
Wood	7738.61	Spain	Montejo et al. (2011).
Plastic	12467.8	Spain	Montejo et al. (2011).
Textile	4170.25	Spain	Montejo et al. (2011).

Organic Fraction	1719.69	Spain	Montejo et al. (2011).
Non-recycled paper	6698.1943	Canada	Shi et al.,2015
Wood/yard waste	7919.1745	Canada	Shi et al.,2015
Plastic-rigid	15356.836	Canada	Shi et al.,2015
Plastic-film and Styrofoam	18254.514	Canada	Shi et al.,2015
Rubber	8959.5873	Canada	Shi et al.,2015
Plastic-Textile	8916.595	Canada	Shi et al.,2015
Mixed Waste	4472	New York, USA	Chin and Franconeri,1980
MSW	5576	National Average	GAA,1997
MSW	8186.322	Texas, USA	Change and Davila,2007
MSW	5159.07	India	Mboowa et al.,2017
MSW	2698.194-4676.87	Malaysia	Kathirvale et al.,2003

2.6 Energy potential from landfill mined waste

Hogland et al., 2003 conducted a detailed study on the Måsalycke and Gladsax landfills for municipal solid waste (MSW) in Sweden. The mined waste in these two landfills was 17 - 22 and 23 - 25 years old, respectively. The major part of the Måsalycke landfill was not found degraded that much and no substantial amount of biogas was detected during excavations. After screening, three sizes of fractions were obtained: <18mm, 18–50mm, and >50mm. The distribution of the particles are shown in Table 2-11.

Table 2-11 Particle size of excavated waste (Hogland et al., 2003)



Depth (m)	Fraction (mm)			
	>50 (wt. %)	18–50 (wt. %)	<18 (wt. %)	Total (tons)
0.5–2	59.21	21.81	18.97	18.34
2–4	50.28	25.00	24.72	14.32
4–6	48.17	31.41	20.42	11.46
6–8	55.26	29.93	14.81	13.50

The coarse fraction >50mm contained large amounts of paper (29%) and wood (19%). The calorific value will be high if the material is dry. The dry matte concentration at the Måsalycke landfill was 70% - 80%, while the ash content was about 90% - 95% in the two finer fractions. The calorific value was very low in these two fractions, ranging from 0 to 1MJ/kg. The fine fraction seemed unsuitable for further biological or thermal treatment. The fraction > 50mm consisted mainly of paper, wood, and plastic, and therefore had a higher calorific value (7MJ/kg or more). However, 70 - 90% of the plastic, 80 - 95% of the ferrous metal, and 85 - 90% of the soil from excavated waste can be recovered through a proper screening process (Savage et al., 1993),

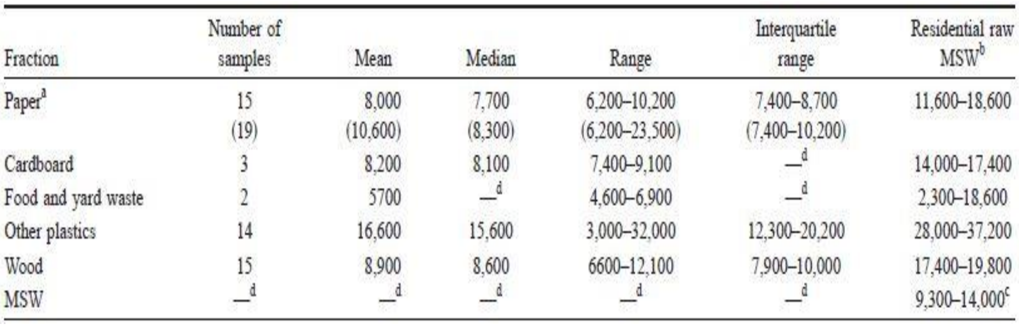
Cossu et al., 1995 found the energy value of mined waste in Italy to be between 3.4 and 8.7MJ/kg (mean 4.5MJ/kg). The value was found 6.9 - 7.9 MJ/kg in the light fraction, and less than 2 MJ/kg in the fine fraction from the Filborna landfill in Sweden. For unsorted light fractions, Obermeier and Saure (1995) determined a value of 11MJ/kg, and Cossu et al. (1995), Rettenberger (1995), and Schillinger et al. (1994) found values up to 20 MJ/kg.

Brammer et al. (1995) presented a project in which 15-year old lysimeter material was studied in Germany. The energy values of the various fractions were from 6 to 13 MJ/kg. Hogland et al., 2003 concluded by indicating the clear feasibility of incinerating some fractions without any additional fuel.

Hull et al., 2005 conducted comprehensive research on the composition of material excavated from the Burlington County landfill in New Jersey, followed by the physical and chemical characteristics of the excavated waste. Excavated waste was collected and hand sorted into 14 fractions and fines <2.54 cm that fell through the screen. At least 50%, by weight, of the material was fines. During data analysis, the landfill age was divided into three periods: Age A, February 1989 through March 1993; Age B, April 1993 through March 1997; and Age C, April 1997 through November 1999.

The calorific value calculated for the paper, cardboard, plastics, and wood fractions from the Burlington Landfill were lower than the values from raw MSW (Tchobanoglous et al., 1993) as shown in Table 2-12.

Table 2-12 Calorific value of paper, cardboard, plastics, and wood fractions from Burlington landfill (Hull et al., 2005)



Fraction	Number of samples	Mean	Median	Range	Interquartile range	Residential raw MSW[b]
Paper[a]	15 (19)	8,000 (10,600)	7,700 (8,300)	6,200–10,200 (6,200–23,500)	7,400–8,700 (7,400–10,200)	11,600–18,600
Cardboard	3	8,200	8,100	7,400–9,100	—[d]	14,000–17,400
Food and yard waste	2	5700	—[d]	4,600–6,900	—[d]	2,300–18,600
Other plastics	14	16,600	15,600	3,000–32,000	12,300–20,200	28,000–37,200
Wood	15	8,900	8,600	6600–12,100	7,900–10,000	17,400–19,800
MSW	—[d]	—[d]	—[d]	—[d]	—[d]	9,300–14,000[c]

The calorific value of food and yard waste was found approximately equal to the calorific value of food and yard waste in the raw MSW. The probable cause was the lower moisture content of the food and yard waste, compared to the raw waste, when excavated from the landfill (Hull et al., 2005).

With the greater number of the higher caloric fractions, such as plastic, and less amount of lower caloric fractions, such as food and yard waste, the calorific value became closer to the calorific value of the raw municipal solid waste (Salerni et al., 1997). Salerni (1997) determined the calorific value 13100 KJ/kg using a 50/50 mixture of mined waste and fresh waste, which is almost close to energy of 100% fresh waste

Forster (1994) reported the successful, full-scale use of excavated material as part of a fuel mixture with fresh MSW in an MSW incinerator in Lancaster County, Pennsylvania. Forster used a mixture of fresh waste components (MSW, tire chips, wood chips, and selected residual wastes) and mined waste in a 4:1 ratio, which had approximately similar energy value as raw MSW However, some of the issues like ash generation, emissions were found higher during the mixing processing of fresh and mined waste.

Collins's 2001 study (as cited in Hull et al.,2005) suggested composting to dry the mined waste before thermal processing to improve the screening efficiency of the removal of fines and reduce adhering solids, thereby reducing the ash generation during thermal processing.

Quaghebeur et al., (2012) evaluated the valorization potential of excavated solid waste from the REMO landfill, Belgium, which has been active since the start of the 1970s. The average calorific value and the average total organic content (TOC) content of the waste mined at the four locations were calculated by using the individual material fractions (<10 mm, plastic, paper/cardboard, wood, textile, glass/ceramic, metal, and stone) at each location. For glass/ceramic, metal, and stone, the calorific value and the TOC content were ignored. The amount of combustibles in the mined waste varied between 23 and 50% (w/w), with a calorific value of around 18 MJ/kg, and confirms the enormous potential of waste-to-energy from landfill mining. From Fig. 2-9, the calorific value and the TOC concentrations in the MSW decreased, respectively, from 11.8 to 6.7 MJ/kg and 28 to 19% (w/w), with increasing storage time in the landfill. Decomposition of C-rich material into landfill gas over time is the most likely reason behind the decrease of calorific value.

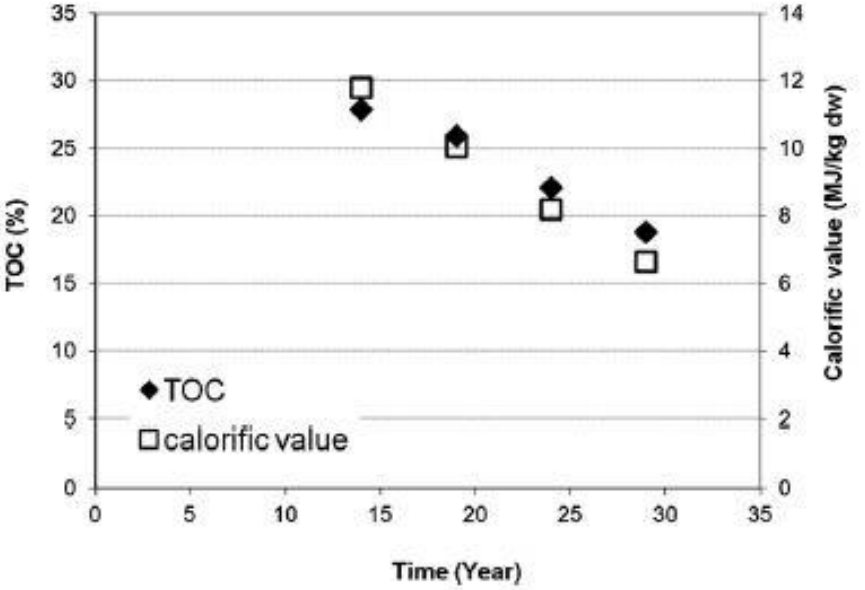


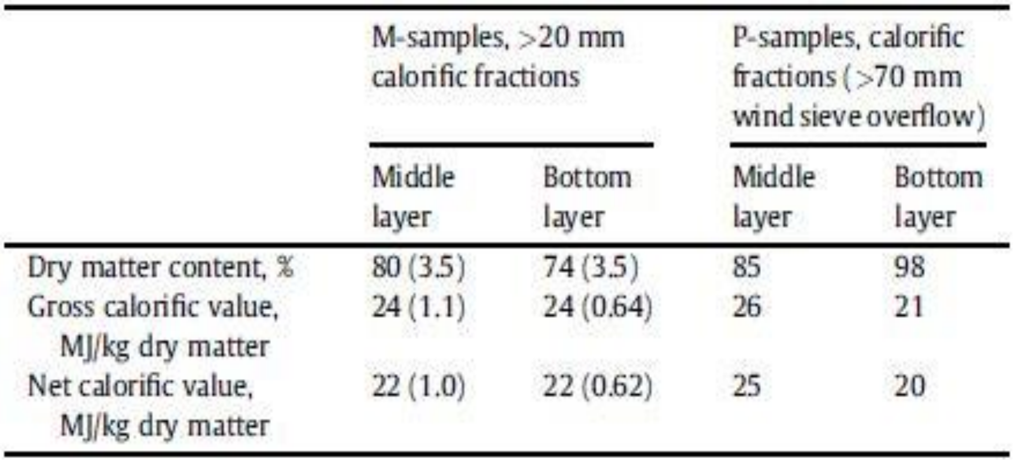
Figure 2-9 Change of calorific value and TOC with time (Quaghebeur et al., 2012)

Quaghebeur et al., (2012) found the finer fraction (<10mm) major in both MSW and IW (institutional waste), which is composed of all the waste materials that pass through a sieve with a mesh size of 10 mm. The calorific value for the soil, like MSW, was higher (2.2-4.8 MJ/kg) than that of the fine fraction IW. In addition, the calorific value decreased with increasing storage time of the MSW. In Sweden, lower calorific values (0.4-0.9 MJ/kg) were reported for fines screened from waste that had been landfilled for a period of 14 years (Hogland et al., 2004).

The recovered plastic in the REMO landfill was found to have a lower calorific value (19-28 MJ/kg), which was comparable, according to Quaghebeur et al. (2012), to a mixed plastic stream (35 Mj/kg) (Phyllis Database). Since the plastics were separated from the waste by handpicking, without further washing or treatment, it is likely that some dust or sand particles stuck to the plastics and influenced the measurements. No indication was found that the calorific value of the plastic waste was influenced by degradation of the plastic during storage, since no change in calorific value with increasing storage time of the plastic waste was observed. It is known that plastics are very durable and degrade little during landfilling (Shah et al., 2008). The net calorific value (lower heating value) was between 6.7 and 12 MJ.kg, which is slightly lower than the caloric value reported for mixed paper streams (15 MJ kg) (Quaghebeur et al., 2012).

Kaartinen et al. (2013) conducted a detailed study on sampling, processing, and characterization of the landfill mined waste from a 10-year-old Finish landfill. By manual sorting, the study found that 40-45% (w/w) of the possible fuel fraction in the landfilled waste had a net calorific value of approximately 20 MJ/kg. The excavated waste was considered as Class 1 solid recovered fuel, according to the standard EN (CEN, 2011) and based on the calorific value (Table 2-13). No difference was found between the calorific values of the manually sorted and prepared calorific fractions of the >20 mm M-samples and the light wind sieve fraction of the P-samples. The fuel potential was found in the 20-70 mm fractions. The calorific value of the manually sorted waste averaged approximately 40-45% (w/w) of all of the waste.

Table 2-13 Calorific value of excavated waste from a finish landfill (Kaartinen et al., 2013)



	M-samples, >20 mm calorific fractions		P-samples, calorific fractions (>70 mm wind sieve overflow)	
	Middle layer	Bottom layer	Middle layer	Bottom layer
Dry matter content, %	80 (3.5)	74 (3.5)	85	98
Gross calorific value, MJ/kg dry matter	24 (1.1)	24 (0.64)	26	21
Net calorific value, MJ/kg dry matter	22 (1.0)	22 (0.62)	25	20

Kaartinen et al., (2013) found little potential benefit from further refining of the fine fraction, e.g., for production of fuel. Relatively low proportions of plastics, paper/cardboard, textiles, and wood were indicative of the poor potential heating value in MSW fines.

Forster (1995) calculated the HHV of the total Lancaster County Solid Waste Management Authority (LCSWMA) fuel mixture (5121 BTU per pound) and for the LCSWMA reclaimed waste stream (3,084 BTU per pound).

The calorific value of the mixed waste and individual components of waste around the world are listed in Table 2-14, with proper reference.

Table 2-14 Calorific value of mined waste in the literature

Waste Type	Average Calorific value(Btu)	Range (Btu)	Location	Reference
Paper	3439.381	2665.52-4385.2107	Burlington County Landfill, New Jersey, USA	Hull et al.,2005
Cardboard	3525.365	3181.427-3912.296		
Food and yard waste	2450.559	1977.644-2966.466		
Other plastic	7136.7154	1289.768-13757.524		
Wood	3826.311	2837.489-5202.0636		
Plastic	18564.058	17924.058-19204.058	Yingchun landfill,Central China	Zhou et al.,2014
Municipal Solid waste (Fine<10 mm)	1771.281	1031.81-2450.56	REMO Landfill,Belgium	Quaghebeur et al.,2012

Industrial Waste (Fine<10 mm)	945.83	902.837-988.822	REMO Landfill,Belgium	Quaghebeur et al.,2012
Municipal Solid waste	10210.662	8168.53-12037.8	REMO Landfill,Belgium	Quaghebeur et al.,2012
Industrial Waste	10748.1	9458.3-12037.8	REMO Landfill,Belgium	Quaghebeur et al.,2012
Municipal Solid waste (Fine<18 mm)		0- 429.923	Masalycke and Gladsax Lnadfill,Sweden	Hogland et al.,2003
Municipal Solid waste (>50 mm)		3009.46	Masalycke and Gladsax Lnadfill,Sweden	Hogland et al.,2003
Excavated Waste	1934.65	1461.74-3740.33	Italy	Cossu et al.,1995
Excavated Waste(Fine)	< 859.845		Fiborna Landfill,Sweden	Hogland et al.,2003
Excavated Waste(Fine)		2966.47-3396.39	Fiborna Landfill,Sweden	Hogland et al.,2003
	4729.15			Obermeier and Saure,1995

		2579.54-5588.99	Germany	Brammer et al.,1995
	Up to 8598.45			Cossu et al.,1995 Rottenberger G(19950
Excavated waste >20 mm	10318.1		Kuopio,Finland	Kaartinen et al.,2013
Excavated waste >70 mm	10103.18	9028.37-11178	Kuopio,Finland	Kaartinen et al.,2013
Waste	3084		Lancaster County, Pennsylvania, USA	Forster G,1995

2.7 Proximate Analysis

2.7.1 Importance of Proximate Analysis

Currently, the calorific value of MSW samples is determined by either experimentally using a calorimeter, or by a developed mathematical model (Kathiravale et al., 2003). The sample size used for a calorimeter is around 1 g, which is inadequate for addressing the heterogeneity of waste composition; therefore, a relatively bigger sample size is preferred. Furthermore, the experimental method is tedious, and requires technical skills in handling the equipment and the combustion byproducts (Kathiravale et al., 2003). On the other hand, the fuel quality of solid waste can easily be assessed by proximate analysis, using a muffle furnace. A simple muffle furnace, which is less expensive than a bomb calorimeter, can be operated by a moderately-trained chemist (Majumder et al., 2008). Volatile solids (VS), ash (A), and fixed carbons (FC) are determined easily by proximate analysis. A thermogravimetric analyzer (TGA) can also be used to accomplish proximate analyses (Shi et al., 2015).

Organic matter, measured as volatile solid, is one of the important properties in waste. It is directly related to degradation and the energy value. Organic fractions (paper, plastic, food, food waste, and textiles) are supposed to degrade with age in soil type fractions, but degradation does not take place in this way in anaerobic conditions such as landfills. Only 5-10% of cellulose is degraded in nature under anaerobic conditions (Bosmans et. al., 2014). The presence of higher volatile solids indicates the good quality of the solid waste in terms of combustibility, whereas a low fixed carbon content, such as the high ash yield, confirms the poor fuel quality of solid waste (Ozyuguran and Yaman, 2016; (Komilis et al., 2012).

2.7.2 Proximate Analysis from Landfill mined waste

Kelly et al. (2006) conducted a study on the samples of different ages (From Fresh to 12 years old) which were excavated/collected from twelve different landfills. Different tests like volatile solid, BMP (Biological methane potential), lignin, cellulose was investigated to assess the biodegradability. The main objective of the study was to determine which methods accurately predict the biodegradable or organic fractions of waste and the point where the degradation of waste becomes stable. The degradation phenomenon was different for individual landfills because of the heterogeneity of waste and the unique landfill conditions. The researchers plotted the VS, cellulose, BMP and lignin of the samples with the age of the waste. It was observed that most samples had less than 5% cellulose after 5 years in the landfill. From the data, it was observed that the bioreactor landfills were more degraded and the values of VS, cellulose, lignin and BMP were lower for ELR landfills. Kelly et al. developed correlations between cellulose and VS, lignin and VS, BMP and VS and cellulose + lignin and VS. The cellulose versus VS showed a stronger correlation with VS than the lignin and BMP as illustrated in Figure 2-10. The authors commented that cellulose could be reasonably predicted from VS.

Gomes et al. (2005) conducted a study to characterize the solid waste being disposed of at the San Tirso landfill. Three profiles were selected for the different ages of waste. The organic content at the surface ranged from 43% - 63% for recent wastes and 56% for 3-year-old waste.

Kavazanjian et al. (2010) collected landfilled samples from the Tri-Cities landfill. For the sample groups A3, C6, and C3, the organic content was estimated to be 13% - 23%, 11% - 13%, and 17% - 27%, respectively. A3 waste was 15 years old, and was retrieved from a depth of 25.6- 26.2 m; C3 was 2 years old and was retrieved from depth of 3.5-4.5m and the C6 group samples were less than 1 year old at the time of drilling and were retrieved from depth of 7.6- 9.6 m.

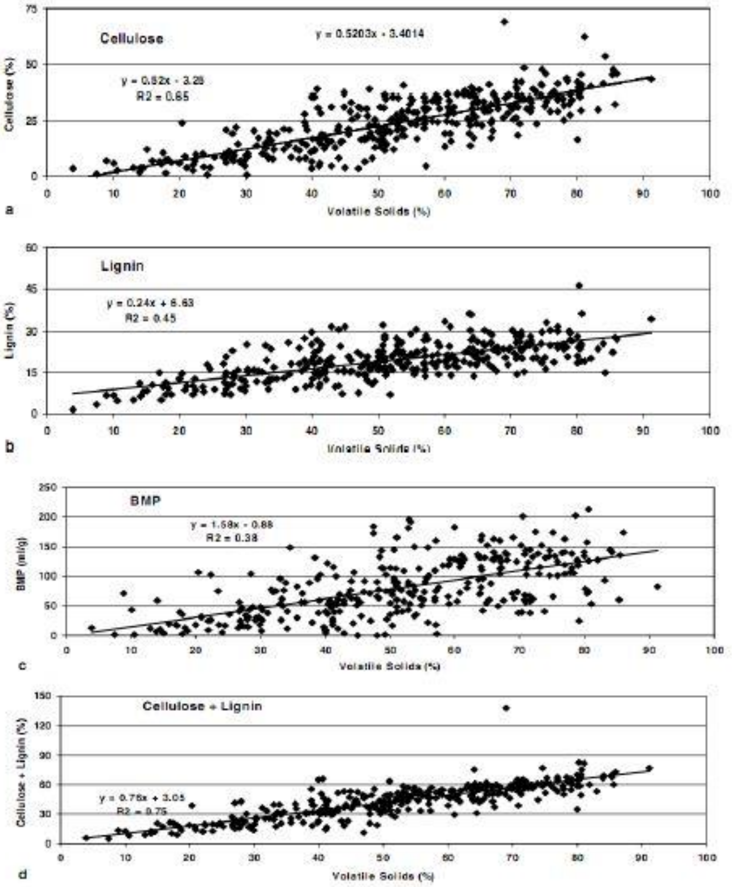


Figure 2-10 Correlation between volatile solids and (a) Cellulose, (b) Lignin, (c) BMP and (d) Cellulose + Lignin (Kelly et al. 2006)

Townsend et al. (1996) conducted a study on converting an active conventional landfill to leachate recirculated landfill considering the recirculation of exiting leachate. The total sample of volatile solids, biodegradable organic fractions, (BDOF) volatile solids and BDOF ultimate methane yield were plotted with the estimated age of the samples, as presented in Figure 2-11.

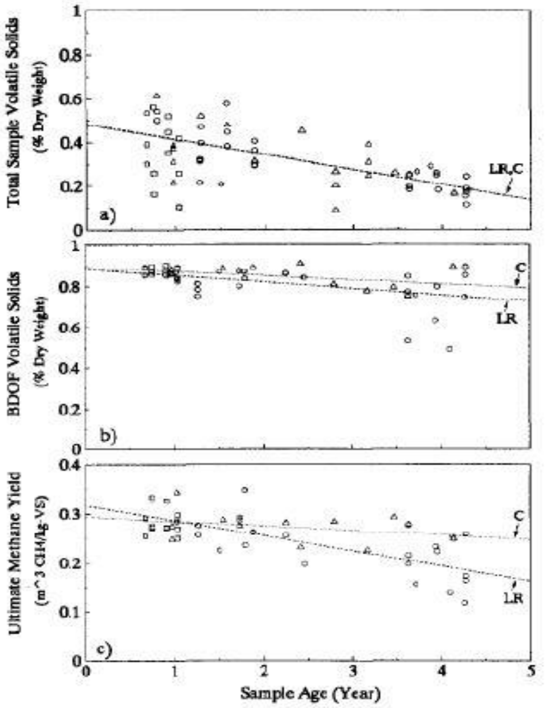


Figure 2-11 Correlation between age and (a) Total volatile solids, (b) BDOF volatile solids and (c) Ultimate methane yield BDOF

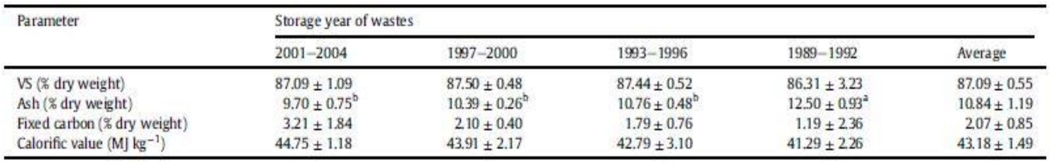
Bosmans et al., 2014 conducted research on the pyrolysis characteristics of the landfill-mined waste from the REMO landfill, Belgium and the processes used to convert it to refuse-derived fuel (RDF). Thermogravimetric analyses were performed on RDF fractions, which are the combustible fractions of the mined waste stream that are ineligible for material recovery or recycling. For better understanding of the thermal degradation behavior, two waste fractions (municipal and industrial waste) were analyzed separately, and combined with municipal solid waste (59%) and industrial waste (41%). The volatile solids and ash content are shown in Table 2-15.

Table 2-15 Pyrolysis characteristics of landfill mined waste from REMO landfill. (Bosmans et al., 2014)

Proximate Parameters	Landfill mined waste		
	59%MSW+41%IW	MSW	IW
Volatile Solid	69.3%	72.2%	71.7
Ash	22.1%	17	17.8
Fixed Carbon	8.6%	10.8	10.5

Zhou et al., 2014 studied the recovery potential of mined plastic from the Yingchun landfill, China. A total of 22 samples, each weighing approximately 50 kg, were collected from different landfill layers. The first layer was comprised of 9 samples that were taken at 0-6 m; the second layer was comprised of 7 samples that were taken at 6-12 m; the third layer was comprised of 4 samples that were taken at 12-18 m, and the fourth layer was comprised of 2 samples that were taken at 18-24 m. According to the historical data of the landfill, the first to the fourth layers of the solid waste were generated from waste disposed of in the years of 2001-2004, 1997-2000, 1993-1996, and 1989-1992, respectively. The detailed results are shown in Table 2-16.

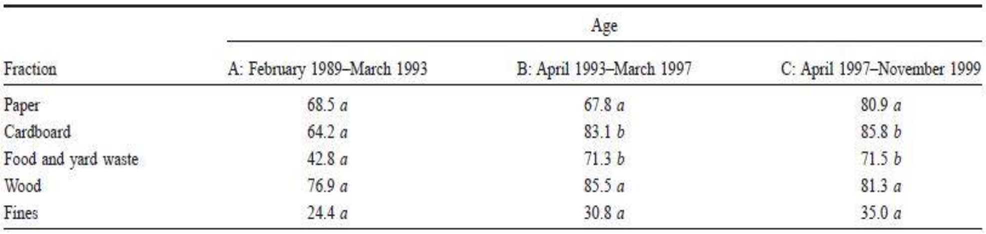
Table 2-16 Pyrolysis characteristics of landfill mined plastic (Zhou et al., 2014)



Parameter	Storage year of wastes				
	2001–2004	1997–2000	1993–1996	1989–1992	Average
VS (% dry weight)	87.09 ± 1.09	87.50 ± 0.48	87.44 ± 0.52	86.31 ± 3.23	87.09 ± 0.55
Ash (% dry weight)	9.70 ± 0.75[b]	10.39 ± 0.26[b]	10.76 ± 0.48[b]	12.50 ± 0.93[a]	10.84 ± 1.19
Fixed carbon (% dry weight)	3.21 ± 1.84	2.10 ± 0.40	1.79 ± 0.76	1.19 ± 2.36	2.07 ± 0.85
Calorific value (MJ kg^{-1})	44.75 ± 1.18	43.91 ± 2.17	42.79 ± 3.10	41.29 ± 2.26	43.18 ± 1.49

Hull et al., 2005 conducted a detailed study on the excavated waste composition of the New Jersey landfill. The individual waste fractions of volatile solids were measured at different ages (Table 2-17). The volatile solids of cardboard, food, and yard waste fractions decreased with the age of the waste. The same trend followed for the paper, wood, and fines fractions, although it was not statistically significant. Organic matter is one of the waste properties that might influence the field capacity of waste to hold water (Zornberg et al. 1999); therefore, higher moisture contents would be expected with an increase in organic matter. No correlation was found between moisture content and organic matter measured as VS, except for the fines fraction.

Table 2-17 Volatile solid was measured of individual waste fractions at different age (Hull et al., 2005)



	Age		
Fraction	A: February 1989–March 1993	B: April 1993–March 1997	C: April 1997–November 1999
Paper	68.5 *a*	67.8 *a*	80.9 *a*
Cardboard	64.2 *a*	83.1 *b*	85.8 *b*
Food and yard waste	42.8 *a*	71.3 *b*	71.5 *b*
Wood	76.9 *a*	85.5 *a*	81.3 *a*
Fines	24.4 *a*	30.8 *a*	35.0 *a*

2.8 Elemental Analysis

2.8.1 Importance of elemental Analysis

Historically, proximate analysis has received little attention due to the greater accuracy of elemental analysis (Vargas-Moreno et al., 2012). High volatile solids do not guarantee a high calorific value, due to the formation of volatile solids from non-combustible gases such as CO2 and H_2O (Ozyuguran and Yaman, 2016). Therefore, both volatile solids and fixed carbons contain elemental carbon. The amount of fixed carbon and volatile solids indicates the overall combustion process, or the quality of combustion (Averal et al., 2016).

The main components of solid biosolids are carbon, hydrogen, and oxygen. The concentration of carbon (C) positively affects the calorific value (Vargas-Moreno et al., 2012). Hydrogen plays a vital role in all fuel combustion systems. The calorific value increases with the increase of the ratio of H+ (C/O).

The elemental composition (commonly the content of carbon, hydrogen, nitrogen, oxygen) of municipal solid waste significantly varies among countries, regions, and cities. The widely used elemental components found in the literature are partly based on original research performed more than 30 years ago. Therefore an update of elemental composition of solid waste is deemed necessary (Komilis et al., 2011).

2.8.2 Elemental composition of Landfill mined waste

Quaghebeur et al., (2012) evaluated the valorization potential of excavated solid waste from the REMO landfill, Belgium, which has been in operation since the start of the 1970s. The average calorific value and the average total organic content (TOC) of the waste excavated at the four locations were calculated using the calorific value of individual material fractions (<10 mm, plastic, paper/cardboard, wood, textile, glass/ceramic, metal, and stone) at each location. For glass/ceramics, metal, and stone, the calorific value and the TOC content were neglected. The calorific value and the TOC concentration for the soil, like MSW, seemed higher than those for the fine fraction IW. The total organic carbon (TOC) concentration (7.6-12% (w/w)) decreased with increasing storage time of the MSW (Figure 2-12). A large portion of the organic carbon in the soil-like fraction was converted and recovered as landfill gas during storage in the REMO landfill.

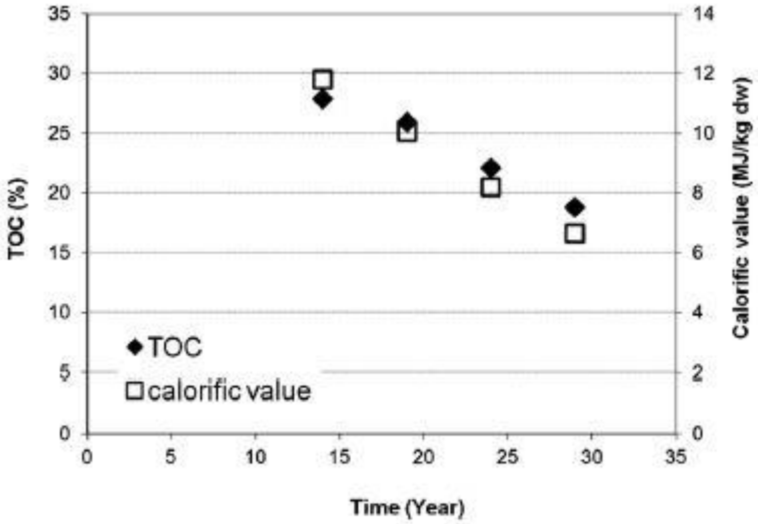
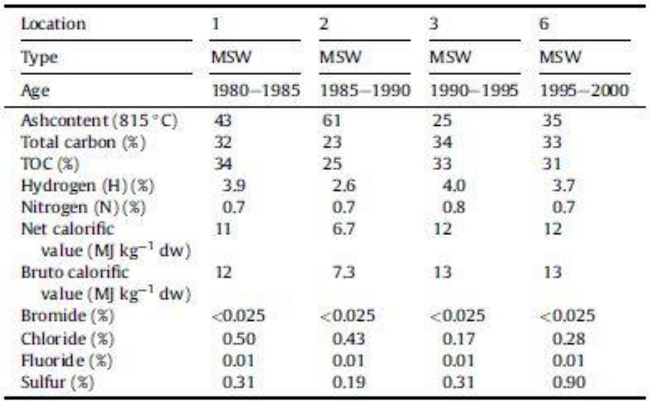


Figure 2-12 Change of total organic carbon (TOC) with age (Quaghebeur et al., 2012)

The TOC concentration of the plastic fractions separated from IW, versus MSW, was found same in the study. The amount of TOC compared well with the values reported for plastics in MSW in the Netherlands (59%, w/w) (Agentschap N.L., 2010). The average characteristics of paper/cardboard are shown in Table 2-18.

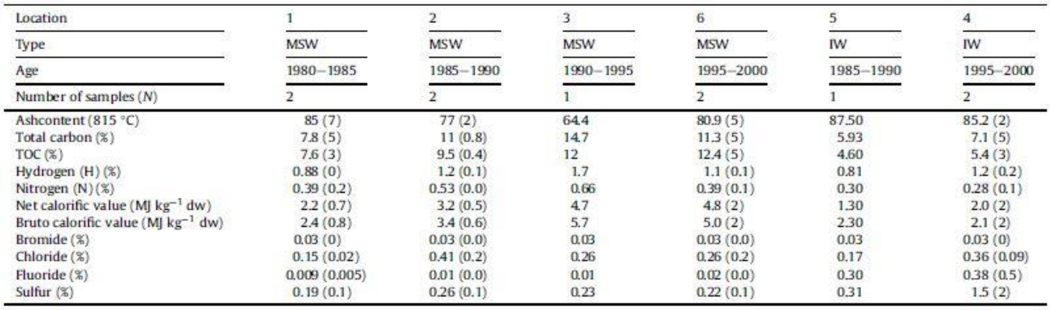
Table 2-18 The average characteristics of paper/cardboard from REMO landfill (Quaghebeur et al., 2012)



Location	1	2	3	6
Type	MSW	MSW	MSW	MSW
Age	1980–1985	1985–1990	1990–1995	1995–2000
Ashcontent (815 °C)	43	61	25	35
Total carbon (%)	32	23	34	33
TOC (%)	34	25	33	31
Hydrogen (H) (%)	3.9	2.6	4.0	3.7
Nitrogen (N) (%)	0.7	0.7	0.8	0.7
Net calorific value (MJ kg^{-1} dw)	11	6.7	12	12
Bruto calorific value (MJ kg^{-1} dw)	12	7.3	13	13
Bromide (%)	<0.025	<0.025	<0.025	<0.025
Chloride (%)	0.50	0.43	0.17	0.28
Fluoride (%)	0.01	0.01	0.01	0.01
Sulfur (%)	0.31	0.19	0.31	0.90

Due to the unknown and heterogeneous nature of the material, the fine; soil type fraction (<10 mm) was analyzed in detail. The results of the properties relevant for energy recovery and material valorization are presented in Table 2-19

Table 2-19 The average characteristics of fine fraction from REMO landfill (Quaghebeur et al., 2012)



Location	1	2	3	6	5	4
Type	MSW	MSW	MSW	MSW	IW	IW
Age	1980–1985	1985–1990	1990–1995	1995–2000	1985–1990	1995–2000
Number of samples (*N*)	2	2	1	2	1	2
Ashcontent (815 °C)	85 (7)	77 (2)	64.4	80.9 (5)	87.50	85.2 (2)
Total carbon (%)	7.8 (5)	11 (0.8)	14.7	11.3 (5)	5.93	7.1 (5)
TOC (%)	7.6 (3)	9.5 (0.4)	12	12.4 (5)	4.60	5.4 (3)
Hydrogen (H) (%)	0.88 (0)	1.2 (0.1)	1.7	1.1 (0.1)	0.81	1.2 (0.2)
Nitrogen (N) (%)	0.39 (0.2)	0.53 (0.0)	0.66	0.39 (0.1)	0.30	0.28 (0.1)
Net calorific value (MJ kg^{-1} dw)	2.2 (0.7)	3.2 (0.5)	4.7	4.8 (2)	1.30	2.0 (2)
Bruto calorific value (MJ kg^{-1} dw)	2.4 (0.8)	3.4 (0.6)	5.7	5.0 (2)	2.30	2.1 (2)
Bromide (%)	0.03 (0)	0.03 (0.0)	0.03	0.03 (0.0)	0.03	0.03 (0)
Chloride (%)	0.15 (0.02)	0.41 (0.2)	0.26	0.26 (0.2)	0.17	0.36 (0.09)
Fluoride (%)	0.009 (0.005)	0.01 (0.0)	0.01	0.02 (0.0)	0.30	0.38 (0.5)
Sulfur (%)	0.19 (0.1)	0.26 (0.1)	0.23	0.22 (0.1)	0.31	1.5 (2)

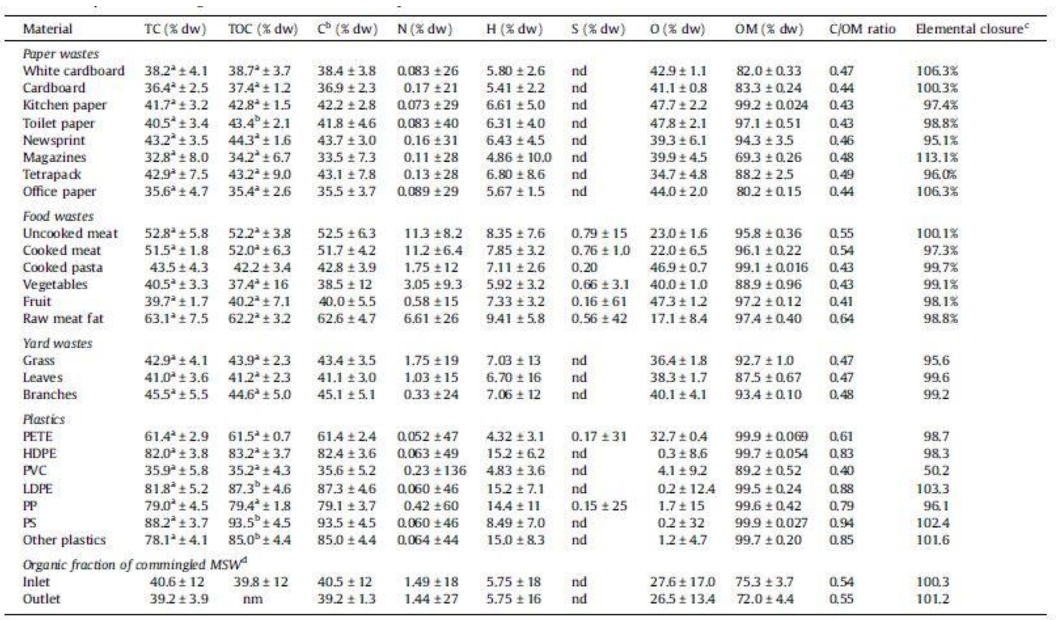
Kaartinen et al., (2013) conducted a detailed study on sampling, processing, and characterization of the landfill mined waste from a 10-year-old Finish landfill. The study found 40-45% (w/w) of the possible fuel fraction in the landfilled waste through manual sorting. The TOC was found as 5.8% for the middle layers and 4.7% for the bottom layer, based on the analysis of the fine materials (<20mm). Hogland et al., 2003 determined the elemental components of the mined waste, and the results are presented in Table 2-20.

Table 2-20 Elemental component of the mined waste (Hogland et al., 2003)

Depth	Fraction	Carbon	Nitrogen	Hydrogen
2-4 m	<18 mm	6.6	.3	.9
2-4 m	18-50 mm	32.2	.5	4.3
6-8 m	<18 mm	19.2	.5	1.3
6-8 m	18-50 mm	38	.5	5

Komilis et al., 2011 conducted a detailed and comprehensive study of the elemental analysis of organic fractions of municipal solid waste. (Table 2-21). Newsprint had the highest C content (43.7% dw), and magazines had the lowest C content (33.5% dw) among paper wastes. Newsprint, kitchen paper and toilet paper had C contents close to 44%, which is the C content of cellulose (C6H10O5), a primary constituent of paper. Office paper, cardboard, and magazines had C contents far lower than 44% (dw. Yard wastes had carbon contents between 40% and 45% (dw). Plastics had some of the highest C contents among all components, except in the case of PETE and PVC. PVC had one of the lowest carbon contents (35.6% dw) among all of the plastic products. This is probably attributed to the high chlorine content of the material (Alter et al., 1974), although no chlorine measurements were performed.

Table 2-21 Elemental analysis of organic fraction of municipal solid waste (Komilis et al., 2011)



Material	TC (% dw)	TOC (% dw)	C^b (% dw)	N (% dw)	H (% dw)	S (% dw)	O (% dw)	OM (% dw)	C/OM ratio	Elemental closure^c
Paper wastes										
White cardboard	38.2^a ± 4.1	38.7^a ± 3.7	38.4 ± 3.8	0.083 ± 26	5.80 ± 2.6	nd	42.9 ± 1.1	82.0 ± 0.33	0.47	106.3%
Cardboard	36.4^a ± 2.5	37.4^a ± 1.2	36.9 ± 2.3	0.17 ± 21	5.41 ± 2.2	nd	41.1 ± 0.8	83.3 ± 0.24	0.44	100.3%
Kitchen paper	41.7^a ± 3.2	42.8^a ± 1.5	42.2 ± 2.8	0.073 ± 29	6.61 ± 5.0	nd	47.7 ± 2.2	99.2 ± 0.024	0.43	97.4%
Toilet paper	40.5^a ± 3.4	43.4^b ± 2.1	41.8 ± 4.6	0.083 ± 40	6.31 ± 4.0	nd	47.8 ± 2.1	97.1 ± 0.51	0.43	98.8%
Newsprint	43.2^a ± 3.5	44.3^a ± 1.6	43.7 ± 3.0	0.16 ± 31	6.43 ± 4.5	nd	39.3 ± 6.1	94.3 ± 3.5	0.46	95.1%
Magazines	32.8^a ± 8.0	34.2^a ± 6.7	33.5 ± 7.3	0.11 ± 28	4.86 ± 10.0	nd	39.9 ± 4.5	69.3 ± 0.26	0.48	113.1%
Tetrapack	42.9^a ± 7.5	43.2^a ± 9.0	43.1 ± 7.8	0.13 ± 28	6.80 ± 8.6	nd	34.7 ± 4.8	88.2 ± 2.5	0.49	96.0%
Office paper	35.6^a ± 4.7	35.4^a ± 2.6	35.5 ± 3.7	0.089 ± 29	5.67 ± 1.5	nd	44.0 ± 2.0	80.2 ± 0.15	0.44	106.3%
Food wastes										
Uncooked meat	52.8^a ± 5.8	52.2^a ± 3.8	52.5 ± 6.3	11.3 ± 8.2	8.35 ± 7.6	0.79 ± 15	23.0 ± 1.6	95.8 ± 0.36	0.55	100.1%
Cooked meat	51.5^a ± 1.8	52.0^a ± 6.3	51.7 ± 4.2	11.2 ± 6.4	7.85 ± 3.2	0.76 ± 1.0	22.0 ± 6.5	96.1 ± 0.22	0.54	97.3%
Cooked pasta	43.5 ± 4.3	42.2 ± 3.4	42.8 ± 3.9	1.75 ± 12	7.11 ± 2.6	0.20	46.9 ± 0.7	99.1 ± 0.016	0.43	99.7%
Vegetables	40.5^a ± 3.3	37.4^a ± 16	38.5 ± 12	3.05 ± 9.3	5.92 ± 3.2	0.66 ± 3.1	40.0 ± 1.0	88.9 ± 0.96	0.43	99.1%
Fruit	39.7^a ± 1.7	40.2^a ± 7.1	40.0 ± 5.5	0.58 ± 15	7.33 ± 3.2	0.16 ± 61	47.3 ± 1.2	97.2 ± 0.12	0.41	98.1%
Raw meat fat	63.1^a ± 7.5	62.2^a ± 3.2	62.6 ± 4.7	6.61 ± 26	9.41 ± 5.8	0.56 ± 42	17.1 ± 8.4	97.4 ± 0.40	0.64	98.8%
Yard wastes										
Grass	42.9^a ± 4.1	43.9^a ± 2.3	43.4 ± 3.5	1.75 ± 19	7.03 ± 13	nd	36.4 ± 1.8	92.7 ± 1.0	0.47	95.6
Leaves	41.0^a ± 3.6	41.2^a ± 2.3	41.1 ± 3.0	1.03 ± 15	6.70 ± 16	nd	38.3 ± 1.7	87.5 ± 0.67	0.47	99.6
Branches	45.5^a ± 5.5	44.6^a ± 5.0	45.1 ± 5.1	0.33 ± 24	7.06 ± 12	nd	40.1 ± 4.1	93.4 ± 0.10	0.48	99.2
Plastics										
PETE	61.4^a ± 2.9	61.5^a ± 0.7	61.4 ± 2.4	0.052 ± 47	4.32 ± 3.1	0.17 ± 31	32.7 ± 0.4	99.9 ± 0.069	0.61	98.7
HDPE	82.0^a ± 3.8	83.2^a ± 3.7	82.4 ± 3.6	0.063 ± 49	15.2 ± 6.2	nd	0.3 ± 8.6	99.7 ± 0.054	0.83	98.3
PVC	35.9^a ± 5.8	35.2^a ± 4.3	35.6 ± 5.2	0.23 ± 136	4.83 ± 3.6	nd	4.1 ± 9.2	89.2 ± 0.52	0.40	50.2
LDPE	81.8^a ± 5.2	87.3^b ± 4.6	87.3 ± 4.6	0.060 ± 46	15.2 ± 7.1	nd	0.2 ± 12.4	99.5 ± 0.24	0.88	103.3
PP	79.0^a ± 4.5	79.4^a ± 1.8	79.1 ± 3.7	0.42 ± 60	14.4 ± 11	0.15 ± 25	1.7 ± 15	99.6 ± 0.42	0.79	96.1
PS	88.2^a ± 3.7	93.5^b ± 4.5	93.5 ± 4.5	0.060 ± 46	8.49 ± 7.0	nd	0.2 ± 32	99.9 ± 0.027	0.94	102.4
Other plastics	78.1^a ± 4.1	85.0^b ± 4.4	85.0 ± 4.4	0.064 ± 44	15.0 ± 8.3	nd	1.2 ± 4.7	99.7 ± 0.20	0.85	101.6
Organic fraction of commingled MSW^d										
Inlet	40.6 ± 12	39.8 ± 12	40.5 ± 12	1.49 ± 18	5.75 ± 18	nd	27.6 ± 17.0	75.3 ± 3.7	0.54	100.3
Outlet	39.2 ± 3.9	nm	39.2 ± 1.3	1.44 ± 27	5.75 ± 16	nd	26.5 ± 13.4	72.0 ± 4.4	0.55	101.2

Researchers still seek a correlation between total carbon (measured by elemental analysis) and organic matter (measured as volatile solids) (Komilis et al., 2011). Such a ratio would be desirable, since the measurement of organic matter is much less tedious than carbon (elemental) analysis. Therefore, if a constant ratio existed, the carbon content could easily be estimated, using the relatively simpler process to perform organic matter measurements. C/OM ratios are shown in Figure 2-13, based on 26 MSW materials and 18 organic composts mentioned in Komilis and Tziouvaras (2009) and Komilis et al. (2011). No uniform C/OM ratio was found for MSW organic components. The C/OM ratios varied widely for the organic waste measured by Komilis and Tziouvaras (2009) and Komilis et al. (2011). In Komilis and Tziouvaras (2009), in particular, the C/OM ratios were found to range from 0.46 to 0.69 for six composts. Komilis et al. (2011) found that the C/OM ratios of 12 organic composts ranged from 0.48 to 0.99, with an average of 0.68 ± 22% (Figure 2-13)

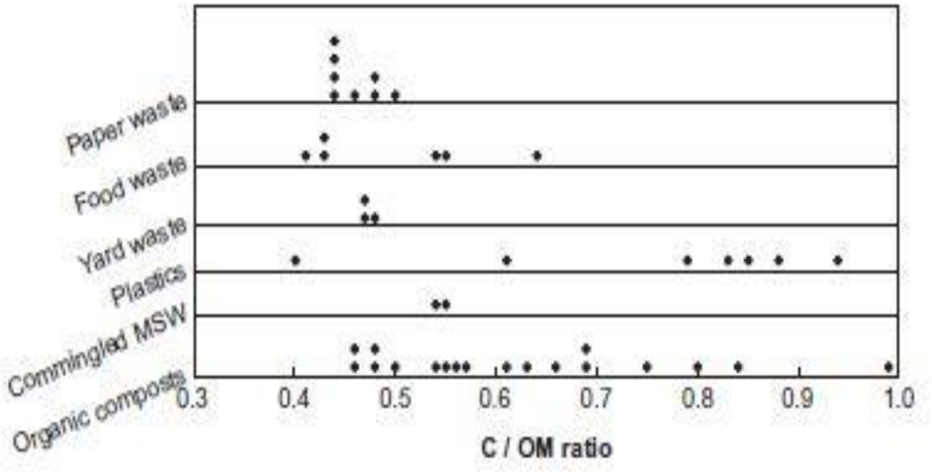


Figure 2-13 Ratio between total carbon and organic carbon (Komilis et al. 2011)

2.9 Statistical Models of Energy Potential

Currently, the energy potential of municipal solid waste is measured either experimentally, or by using the mathematical models (Kathiravale et al., 2003), presented in Table 2-22. The sample size (1 g) required for experimental determination by calorimeter is inadequate to accommodate the heterogeneity of waste. Furthermore, the experimental method is lengthy, cost intensive, and requires technical skills for handling the equipment. The statistical model is very useful for avoiding over reliance on lengthy experimental techniques; however, the prediction is best suited in its own area of study. The three types of mathematical models to predict energy potential of solid waste are physical composition, proximate analysis, and elemental analysis (Liu et al., 1996).

Kathiravale et al., 2003 developed several prediction models of energy values of Malaysia waste, using three different analyses that were based on 30 samples (Table 2-23). A multiple linear regression analysis was performed for building these models. Plastic has weightage of around 20% in equations, followed by paper and food waste. The R^2 values of the equations were .625 to.779. The model was compared with the traditional models found in the literature. Volatile solid waste found as the main predictor for the calorific value in the proximate equation. Carbon, hydrogen, and nitrogen had positive impacts on the prediction models, based on elemental analysis, whereas hydrogen had a negative impact.

Table 2-22 Mathematical models to predict calorific value in the literature (Kathiravale et al., 2003).

Name	Equation	Units	Remarks	Application	Ref.
1. **Models based on ultimate analysis**					
Dulong	$HHV = 8080C + 34,460H - 4,308O + 2250S$	kcal/kg	Original (wt fraction)	Coal	[9]
Dulong	$HHV = 81C + 342.5(H - O/8) + 22.5S - 6(9H - W)$	kcal/kg	Modified (wt%)	MSW/Coal	[18]
Dulong	$HHV = 144.5C + 609.6H - 76.2O + 40S + 10N$	Btu/lb	Modified (wt%)	Coal	[26]
Dulong	$HHV = 78.31C + 359.32(H - O/8) + 22.12S + 11.87O + 5.78N$	kcal/kg	Modified (wt%)	Coal	[9]
Steuer	$HHV = 81(C - 3 \times O/8) + 57 \times 3 \times O/8 + 345(H - O/10) + 25S - 6(9H + W)$	kcal/kg	(wt%)	MSW	[18]
Scheurer–Kestner	$HHV = 81(C - 3 \times O/4) + 342.5H + 22.5S + 57 \times 3 \times O/4 - 6(9H + W)$	kcal/kg	(wt%)	MSW	[18]
Chang	$HHV = 8561.11 + 179.72H - 63.89S - 111.17O - 91.11Cl - 66.94N$	kcal/kg	(wt%)	MSW	[24]
Boie	$HHV = 83.22C + 274.3H - 25.8O + 15N + 9.4Cl + 65P$	kcal/kg	(wt%)	Refuse	[24]
Vondracek	$HHV = C(89.17 - 0.0622C_1) + 270(H - O/10) + 25S$ (C_1—carbon content on moisture and ash free basis)	kcal/kg	(wt%)	Refuse	[24]
Wilson	$HHV = 7831C_{org} + 35,932(H - O/8) + 2212S - 3545C_{inorg} + 1187O + 578N$	kcal/kg	(wt fraction)	MSW	[24]
Mott and Spooner	$HHV = 0.336C + 1.418H - 0.0145O + 0.0941S$	MJ/kg	(wt%)	Coal/Refuse	[26]
Inst. for Gas Tech., USA	$HHV = 0.3417C + 1.3221H + 0.1232S - 0.1198(O + N) - 0.0153A$	MJ/kg	(wt%)	Coal/Refuse	[26]
2. **Models based on proximate analysis**					
Goutal	$HHV = 147.6 \times FC + K \times VM$ (K is a constant that varies with the value of VM)	Btu/lb	(wt%)	Coal/refuse	[9]
Bento	$HHV = 44.75 \times VM - 5.85 \times W + 21.2$	kcal/kg	(wt%)	Refuse	[18]
Traditional	$HHV = 45 \times VM - 6 \times W$	kcal/kg	(wt%)	Refuse	[18]
3. **Models based on physical composition**					
Conventional	$HHV = 88.2Pl + 40.5(Ga + Pa) - 6W$	kcal/kg	(wt%)	Refuse	[18]
Tokyo	$HHV = [(100W)/100]\{38.8(Pa + Ga + T + Oc) + 50.9(Te + Ru) + 73.7Pl\} - 6W$	kcal/kg	(wt%)	MSW	[25]
Ali Khan	$HHV = [23(Ga + 3.6 \times Pa)] + [160(Pl + Ru)]$	Btu/lb	(wt%)	MSW	[9]

HHV = net calorific value; W = wt% of water, dry basis; A = wt% of ash, dry basis; VM = %volatile matter; FC = %fixed carbon; W = total moisture; Pa = paper; Ga = garbage/food; Te = textile; Ru = rubber and leather; Pl = plastics; Oc = other combustibles; T = wood and grass.

Table 2-23 Mathematical models to predict calorific value in Malaysia (Kathiravale et al., 2003).

Name	Equation	Units	Remarks	R^2
1. *Models based on ultimate analysis*				
Eq. (5)	$HHV = 416.638C - 570.017H + 259.031O + 598.955N - 5829.078$	kJ/kg	Dry (wt%)	0.625
2. *Models based on proximate analysis*				
Eq. (4)	$HHV = 356.248VM - 6998.497$	kJ/kg	Dry (wt%)	0.682
Eq. (3)	$HHV = 356.047VM - 118.035FC - 5600.613$	kJ/kg	Dry (wt%)	0.691
3. *Models based on physical composition*				
Eq. (1)	$HHV = 112.157Ga + 183.386Pa + 288.737Pl + 5064.701$	kJ/kg	(wt%)	0.779
Eq. (2)	$HHV = 81.209Ga + 285.035Pl + 8724.209$	kJ/kg	(wt%)	0.645
Eq. (6)	$HHV = 112.815Ga + 184.366Pa + 298.343Pl - 1.920W + 5130.380$	kJ/kg	(wt%)	0.779

HHV = net calorific value; W = wt% of water, dry basis; A = wt% of ash, dry basis; VM = %volatile matter; FC = %fixed carbon; W = total moisture; Pa = paper; Ga = garbage/food; Te = textile; Ru = rubber and leather; Pl = plastics; Oc = other combustibles; T = wood and grass.

Liu et al., 1996 developed a couple of equations (Table 2-24) to predict the calorific values of a landfill in Taiwan, using multiple linear regression, and based on 34 samples (physical composition) and 40 samples (elemental analysis). The model based on physical composition was found superior to the conventional equation found in the literature. The modelling based on proximate analysis was unsuccessful.

Table 2-24 Mathematical models to predict calorific value in Taiwan (Liu et al., 1996)

$Hn=2229.92+28.16R+7.90P+4.87G-37.28W$ (Physical Composition)	Hn=Net Calorific value(Kcal/kg) R=Plastic (% by weight) P=Paper (% by weight) G=Garbage (Food waste, textile, garden waste) (% by weight) W=Moisture Content (%)
$Hn=1558.80+19.96C+44.3O-671.82S-19.92W$	C=Carbon (% by weight) O=Oxygen (% by weight) S=Sulphur (% by weight) W=Moisture Content (%)

Chang and Davila, 2007 developed a prediction model based on physical composition of waste in the Lower Rio Grande Valley, Texas. Multiple linear regression analyses were used to determine the relationship between energy content and waste composition. The derived model was $LHV=4809.5Plastic-568.4Paper-2205.9Food+3510.7$ Kcal/kg.

Shi et al., 2015 developed a prediction model based on elemental analyses of municipal solid waste from the city of Red Deer, Alberta, Canada. A total 193 experimental data (mostly collected from literature) were used to develop the prediction model: 161 data were used for model derivation, and 32 data were used for model validation. The derived model was HHV (MJ/kg) $=.350C+1.01H-.0826O$, where C=carbon (% by weight), O=oxygen (% by weight), and H=hydrogen (% by weight).

Komilis et al., 2011 developed a prediction model based on an elemental analysis of the organic fraction of municipal solid waste. The data set was 26. Multiple linear regression analysis was used to derive the model. Carbon was found as the highest relative contributor to predicting the calorific value, followed by hydrogen and oxygen. The reduced derived model was $CV=81.8(6.99)\,C+304.2(43.9)\,H-35.8(3.18)\,O$, where C=carbon (% by weight), O=oxygen (% by weight), and H=hydrogen (% by weight).

2.10 Summary

For past few years, there have been numerous studies on screening, waste composition, contamination assessment, and valorization potential of landfill mined waste. Several studies emphasized the recovery potential of plastic waste from landfill mining. However, there were major limitations in the previous studies, as listed below.

1. Very few studies focused on the technical aspects of landfill mining. Most of the research emphasized the conceptual design, and financial and legislative aspects of landfill mining.
2. Numerous studies were conducted on the waste composition of landfill mined waste; however, none of them addressed the correlations of the variations of the energy potential of mined waste with the waste composition.
3. No systematic and comprehensive study has been conducted that focuses on the energy potential of mined waste, including all of the affecting factors according to the different depths.
4. Several prediction models for energy potential are available in the literature. However, the dataset is based on fresh waste composition data of a specific area/location. No prediction model has been developed that considers the mined waste composition data of the US

3 Chapter: Methodology

3.1 Introduction

In this chapter, investigation program of the study is presented at the beginning, followed by the selection of the study area. The methodology for collection of sample and storage is presented along with the test procedures followed for determining the physical characteristics of municipal solid waste. The experimental method, oxygen bomb calorimeter was used to determine the energy potential Therefore, a detail description of the bomb calorimeter is presented in this chapter. In addition, elemental analyzer was used to determine the elemental composition of the solid waste. A detail description of the equipment is also presented later in this chapter. Finally, development of three different mathematical model is discussed for the energy potential of municipal solid waste.

3.2 Investigation Program

The investigation program includes the field activities and laboratory experiment on energy potential of solid waste. The field activities consist of sample collection from old and active phase of landfill. The solid waste samples were collected to determine physical characteristics. The laboratory investigation program includes the calorimeter test for determining the Higher Heating value/gross heating value as discussed in section. Tests were conducted in presence of oxygen and nitrogen gas according to the principal of calorimetry. The experimental programs also include the proximate analysis to determine volatile solid and elemental analysis to determine the elemental composition Figure 3.1 summarize an overview of the investigation program of the study.

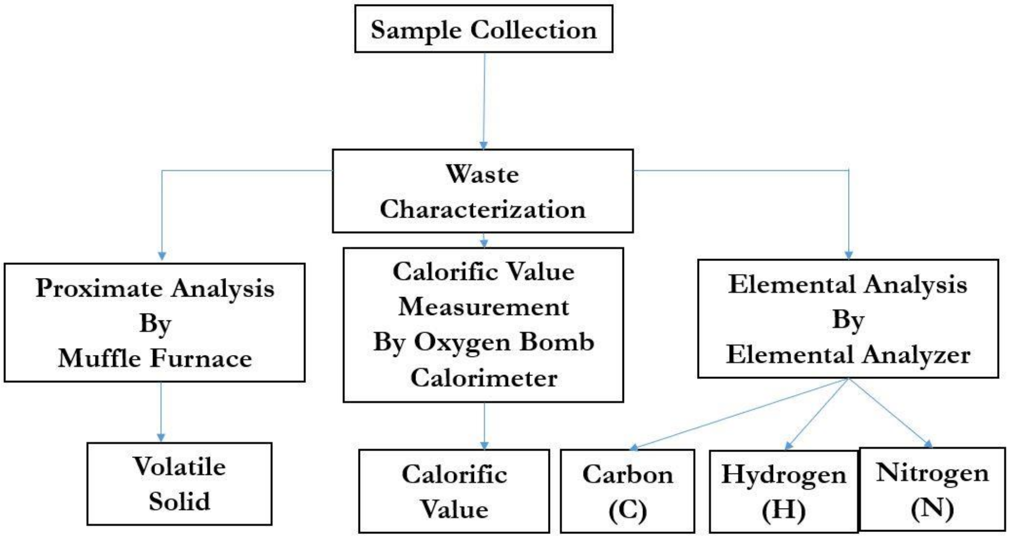


Figure 3-1 Overall investigation program of the study.

3.3 Selection of Study Area

3.3.1 City of Denton Landfill

This Landfill is located on the south east side of Denton, Texas. The aerial view of the City of Denton Landfill is shown in Figure 3.2

Figure 3-2 City of Denton landfill

The landfill is owned and operated by the city of Denton. It opened in 1984 under permit 1590 which was pre subtitle D. The landfill started with 32 acres and in 1998 and then expanded the landfill 252 acres, which covers 152 acres for waste and 100 acres for office, compost area, buffer zone and extra rented land. Currently, there are six cells in the landfill and the former cell is considered as cell zero or cell 1590. It follows operational rules given in the 30 TAC 330 subchapters D, which is provided by the Texas Administration Code.

The city of Denton Landfill is a type 1 landfill that means it receives Municipal Solid Waste (MSW). There are 20 groundwater monitoring wells and 20 gas monitoring wells. Cell 0 is pre-subtitle D landfill and the rest of the landfill is sub-title D landfill with a liner system which protects the groundwater from pollution. The waste in the landfills decomposes very slowly due to lack of oxygen. Adding oxygen to the waste increases the rate of decomposition and the waste decomposes faster.

In 2008, the city of Denton landfill installed a landfill gas collection system to collect and use landfill gas energy as a green energy source. The electric power generator on site takes the collected gas. The capacity of the electric generator is 1.6 megawatts, which is equivalent to powering 1,200 homes per year. The electric power station was designed to expand as methane gas production increases.

For the present study, sample waste was collected from seven boreholes (BH-D to BH-G and BH-05 to BH-07) at different depths of Cell 0 for the conventional cells and six boreholes (BH-A to BH-C and BH- 3A, 3B, 3C) from Cell 2 and Cell 3 for the ELR cells. The fresh waste was collected from the active Cell in five bags (F1 to F5). Figure 3-3 gives a demonstration of the positions of the boreholes.

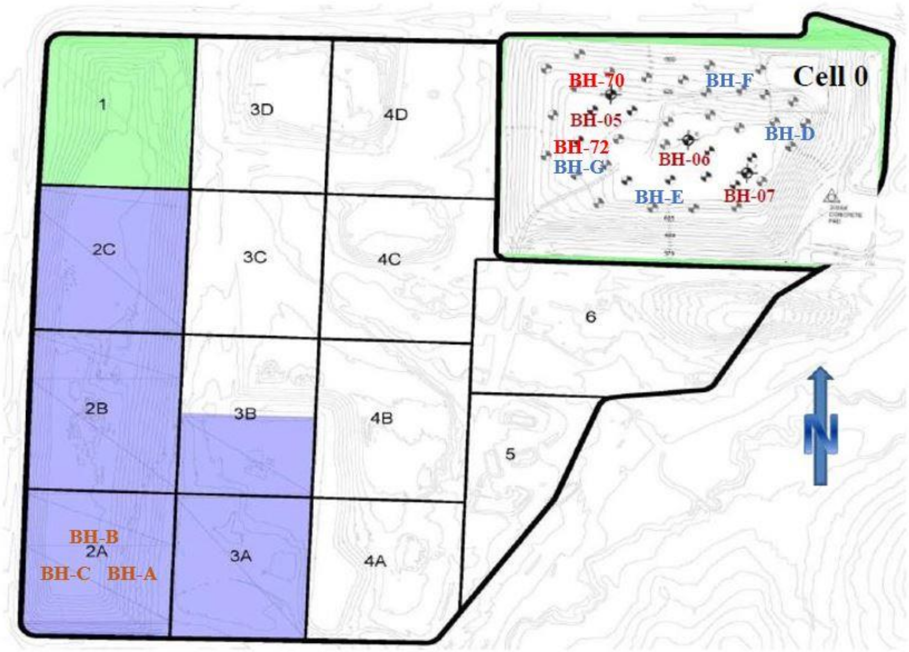


Figure 3-3 Positions of the boreholes in City of Denton landfill

3.3.2 City of Irving Landfill

The City of Irving Landfill is located on the south side of Irving, Texas, and is owned and operated by the City of Irving. The permit was approved in 1981, and waste was first accepted in the following year, 1982. Currently, this landfill accepts 550 tons/day. Figure 3-4 shows the current layout and borehole position of the only active cell of the landfill. For the current study, samples were collected from three boreholes (X, Y & Z). Borehole X was from the initial landfill location, which accepted waste from 1982 - 1992. The cell was extended later to the current cell layout, which was divided into two sections: Phase 2 (north) and Phase 2 (south). Boreholes Y & Z were selected from the two sections, respectively.

Figure 3-4 Positions of the boreholes in City of Irving landfill

3.4 Sample collection & storage

Municipal Solid waste samples were collected from the city of Denton landfill in November 2010.An AF130 Hydraulic Drill Rig was used for drilling which has a 3 ft diameter bucket augur, as shown in Figure 3.5. 2 boreholes (B70 and B72) were dug at site. Solid waste was collected from these 2 boreholes. The boreholes were dug on Cell 1590 of this landfill. This section of the landfill contained solid waste as old as 25 years. The dated newspapers and magazines of the collected samples were used to estimate the age of the waste. Six samples were collected from each borehole starting at 10 ft depth and then at every 10 ft interval up to 60 ft. It was observed that the required MSW sample weight for characterization is 25 to 30 lbs from previous research work conducted by Taufiq (2010), Therefore, 25 to 30 lbs of MSW was collected for each sample.

(a) (b)

(c)

Figure 3-5 a) AF 130 Hydraulic drill rig, (b) 3-ft diameter bucket augur (c) Sample collection

Lidded plastic buckets were used to collect samples and they were brought to the laboratory. All the samples in the buckets were stored and preserved at approximately 38°F (below 4°C) in an environmental growth chamber to avoid the loss of moisture. Figures 3.6 shows the environmental growth chamber.

(a) (b)

Figure 3-6 (a) Environmental growth chamber (b) Storage of sample in environmental growth chamber

3.5 Experimental Program for Physical Composition

An extensive experimental program was developed for the current study. The experimental program is presented in Table 3.1.

Table 3-1 Experimental program for physical characteristics

Test Type	Fresh Sample from City of Denton Landfill	Mined Sample from City of Irving Landfill	No of Test
Physical Composition	18 Bag	22 Bag	40
Moisture Content	18 Bag	22 Bag	40
Volatile Solid	18 Bag	22 Bag	40

The methodologies adopted for determination of the physical characteristics and hydraulic characteristics are described in the following subsections.

3.5.1 Physical Composition

The physical composition of the samples was determined, by pouring waste from each bucket onto a large plastic sheet and manually separating them into the following categories: paper, plastic, leather & textile, food waste, wood & yard waste, glass, metals, styro-foam & sponge, others (soil & fines) and construction debris, as shown in Figure 3.7

Figure 3-7 Physical composition of waste

The paper category comprises of all kinds of papers like cardboard packaging, newspaper, magazines, office papers, etc. All plastic category comprises of polythene bags, containers, food wrappers and plastic bottles. Rubber was also considered under plastic. All leathers, clothes, fabrics, etc., and the construction insulation materials thrown after demolition were also categorized as leather & textile. Garden waste, and also broken pieces of wood i.e construction & demolition waste was categorized as wood and yard waste. All cutlery, metal cans and food containers were placed under metal category. Lime, bricks and stone chips, broken tiles etc were considered as construction debris. Any portion of the solid waste that could not be placed under any of the above mentioned categories such as lumps of mud and objects too small to separate were categorized as others. Also the other components were separated into degraded portion and soils later. All the samples were sorted manually and were then individually weighed and these weights were presented as a percentage of total weight. The total weight in paper, leather & textile, food waste, and wood & yard waste were considered as degradable and the rest of the total weight as non-degradable. The percentages of non-degradable and degradable portions were also determined.

3.5.2 Moisture Content

For determination of moisture content, three types of specimens can be used:

1. Specimens sampled before sorting.

2. Taking each component proportionately according to physical composition after sorting

3. Taking standard proctor compacted samples (proportional to composition)

For this study, method 1 was used for moisture content determination. Moisture content of the samples were determined according to standards set by ASTM D 2974 – 00 and APHA 2540 – B (Kelly, 2002). A minimum 2 lbs of waste was taken for each test, so that it would be more representative of the original MSW.

To determine the moisture loss the samples were dried at 105°C in the oven for 24 hours. The percentage loss was determined on both dry and wet weight basis. Equations 3.1 and 3.2 were used to determine moisture content on wet weight basis and dry weight basis respectively. Figure 3.7 shows sample being dried in the oven for the determination of moisture content. The wet weight moisture content is expressed as follows:

$$Moisture\ Content, \%(wet\ wt\ basis) = \frac{a-b}{a}\ X\ 100 - - - - - - - - (3.1)$$

Where, a = initial weight of the sample as delivered; and

b = weight of the sample after drying.

Moisture contents can also be determined based on the following relationship

$$Moisture\ Content, \%(wet\ wt\ basis) = \frac{a-b}{b}\ X\ 100 - - - - - - - - -(3.2)$$

Where, a = initial weight of the sample as delivered; and

b = weight of the sample after drying.

Figure 3-8 Moisture content determination by oven

3.5.3 Volatile Solid

The volatile solids method followed a modified version of Standard Methods APHA Method 2440-E. Samples were dried once again at 105°C to a constant weight and held in a desiccator. Approximately 50 gm of dried MSW were placed in pre-weighed porcelain crucibles and inserted into a muffle furnace at 550°C for 2 h. Equation 3.4 illustrates how to calculate volatile solids of solid waste. Figure 3.9 illustrates the sample preparation for volatile solids determination

$$Volatile\ Solid\ ,\% = \frac{a-b}{a}\ X\ 100 ------------ (3.3)$$

Where, a = initial weight of dried sample (50 gm) and

b = weight of the sample after the test.

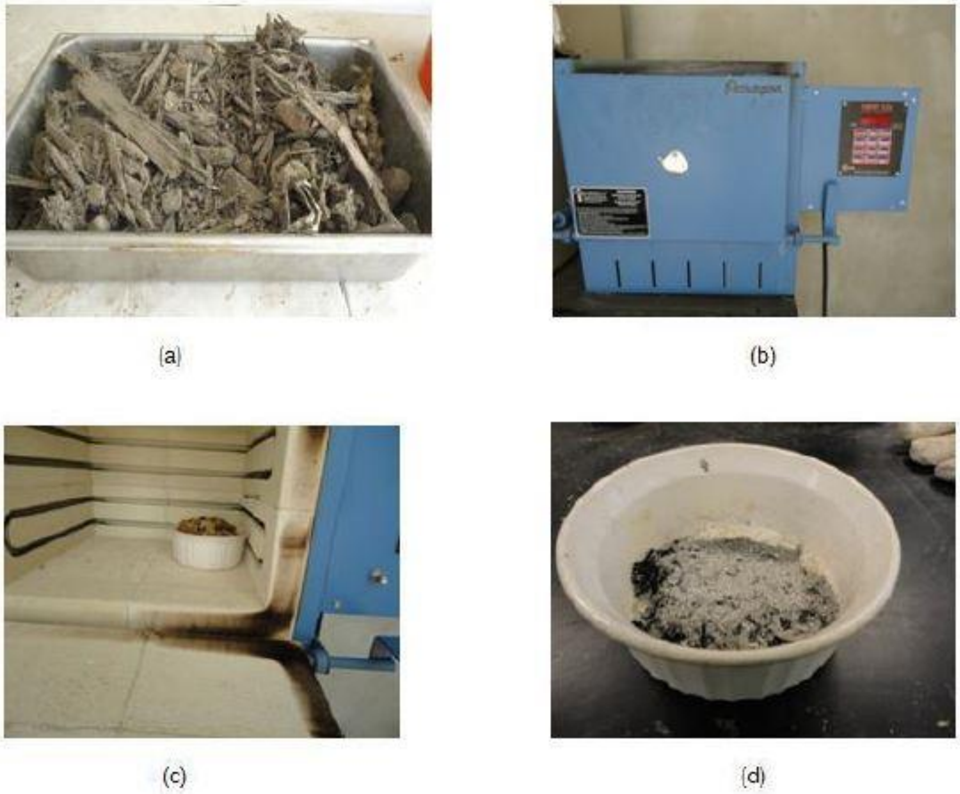
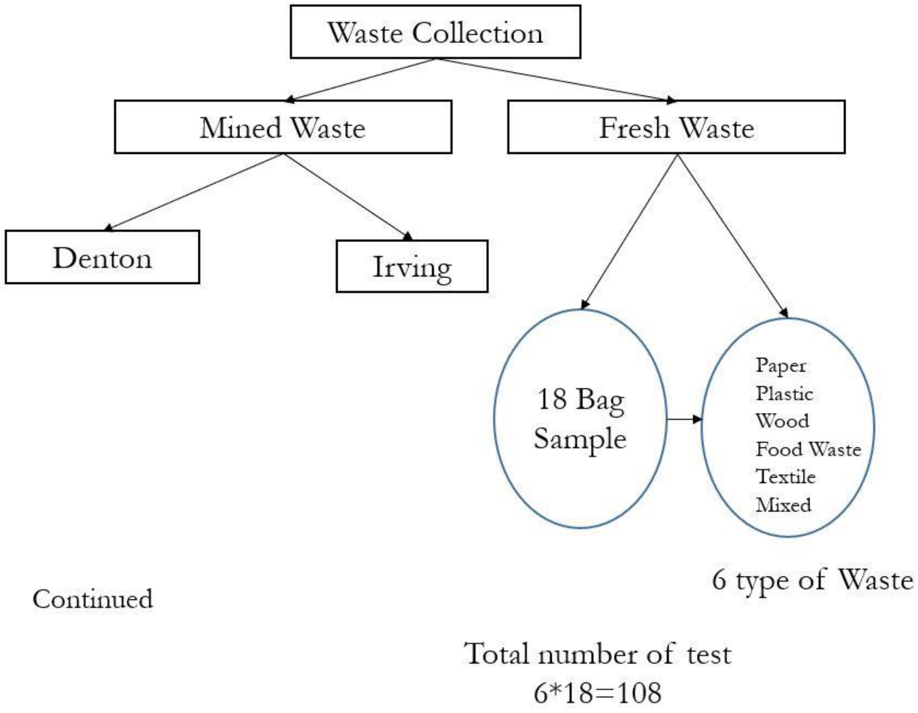


Figure 3-9 (a) Sample after drying (b) Muffle furnace set at 550°C (c) Grinded sample before the test (d) Burnt sample after the test

3.6 Experimental program for Calorific value Determination

An extensive experimental program was developed for the current study and is presented in Table 3.2.



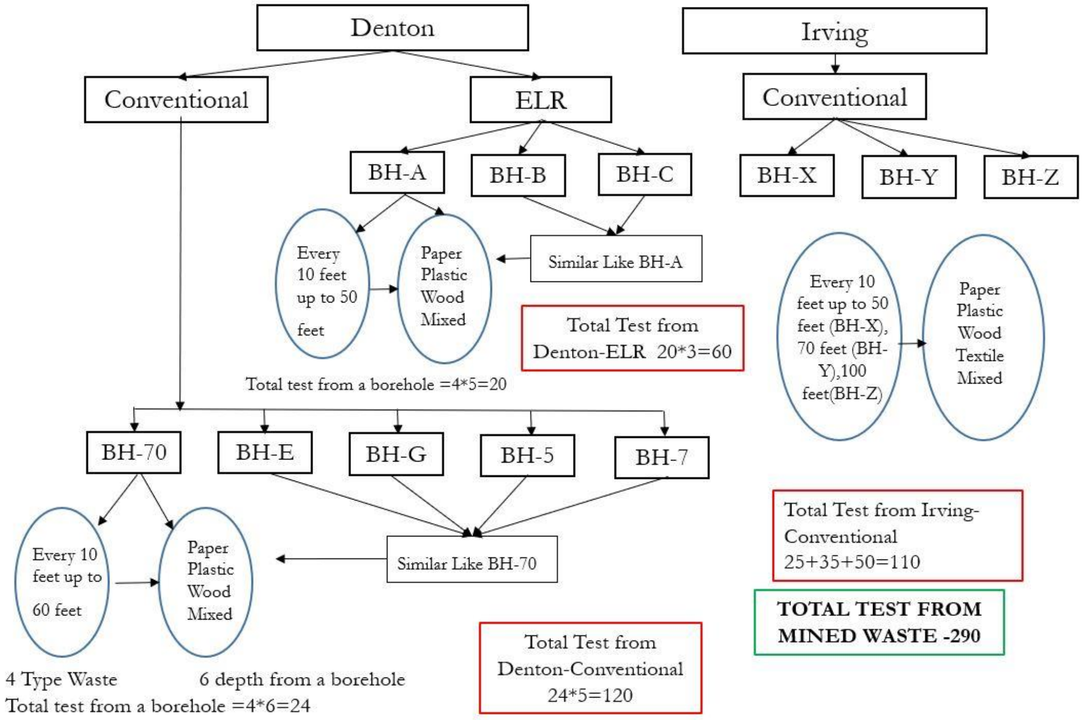


Table 3-2 Experimental program for calorific value determination

3.6.1 Oxygen Bomb Calorimeter

Calorimetry is the science of measuring quantities of heat, as distinct from ”temperature”. The instruments used for such measurements are known as calorimeters. In this study, we are concerned only with oxygen bomb calorimeters, which are the standard instruments for measuring calorific values of solid and liquid combustible samples.

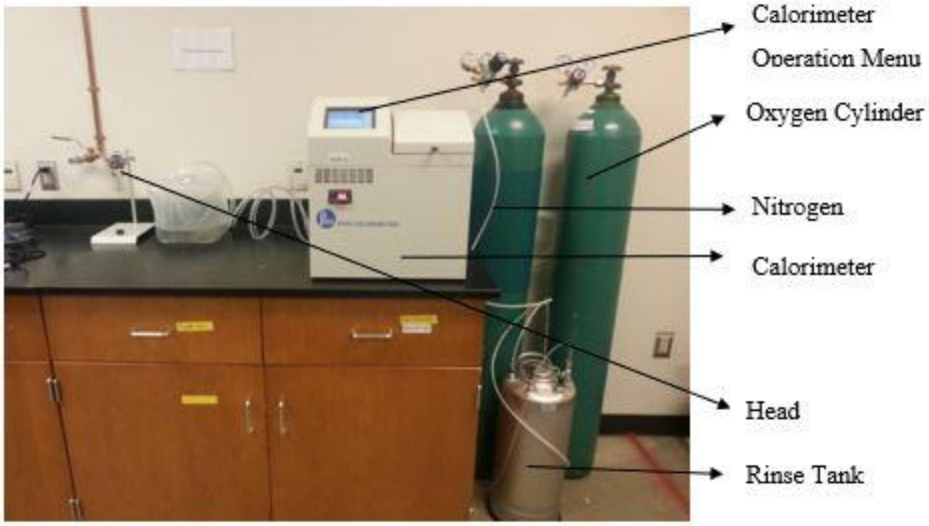


Figure 3-10 Components of oxygen bomb calorimeter

The calorific value (heat of combustion) of a sample may be broadly defined as the number of heat units liberated by a unit mass of a sample when burned with oxygen in an enclosure of constant volume. In this reaction the sample and the oxygen are initially at the same temperature and the products of combustion are cooled to within a few degrees of the initial temperature; also the water vapor formed by the combustion is condensed to the liquid state. A more exact definition would specify the temperature at which the reaction begins and ends. However, the change in the heat of combustion with possible variations in the initial temperature is so small that this specification is not necessary. Also, the initial and final temperatures are not the same – differing by the amount of temperature rise in the calorimeter – but the effect of this difference is small and usually it is neglected. Thus the term calorific value (or heat of combustion) as measured in a bomb calorimeter denotes the heat liberated by the combustion of all carbon and hydrogen with oxygen to form carbon dioxide and water, including the heat liberated by the oxidation of other elements such as sulfur which may be present in the sample.The following sections regarding the bomb calorimeter is based on the manual ‘’Introduction to Bomb Calorimetry’’ by Parr Instrument Company.

Characteristics of Bomb Calorimeters

Heats of combustion as determined in an oxygen bomb calorimeter are measured by a substitution procedure in which the heat obtained from the sample is compared with the heat obtained from combustion of a similar amount of benzoic acid or other standardizing material whose calorific value is known. These measurements are obtained by burning a representative sample in a high-pressure oxygen atmosphere within a metal pressure vessel or “bomb”. The energy released by this combustion is absorbed within the calorimeter and the resulting temperature change within the absorbing medium is noted. The heat of combustion of the sample is then calculated by multiplying the temperature rise in the calorimeter by a previously determined energy equivalent or heat capacity determined from previous tests with a standardizing material. Corrections must be applied to adjust these values for any heat transfer occurring in the calorimeter, as well as for any side reactions which are unique to the bomb combustion process.

Four essential parts are required in any bomb calorimeter:

1. A bomb or vessel in which the combustible charges can be burned.
2. A bucket or container for holding the bomb in a measured quantity of water, together with a stirring mechanism.
3. An insulating jacket to protect the bucket from transient thermal stresses during the combustion process.
4. A thermometer or other sensor for measuring temperature changes within the bucket.

For best precision, the temperature of the calorimeter jacket must be closely controlled. This usually requires a water-filled jacket equipped with a means for adjusting the jacket temperature, either by an immersion heater or by hot and cold water injections. With a temperature controlled jacket the calorimeter can be operated either in an adiabatic or isoperibol mode. In an adiabatic system the jacket temperature is adjusted continuously during a test to keep it equal at all times to the temperature in the bucket. Thus, by maintaining a zero differential between the jacket and bucket, there will be no heat transfer between the jacket and bucket, there will be no heat transfer between these components and the calculations and corrections required for an uncontrolled or isoperibol system can be eliminated. This type of jacketing was the dominate method for bomb calorimetry since Parr introduced the first practical adiabatic jacket nearly 100 years ago. With the introduction of microprocessorbased calorimeter controllers, isoperibol operation has become an extremely attractive option. In this type of system the jacket temperature is controlled and held constant throughout the determination while the bucket temperature is rising. With their less demanding requirements for externally supplied heating and cooling mediums, isoperibol systems offer opportunities for significant savings in energy and installed accessory equipment. Isoperibol calorimeters with microprocessor control are also the preferred choice for laboratories in which large numbers of samples are tested daily on a routine basis, giving the user the ability to complete as many as 7 tests per hour with excellent repeatability.

3.6.2 Test methodology for calorific value

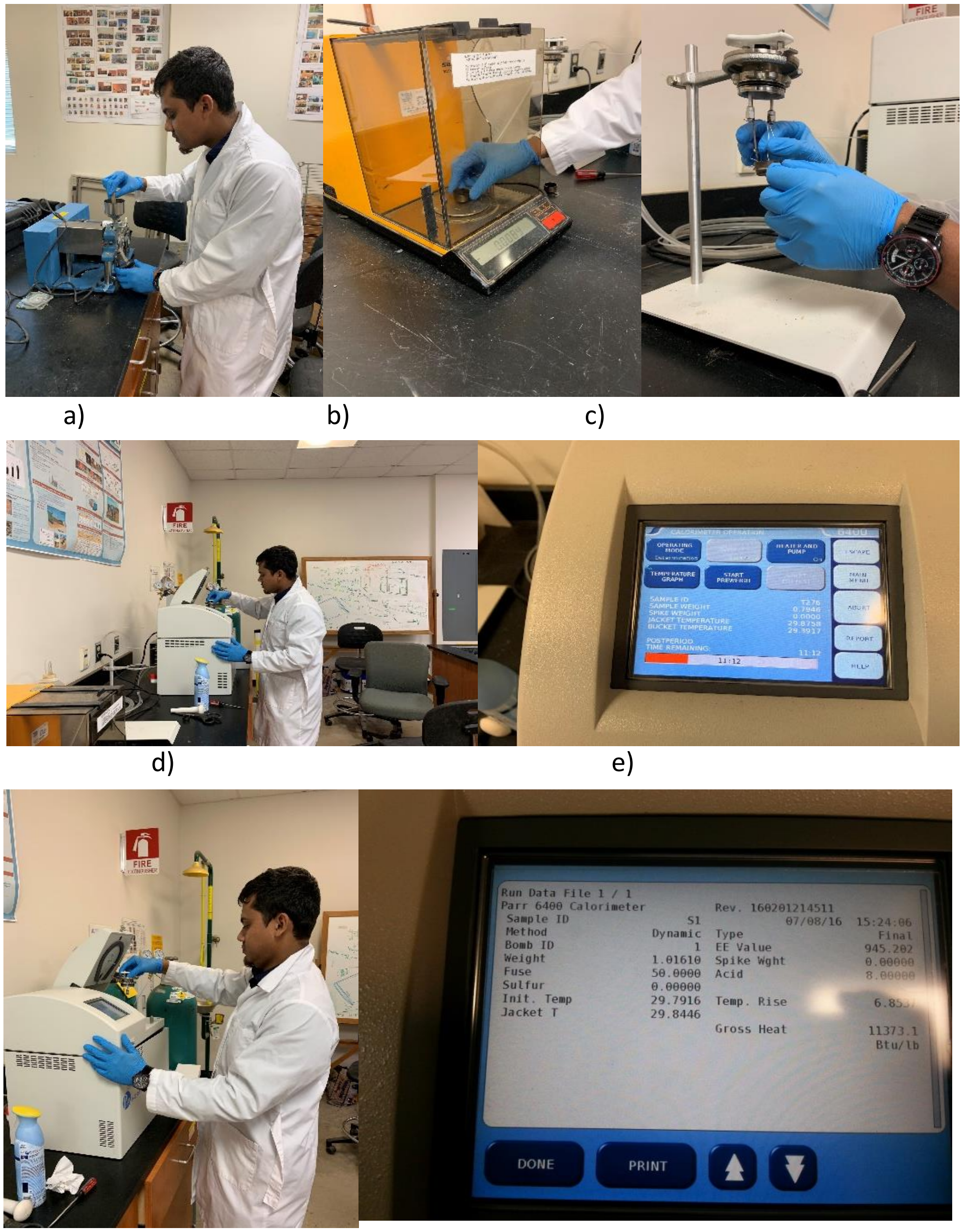
The steps for to measure calorific value are listed below

- The samples were grinded to 60 mesh. Large particles may not burn completely and small particles are easily swept out of the capsule by turbulent gases during rapid combustion
- Prepare and weigh the sample to 0.0001g. The sample of the weight was within 1 g.
- Carefully place the capsule into the capsule holder. A cotton thread (845DD2) is used as an auxiliary fuse to ignite the sample. The ignition

thread should not be buried in a powder or granulated sample. Remove any moisture from the heating wire prior to attaching the cotton thread.

- Load the head into the calorimeter. Place the head into the cylinder. Rotate the handle clockwise to lock the head into position Close and latch the lid.
- Initially the calorimeter was calibrated with one gram benzoic acid pallet. The Parr benzoic acid has been calibrated against NIST benzoic acid. Additional benzoic acid pellets can be obtained from
- Choose Standardization (calibration) or Determination (unknown samples) for Operating Mode.
- Press Start Input the Sample ID Input the Bomb ID Input the Sample weight Input the Spike weight (if spiking is turned on)
- The test will automatically proceed through the following steps:
- Fill Cycle Preperiod Cycle Fire the sample Post Period Cycle Exhaust the bomb Cool/Rinse Cycle
- Once the calorimeter is finished with the cool/rinse cycle the results will print out on the printer or display on the touch screen

The 6400 Calorimeter will automatically make all of the calculations necessary to produce a gross heat of combustion for the sample. However, it is important that the user understands these calculations to ensure the instrument is set up so the calculations match the procedures and the units are consistent throughout the process.



a) b) c)

d) e)

f) g)

```
CALORIMETER OPERATION                                6400
SAMPLE ID                        T276
SAMPLE WEIGHT                    0.7946
SPIKE WEIGHT                     0.0000
JACKET TEMPERATURE               29.8758
BUCKET TEMPERATURE               29.3917

POSTPERIOD
TIME REMAINING:                  11:12
             11:12
```

```
Run Data File 1 / 1
Parr 6400 Calorimeter              Rev. 160201214511
 Sample ID                 S1               07/08/16  15:24:06
 Method               Dynamic      Type                 Final
 Bomb ID                    1      EE Value           945.202
 Weight               1.01610      Spike Wght         0.00000
 Fuse                 50.0000      Acid               8.00000
 Sulfur               0.00000
 Init. Temp           29.7916      Temp. Rise            6.85
 Jacket T             29.8446
                                   Gross Heat         11373.1
                                                       Btu/lb
```

Figure 3-11 a) Grindig the sample b) Weighing the sample c) Putting Ingition thread d) Loading the sample e) Ongoing experiment f) Taking out the sample after the test g) Result display

The 6400 Calorimeter will automatically make all of the calculations necessary to produce a gross heat of combustion for the sample. However, it is important that the user understands these calculations to ensure the instrument is set up so the calculations match the procedures and the units are consistent throughout the process.

The calculation for the gross heat of combustion is done by:

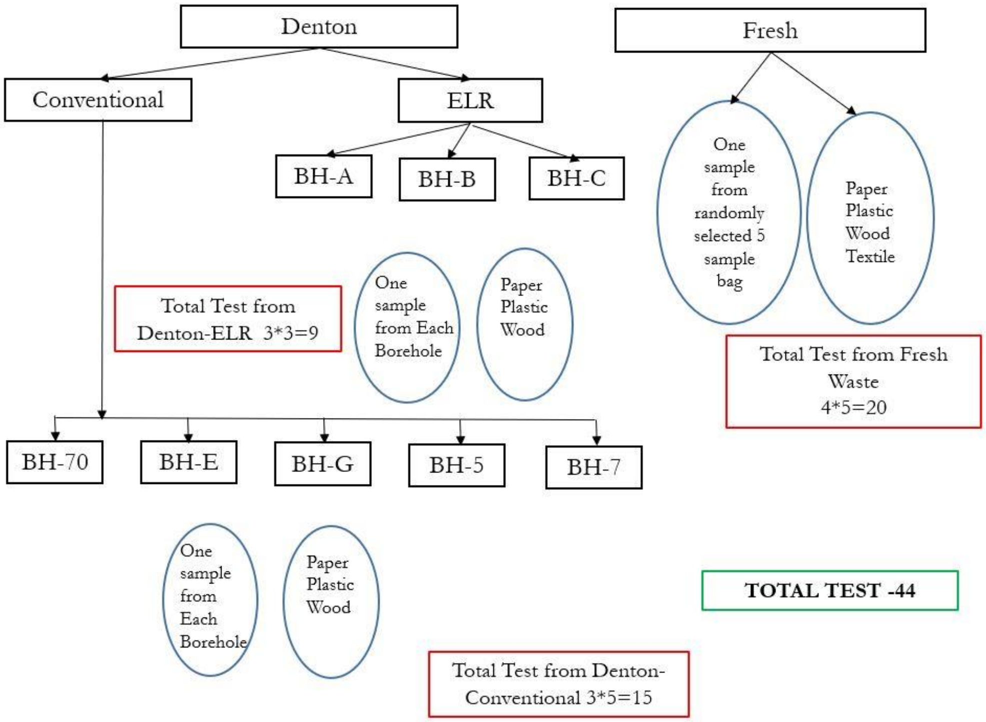
$$H_c = \frac{WT - e_1 - e_2 - e_3}{m}$$

Hc	Gross heat of combustion.
T	Observed temperature rise.
W	Energy equivalent of the calorimeter being used.
e1	Heat produced by burning the nitrogen portion of the air trapped in the bomb to form nitric acid.
e2	The heat produced by the formation of sulfuric acid from the reaction of sulfur dioxide, water and oxygen.
e3	Heat produced by the heating wire and cotton thread.
m	Mass of the sample.

3.7 Experimental Program for Elemental Analysis

An extensive experimental program was developed for the current study, and is presented in Table 3.3

Table 3-3 Experimental program for elemental analysis



3.7.1 Elemental Analyzer

The CHN mode is the most widely used of the analysis modes. A range of reagents and the ability to optimize the combustion parameters offer flexibility for analyzing virtually any sample types. Interfering elements such as halogens and sulfur are removed before detection. The principal and the methodology are based on the product note from PerkinElmer Instrument. The components of an elemental analyzer are shown in Figure 3-12

Figure 3-12 Components of elemental analyzer

The 2400 Series II system is comprised of four major zones:

- Combustion Zone

- Gas Control Zone

- Separation Zone

- Detection Zone

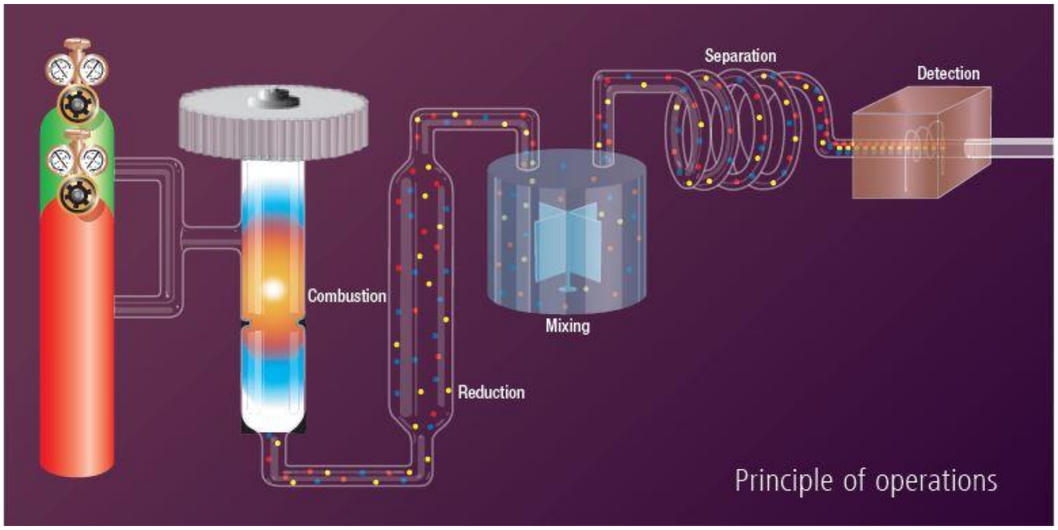


Figure 3-13 Principal of operation in elemental analyzer (Perkin Elmer Manual)

In the Combustion Zone, samples encapsulated n tin or aluminum vials are nserted automatically from the ntegral 60-position autosampler, or manually, using a single-sample auto njector.

In the Combustion Zone, samples encapsulated in tin or aluminum vials are inserted automatically from the integral 60-position autosampler or manually using a single-sample auto injector.

In the presence of excess oxygen and combustion reagents, samples are combusted completely and reduced to the elemental gases CO_2, H_2O, N_2 and SO_2. Users have the flexibility of optimizing static and dynamic combustion conditions to meet the specific sampling need of their laboratory. The combustion products are then passed to the Gas Control Zone of the 2400 Series II.

Gases are captured in the mixing chamber of the Gas Control Zone. Here, gases are rapidly mixed and precisely maintained at controlled conditions of pressure, temperature and volume. By controlling the product gases from combustion/pyrolysis to the same exact conditions (pressure, volume and temperature) for every run, outside influences (barometric pressure changes, altitude) are eliminated. The combustion process is separated from the column and detector which gives the flexibility of varying combustion conditions in the same series of runs without influencing separation and detection and the gases are mechanically homogenized therefore providing precision and accuracy.

After homogenization of product gases, the mixing chamber is depressurized through a column in the Separation Zone of the instrument. The separation approach used is a technique known as Frontal Chromatography.

As the gases elute, illustrated in Figure 2, they are measured by a thermal conductivity detector in the Detection Zone of the analyzer. Since measurements in this design are made as stepwise changes from the carrier gas baseline, the variations associated with the quantification of peak signals in other CHNS/O analyzers is eliminated.

3.7.2 Test methodology for Elemental Analysis.

C, N, H contents were measured via an elemental analyzer (CHNS/O Analyzer, Model 2400 Series II, PerkinElmer Instrument, Connecticut, USA) according to the following procedure: 1–6 mg of the dried and ground samples were placed in tin capsules during the C, N, H analyses. During sample analyses (n = 5), measurements were always kept within the calibration limits (i.e., five tin or silver capsules per substrate). C, N, H were measured concurrently upon insertion of one sample. Electrolytic copper and copper oxide were used as the catalysts during C, N, H analyses and the reaction chamber temperature was kept at 1000 degree celsius. Helium flow was maintained at 120 ml/ min and oxygen injection lasted 60 s. Purity of O_2 used during quantification of C, N, H was 99.9999%. The chromatographic column was a 2 m Teflon PQSW packed column. The GC oven temperature was kept steadily at 60 degree Celsius. C, H, S were quantified as CO_2, N_2, H_2O and SO_2, respectively, using a thermal conductivity detector (TCD).

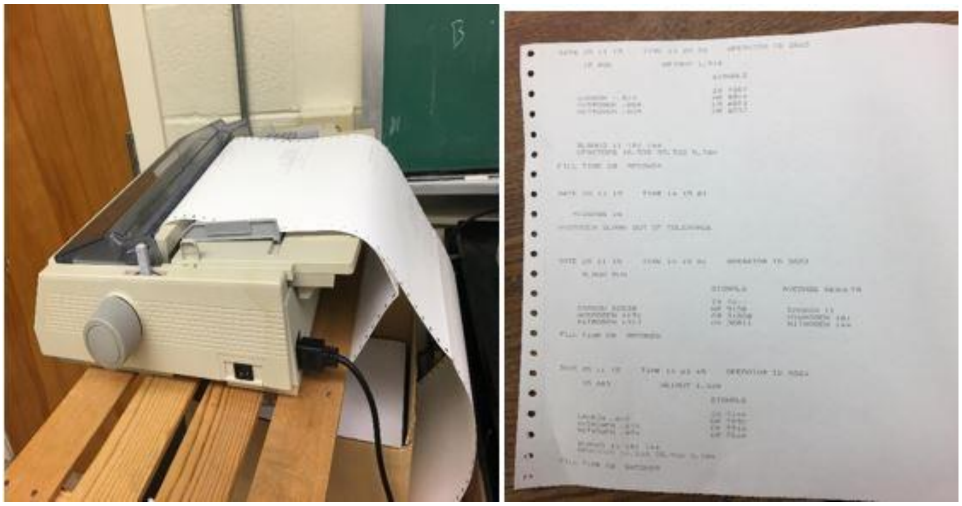


Figure 3-14 Output from elemental analysis

Figure 3-15 Sample preparation for elemental analysis

4 Chapter: Results and Discussion

4.1 Introduction

In this chapter, the results obtained from the waste composition and the experimental study are presented in detail. Both fresh waste and mined waste samples were collected from the City of Denton landfill, and brought to the laboratory for testing. The physical characteristics of the fresh and mined waste were found before evaluating the energy potential of the waste. The energy potential of solid waste (fresh and mined) in the landfill is greatly influenced by the waste composition. In addition, different physical characteristics like moisture content and volatile solids, are good indicators for assessing the energy potential, which is the single most important factor to consider before designing any waste-to-energy plant or incinerator. The waste is heterogeneous material because of the many types of waste components. The current study focuses on the energy potential of different components of solid waste. Factors affecting the energy potential have been studied as a part of a research. An alternative experimental method, elemental analysis, was performed to provide a different view of assessing the energy potential. The experimental results are presented and discussed in this chapter, which is divided into three sections. The first section includes the characteristics of municipal solid waste components (moisture content, physical composition, and volatile solids) from two different cells. The second section provides details of the energy potential of different components of solid waste and mixed waste. Elemental analysis of solid waste was covered in Section 3. The model equations developed in this study to predict energy potential are presented and discussed in Chapter 5.

4.2 Physical Characteristics

4.2.1 Waste composition

4.2.1.1 Fresh waste composition from City of Denton Landfill

The physical composition of the fresh waste samples was determined by manual sorting 22 fresh waste bags that were collected from 4 different months from 2016-2018. The physical composition results are listed in Tables 4-1 to 4-4. The samples are also identified as degradable and non-degradable and are listed in Table 4-5.

Table 4-1 Physical Composition (% by Weight) of MSW of March 2016 Samples

Sample No.	Physical Composition (% by Weight)									
	Paper	**Plastic**	**Food waste**	**Textile and Leather**	**Yard Waste and Wood**	**Metals**	**Glass**	**Styrofoam and Sponge**	**C & D Debris**	**Others (Soils and Fines)**
A-1	58.13	8.16	3.37	6.98	15.30	0.32	0.08	2.20	3.28	8.57
A-2	20.94	24.18	20.39	1.64	14.85	6.10	3.51	2.57	0.00	4.83
A-3	42.98	15.46	5.76	2.49	17.02	1.45	0.15	1.11	8.07	4.46
A-4	19.99	13.21	10.95	26.45	6.74	1.95	2.82	5.55	8.19	2.67
A-5	25.90	18.63	17.41	10.61	1.25	3.63	1.98	2.00	1.34	17.1
A-6	36.33	27.00	19.93	0.055	0.00	3.92	1.44	1.14	0.06	7.41
Average	**34.05**	**17.77**	**12.97**	**8.04**	**9.19**	**2.90**	**1.66**	**2.43**	**3.49**	**7.51**
Standard Deviation	**14.84**	**7.01**	**7.37**	**9.82**	**7.54**	**2.07**	**1.39**	**1.64**	**3.79**	**5.16**
Maximum	**58.13**	**27.00**	**20.39**	**26.45**	**17.02**	**6.1**	**3.51**	**5.55**	**8.19**	**17.1**
Minimum	**19.99**	**8.16**	**3.37**	**0.055**	**0.00**	**0.32**	**0.08**	**1.11**	**0.00**	**2.67**

Table 4-2 Physical Composition (% by Weight) of MSW of November 2016 Samples

Sample No.	Physical Composition (% by Weight)									
	Paper	**Plastic**	**Food waste**	**Textile and Leather**	**Yard Waste and Wood**	**Metals**	**Glass**	**Styrofoam and Sponge**	**C & D Debris**	**Others (Soils and Fines)**
N-1	33.8	17.83	38.60	0.00	6.54	0.00	0.11	1.09	2.03	0.00
N-2	31.90	24.56	8.21	1.57	12.88	8.65	4.45	1.39	0.00	6.29
N-3	63.4	15.99	6.74	6.70	3.16	0.00	1.01	0.36	0.00	2.64
N-4	50.10	15.70	8.97	0.00	15.85	8.09	0.00	1.19	0.00	0.00
N-5	35.62	15.46	6.25	0.00	25.09	0.00	12.01	3.95	0.00	1.61
Average	**43.00**	**17.91**	**13.76**	**1.65**	**12.70**	**3.35**	**3.52**	**1.60**	**0.41**	**2.11**
Standard Deviation	**13.49**	**3.83**	**13.93**	**2.90**	**8.55**	**4.59**	**5.08**	**1.37**	**0.91**	**2.59**
Maximum	**63.40**	**24.56**	**38.60**	**6.70**	**25.09**	**8.65**	**12.01**	**3.95**	**2.03**	**6.29**
Minimum	**31.98**	**15.46**	**6.25**	**0.00**	**3.16**	**0.00**	**0.00**	**0.36**	**0.00**	**0.00**

Table 4-3 Physical Composition (% by Weight) of MSW of May 2017 Sample

Sample No.	Physical Composition (% by Weight)									
	Paper	**Plastic**	**Food waste**	**Textile & Leather**	**Yard Waste and Wood**	**Metals**	**Glass**	**Styrofoam and Sponge**	**C & D Debris**	**Others (Soils and Fines)**
M-1	32.55	26.67	17.25	3.92	0.00	3.92	8.63	0.78	0.00	6.27
M-2	28.34	26.51	5.54	3.73	24.37	6.45	0.00	5.07	0.00	0.00
M-3	35.99	25.68	10.02	7.69	11.31	6.70	1.43	1.19	0.00	0.00
M-4	39.60	23.17	1.79	4.04	25.20	0.88	2.77	2.54	0.00	0.00
M-5	29.91	25.19	19.55	6.30	3.11	4.17	11.21	0.56	0.00	0.00
Average	**33.28**	**25.44**	**10.83**	**5.14**	**12.80**	**4.42**	**4.81**	**2.03**	**0.00**	**1.25**
Standard Deviation	**4.57**	**1.41**	**7.54**	**1.77**	**11.70**	**2.35**	**4.85**	**1.87**	**0.00**	**2.80**
Maximum	**39.60**	**26.67**	**19.55**	**7.69**	**25.20**	**6.70**	**11.21**	**5.07**	**0.00**	**6.27**
Minimum	**28.34**	**23.17**	**1.79**	**3.73**	**0.00**	**0.88**	**0.00**	**0.56**	**0.00**	**0.00**

Table 4-4 Physical Composition (% by Weight) of MSW of February 2018 Samples

Sample No.	Physical Composition (% by Weight)									
	Paper	**Plastic**	**Food waste**	**Textile and Leather**	**Yard Waste and Wood**	**Metals**	**Glass**	**Styrofoam and Sponge**	**C & D Debris**	**Others (Soils and Fines)**
D-4-1	40.12	22.09	0.00	6.13	9.68	4.42	2.86	0.40	0.00	14.29
D-4-2	28.84	27.26	0.21	0.13	15.29	16.90	0.36	0.55	0.70	9.75
D-4-3	46.85	28.75	0.35	1.62	7.72	1.78	0.00	0.92	0.00	12.00
D-4-4	41.71	34.96	2.77	2.19	10.65	1.32	0.00	2.75	0.00	3.65
D-4-5	39.87	23.49	0.55	1.11	11.68	17.62	0.00	0.94	0.00	4.74
D-4-6	53.49	25.94	1.46	9.79	0.31	2.59	0.00	0.21	0.32	5.89
Average	**41.81**	**27.08**	**0.89**	**3.50**	**9.22**	**7.44**	**0.54**	**0.96**	**0.17**	**8.39**
Standard Deviation	**8.21**	**4.56**	**1.05**	**3.71**	**5.04**	**7.68**	**1.15**	**0.92**	**0.29**	**4.29**
Maximum	**53.49**	**34.96**	**2.77**	**9.79**	**15.29**	**17.62**	**2.86**	**2.75**	**0.70**	**14.29**
Minimum	**28.84**	**22.09**	**0.00**	**0.13**	**0.31**	**1.32**	**0.00**	**0.21**	**0.00**	**3.65**

Table 4-5 Degradable and non-degradable composition of Fresh MSW

Bag No	Physical Composition, % (By Degradability)	
	Degradable	Non-Degradable
A-1	83.78	16.22
A-2	57.82	42.18
A-3	68.25	31.75
A-4	64.13	35.87
A-5	55.17	44.83
A-6	56.32	43.69
N-1	78.95	21.05
N-2	54.64	45.36
N-3	80.00	20.00
N-4	75.01	24.99
N-5	66.96	33.04
M-1	53.72	46.28
M-2	61.98	38.02
M-3	65.01	34.99
M-4	70.63	29.37
M-5	58.87	41.13
D-4-1	55.93	44.07
D-4-2	44.47	55.53
D-4-3	56.54	43.46
D-4-4	57.32	42.68
D-4-5	53.21	46.79
D-4-6	65.05	34.95
Average	62.90	37.10
Standard Deviation	9.77	9.77
Maximum	83.78	55.53
Minimum	44.47	16.22

From the physical composition results, paper was found as the major waste fraction (approximately 38%) in the fresh waste. Plastic contributed 22.09% to the waste stream; however, it is lightweight, due to having less water-holding capacity than paper. Food waste is readily degradable and was found as 9.37% on average. Another major component of the waste was the "others" group (5.1% on average), which distinguished the basic waste characterization between fresh and mined waste. It consisted mainly of broken-down pieces that were too small to be sorted manually. Degradable wood and yard waste represented10.82% of the total waste. Altogether, the biodegradable fraction was found as 62.90% in the fresh waste. The average composition of MSW is given in Figure 4-1. The average physical composition of the samples collected from different times is given in Figure 4-2.

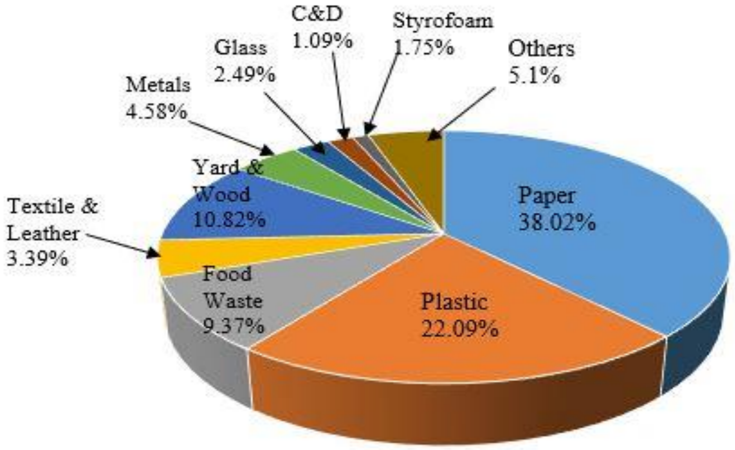


Figure 4-1 Average physical composition of fresh waste by weight

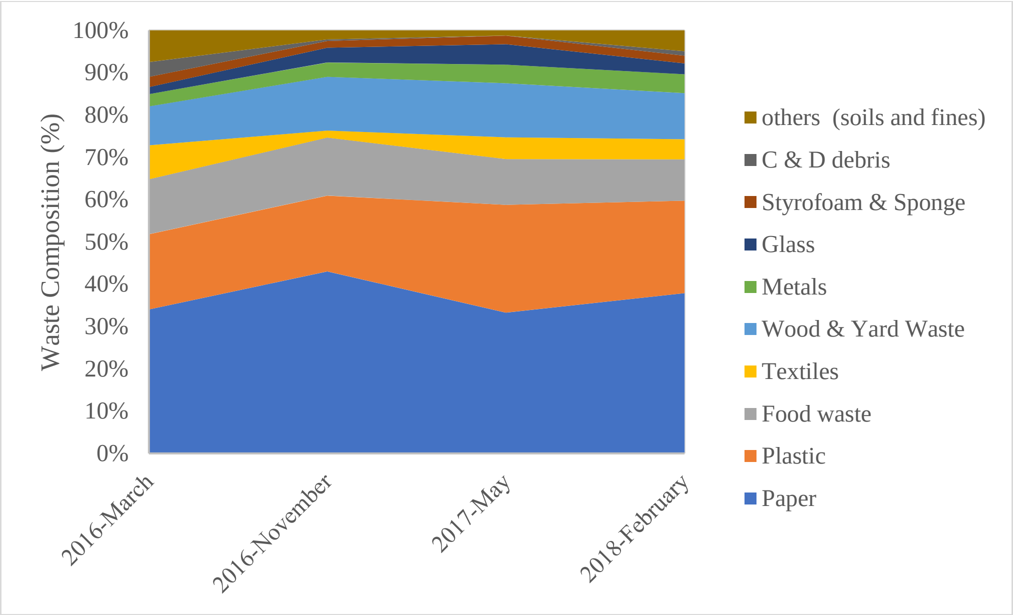


Figure 4-2 Physical composition of fresh waste by weight by collection time

4.2.1.2 Mined Waste Composition from City of Denton Landfill

Samir,2010 and Koganti,2015 determined the mined waste composition from City of Denton landfill. For the relevance of our study, the results are discussed again. Mined waste from the City of Denton landfill was collected from two different cells in three different years. The samples were collected from cell 0 by two boreholes (BH-70, BH-72) in 2010, which were operated conventionally. Four boreholes (BH-D to BH-G) in 2014 and three boreholes (BH-05 to BH-07) in 2015 were drilled to collect the samples from cell 0. Excavated samples were also collected from the ELR-operated landfill (Cell 2) by three boreholes (BH-A to BH-C) in 2014. The details of the sample collection depths from the boreholes are provided in Table 4-6. Sonia et al., 2010 and Koganti et al., 2015 determined the physical compositions of the samples collected from the above-mentioned boreholes that are presented here.

Table 4-6 Mined sample collection depth from City of Denton landfill

Year (Cell no)	Boring	Number of Samples	Sampling Depth
2010 (Cell 0-Conventinal)	BH-70	6	Every 10 feet up to 60 feet depth
	BH-72	6	Every 10 feet up to 60 feet depth
2014 (Cell 0-Conventinal)	BH-D	1	90 feet depth
	BH-E	6	Every 10 feet depth starting from 40 feet depth up to 90 feet depth
	BH-F	2	50 feet depth and 60 feet depth
	BH-G	7	Every 10 feet up to 77 depth
2014 (Cell 2-ELR)	BH-A	8	Every 10 feet up to 80 feet depth
	BH-B	4	Sample collected from 20 ft, 30 ft, 60 ft, 70 ft
	BH-C	8	Every 10 feet up to 80 feet depth
2015 (Cell 0-Conventinal)	BH-05	7	Every 10 feet up to 65 feet depth
	BH-06	6	Every 15 feet depth from 15 ft to 88 ft
	BH-07	8	Every 10 feet up to 80 feet depth

The mined samples were expected to be more degraded with age/depth of the borehole. However, none of the excavated waste from any of the boreholes exhibited any significant trends, rather expressed the true heterogeneity nature of solid waste, as illustrated from Figures 4-3 to 4-10. Moisture is the single most important parameter that contributes to degradation of the waste. The absence of a properly engineered final cover leads to the unanticipated infiltration of moisture into waste. In general, lack of moisture inside the landfill prohibits the regular decomposition process of waste, even though the waste composition varies at different depths.

As expected, no food waste was found in boring B-70 depicted in Figure 4-3, the paper content decreased at 20 ft. and 30 ft. depth, where the degradation was higher, and increased after 30 ft. depth. Based on the visual inspection, it appeared that the paper had not degraded.

The average composition of B-70, presented in Figure 4-3, indicated paper as 44%, plastic as 8%, textile + leather as 2% yard and wood waste as 8%, metals as 1%, glass as 2%, Styrofoam and as sponge 2%, C & D debris as 2%, degraded particles as 7%, and soil as 24%. The degradation level was low in this borehole, indicating a higher percentage of paper, and yard and wood waste.

From the composition illustrated in Figure 4-4, it can be observed that paper and plastic were found as 29.1% and 28.28% at 40 ft., respectively, in boring E. The largest was fines (78.62%) at 60 feet; however, paper and wood waste increased hugely at 70 feet depth. At a greater depth (after 80 feet), most of the samples were degraded/fine.

The average composition of Borehole E was found as 18% paper, 11% plastic, 3% textile + leather, 13% yard and wood waste, 4% metals, 0% glass, 2% Styrofoam and sponge, 2% C & D debris, and 47% fine/degraded

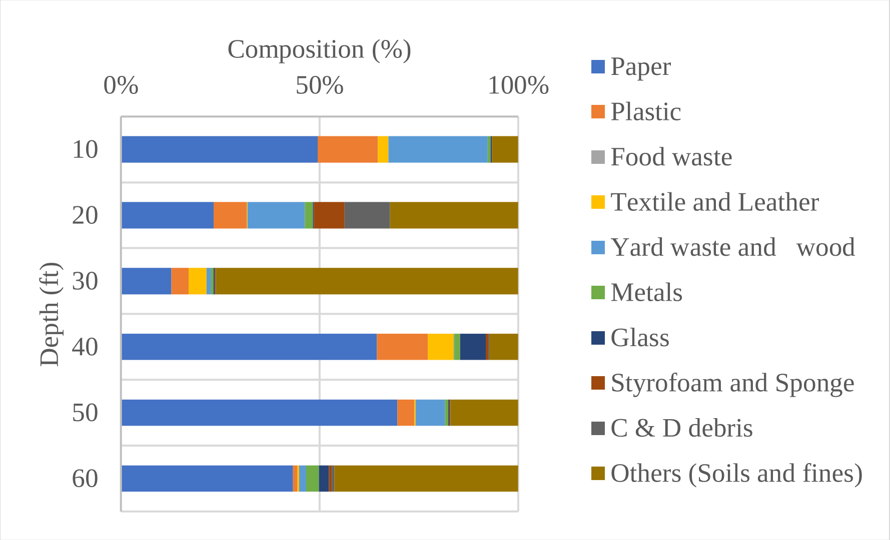


Figure 4-3 Waste composition at different depth in borehole 70

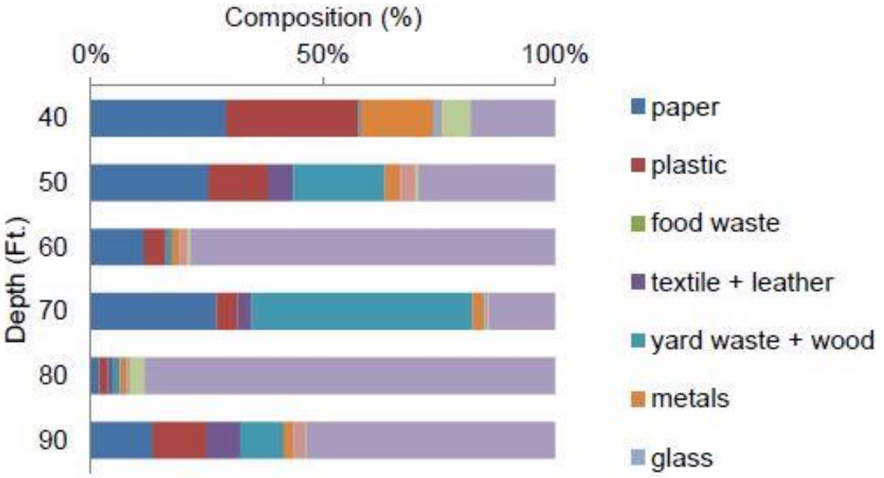


Figure 4-4 Waste composition at different depth in borehole E

From the composition illustrated in Figure 4-5, it can be seen that a high fine fraction (84.21%) was found at 10 ft depth in boring G. Paper and wood (48.37% and 22.4%, respectively) were dominant at a depth of 20 feet. Fine particles were found 50-90% between 30 ft. and 60 ft. At 77 ft., a high fraction of paper was collected (70.37%).

The average composition of Borehole G was found as 22% paper, 8% plastic, 2% textile + leather, 7% yard and wood waste, 2% metals, 1% Styrofoam and sponge, 3% C & D debris, and 55% fine/degraded.

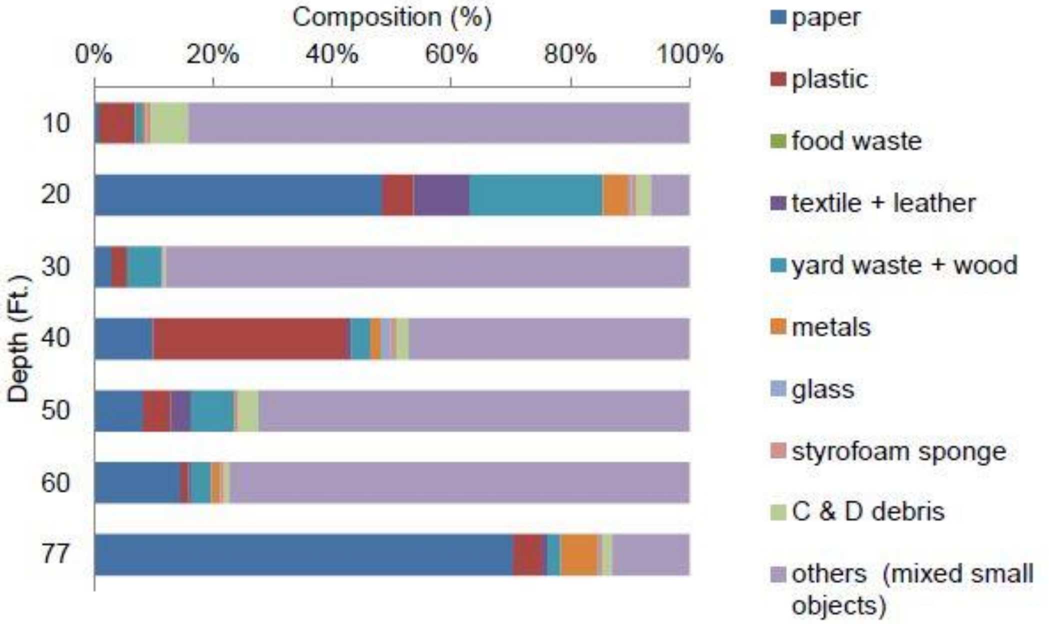


Figure 4-5 Waste composition at different depth in borehole G

As this borehole was from Cell 2 (ELR operated), the decomposition rate was expected to be higher. The plastic component was prominent in Borehole A. In 50 feet depth, the fine particles amounted to more than 75%, resulting in a lower percentage of paper. Surprisingly, the percentage of paper was found around 70% at a greater depth of 77 feet.

The average composition of Boring A, as presented in Figure 4-6, was paper (11%), plastic (19%), textile + leather (6%), yard and wood waste (14%), metals (3%), glass (1%), Styrofoam and sponge (1%), C & D debris (3%), and others (mixed other objects and fines) (42 %).

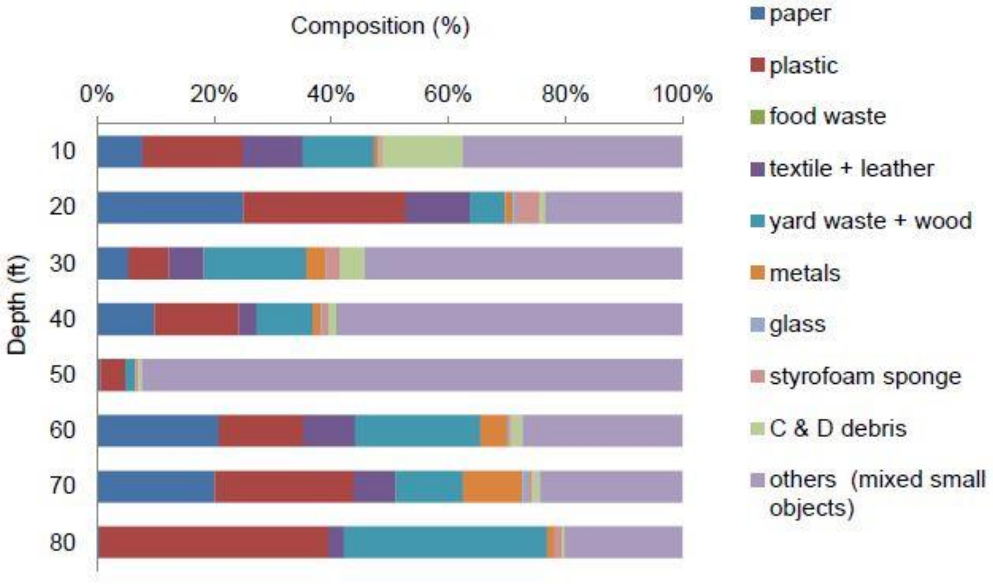


Figure 4-6 Waste composition at different depth in borehole A

From the composition illustrated in Figure 4-7, it can be observed that the paper content was 37.7% at 20 ft. depth for Boring B, which is pretty high in an ELR-operated landfill. Food waste was present in only 20 ft. depth, and 36.39 % plastic was recovered at 60 ft. depth. The paper content decreased after 20 feet, resulting in a higher content of fine materials. The degradation was a function of moisture availability; uneven distribution of moisture determines the different states of decomposition inside the landfill. Borehole B seemed to be more saturated than Borehole A.

The average composition of Boring B was found as paper 11%, plastic 19%, textile + leather 6%, yard and wood waste 14%, metals 3%, glass 1%, Styrofoam and sponge 1%, C & D debris 3% and others (mixed other objects and fines) 42 %.

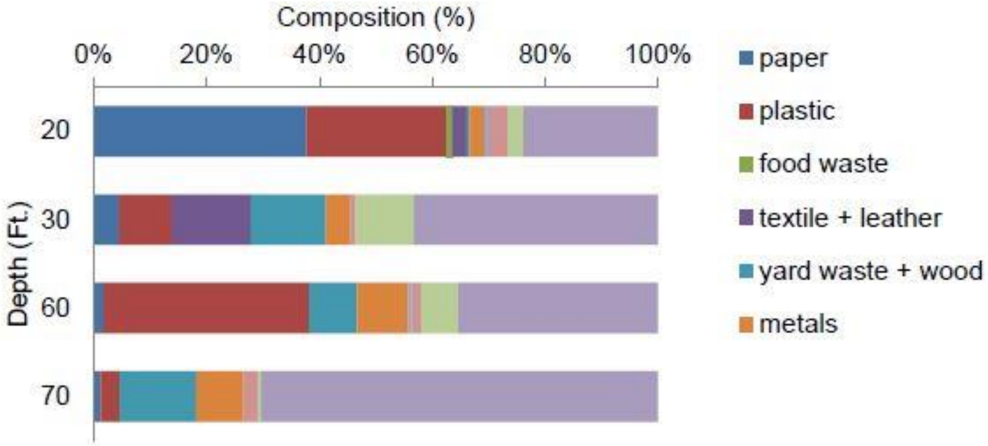


Figure 4-7 Waste composition at different depth in borehole B

From the composition illustrated in Figure 4-8, it can be observed that 50.32% paper was found at 10 ft. depth for Boring C. Plastic and fines, 39.16% and 39.38%, respectively, were observed at 20 feet depth. The percentage of plastic decreased from 30 ft. to 70 ft. but increased to the highest amount at 80 ft. Paper was completely degraded in 80 feet depth.

The average composition of Boring C was found as paper 15%, plastic 24%, textile + leather 3%, yard and wood waste 9%, metals 6%, Styrofoam and sponge 1%, C & D debris 4% and others (mixed other objects and fines) 38 %.

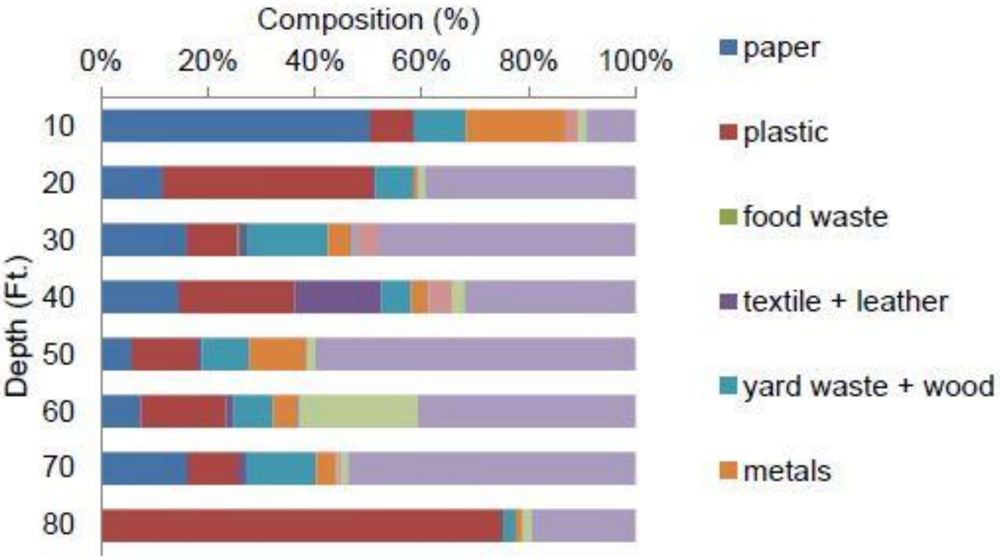


Figure 4-8 Waste composition at different depth in borehole C

The average composition of BH-05, as presented in Figure 4-9, was paper 24%, plastic 7%, textile + leather 2%, yard and wood waste 7%, metals 7%, glass 2%, Styrofoam and sponge 1%, C & D debris 4% and others (mixed other objects and fines) 46%.

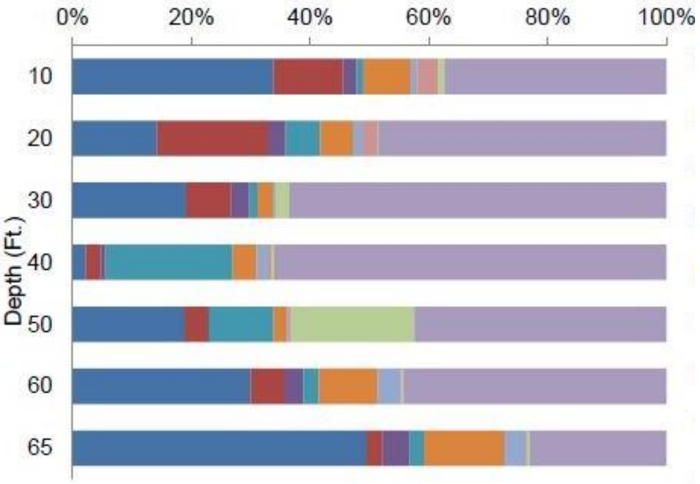


Figure 4-9 Waste composition at different depth in borehole 05

The fine fraction was prominent in all depths in Borehole 07, except at 45 feet, where the yard & wood waste amounted to more than 50%, resulting in a lower percentage of fine material.

The average composition of BH-07, as presented in Figure 4-10, was 9% paper, 9% plastic, 1% textile + leather, 13% yard and wood waste, 3%, metals, 1% glass, 1% Styrofoam and sponge, 4% C & D debris, and 61% others (mixed other objects and fines).

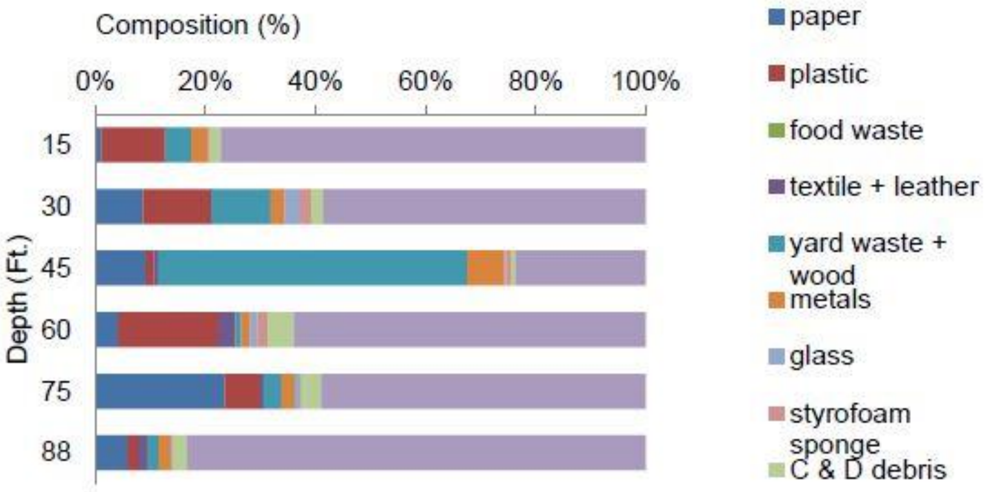


Figure 4-10 Waste composition at different depth in borehole 07

The average waste composition of each borehole is listed in Table 4-7. The average composition of the three borings presented in Figure 4-11 illustrates that the percentage of non-degradable components was much higher than the percentage of degradable components. The non-degradable components, and soil and fine percentage were approximately 73% of the composition. The results indicated that a major portion of the waste was soil and degraded fines (48%). From the combined average for landfilled MSW samples, the main components of waste, other than soils and degraded fines were paper (17%), plastics (13%) wood waste (8%) and metal 5%.

Table 4-7 Average waste composition of all boreholes in City of Denton Landfill

Bore Hole	Paper	Plastic	Food	Textile	wood	Metals	Glass	Styrofoam	C&D	Others/Fine
BH-70	43.87	7.69	0.00	2.43	8.32	1.49	1.68	1.62	2.05	31.00
BH-72	13.2	10.32	0.00	1.06	7.15	3.84	0.61	1.05	6.99	55.83
BH-D	3.20	25.00	0.00	0.96	2.85	3.44	0.72	1.80	3.66	58.30
BH-E	17.9	10.60	0.00	2.89	13.2	4.44	0.44	1.44	1.83	47.00
BH-F	5.43	10.00	0.00	3.39	7.01	22.50	0.73	1.95	1.02	47.80
BH-G	22.10	8.17	0.00	2.12	6.54	2.07	0.42	0.57	2.49	55.40
BH-5	23.90	7.50	0.00	2.48	6.52	6.55	1.86	1.02	3.68	46.40
BH-6	21.40	11.20	0.00	2.62	4.61	4.32	1.46	2.14	2.53	49.50
BH-7	8.73	8.69	0.00	1.01	13.00	3.12	0.98	0.85	2.68	60.90
BH-A	11.17	18.48	0.00	6.13	14.33	2.89	0.35	1.25	3.11	42.29
BH-B	11.29	18.54	0.00	4.11	8.98	6.13	0.39	2.06	5.10	43.16
BH-C	15.24	23.94	0.00	2.77	8.71	5.85	0.24	1.51	3.93	37.80
Average	**16.45**	**13.34**	**0.00**	**2.66**	**8.44**	**5.55**	**0.82**	**1.44**	**3.26**	**47.95**
Std Deviation	**10.36**	**6.11**	**0.00**	**1.39**	**3.36**	**5.33**	**0.53**	**0.48**	**1.53**	**8.38**
Maximum	**43.87**	**25**	**0.00**	**6.13**	**14.33**	**22.50**	**1.86**	**2.14**	**6.99**	**60.9**
Minimum	**3.2**	**7.5**	**0.00**	**0.96**	**2.85**	**1.49**	**0.24**	**0.57**	**1.02**	**31.00**

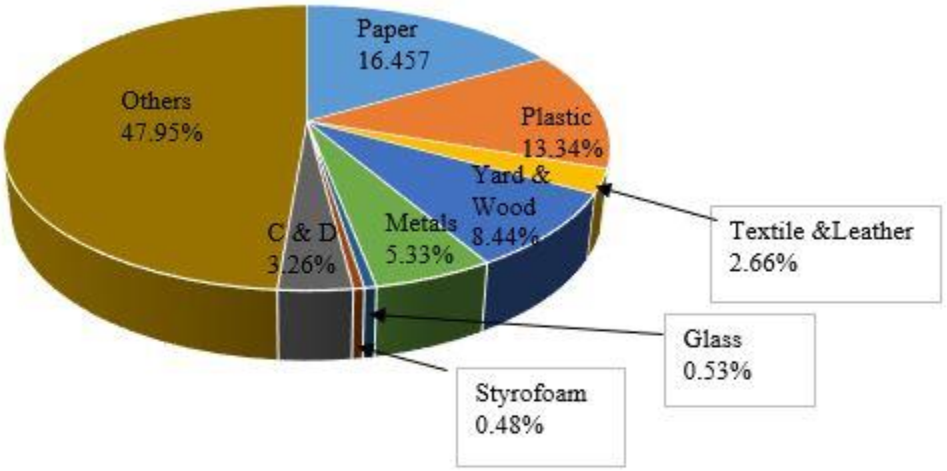


Figure 4-11 Average waste composition of mined waste from City of Denton landfill.

4.2.1.3 Mined Waste Composition from City of Irving Landfill

The degradable fraction was higher in the first 30 feet. From a visual inspection, the excavated waste appeared to relatively fresh, as it was disposed of 1-2 years ago in a cell that was 25-35 years old. The paper fraction gradually deceased from 25.34 % to 5.20% up to 40 feet. The plastic fraction was 22.63% in 20 feet depth, which is higher than average; the fine fraction varied between 37 - 54%.

The average composition of BH-X, as presented in Figure 4-12, was 14% paper, 11% plastic, 13% textile + leather, 8% yard and wood waste, 3% metals, 1% glass, 1% Styrofoam and sponge, 2% C & D debris, and 46% others (mixed other objects and fines).

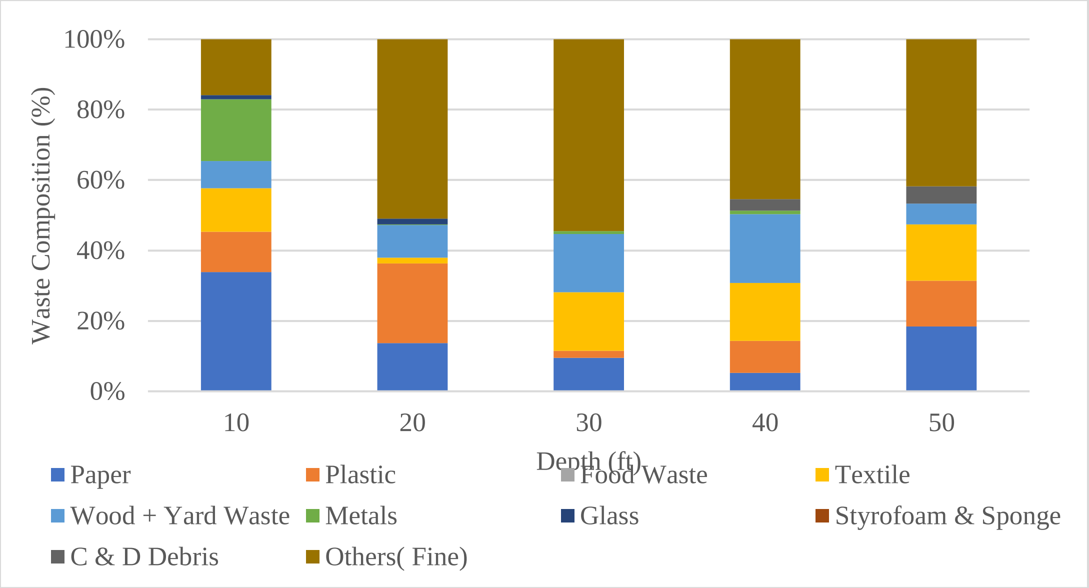


Figure 4-12 Waste composition at different depth in borehole X

The degradation level was high in borehole Y. The fine fraction was found as 57-93%, and paper was found as 29% at a depth of 70 feet. The moisture content was found very low in this borehole; therefore, it can be summarized that the degradation level was highest in this borehole, leaving the remaining environment very dry and unsuitable for further degradation.

The average composition of BH-Y, as presented in Figure 4-13, illustrates paper as 14%, plastic 6%, textile + leather 2 %, yard and wood waste 4%, metals 3%, glass 1%, C & D debris 1%, and others (mixed other objects and fines) 73%.

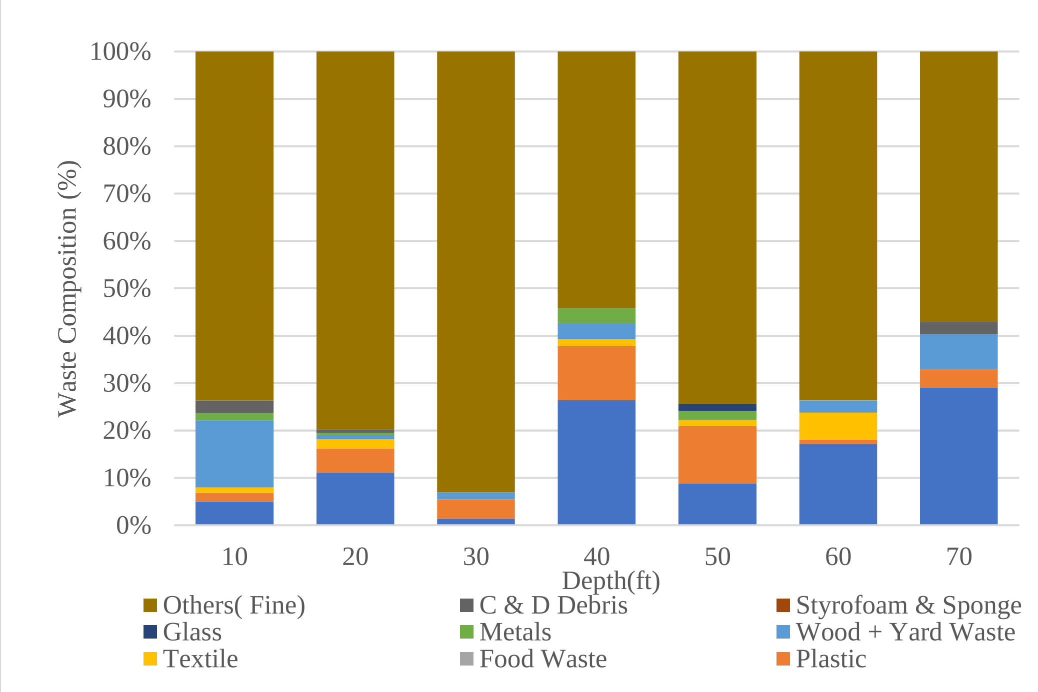


Figure 4-13 Waste composition at different depth in borehole Y

The fine material was found higher in the first 10 feet of Borehole Z, due to the presence of an intermediate cover. The paper fraction was low at all depths. Wood and yard waste were found as 42 % in 20 feet depth. The main source of wood was from the housing industry, and was in a good shape.

The average composition of BH-Z, as presented in Figure 4-14, was 6% paper, 11% plastics, 2% textile + leather, 15% yard and wood waste, 1% metals, 1% glass, and 64% others (mixed other objects and fines).

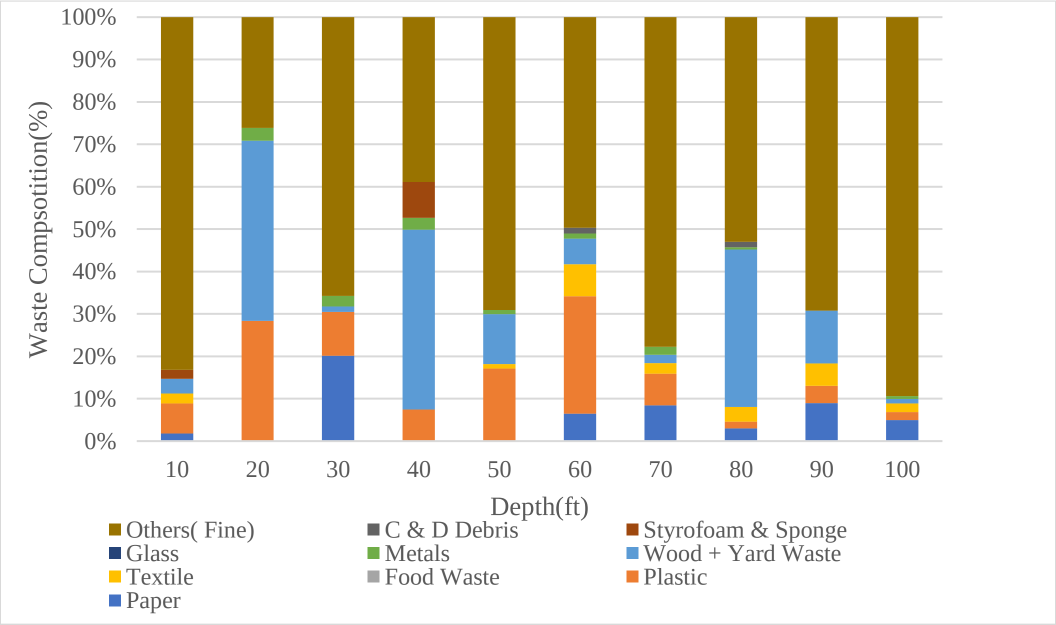


Figure 4-14 Waste composition at different depth in borehole Z

The average waste composition of each borehole is listed in Table 4-8. The average composition of the three borings presented in Figure 4-15 illustrates that the percentage of non-degradable components was much higher than that of the degradable components. The non-degradable components, and soil and fine percentages were approximately 73% of the composition. The results indicated that the major portion of waste was soil and degraded fines (61%). From the combined average for landfilled MSW samples, the main components of waste, other than soils and degraded fines, were paper (11%), plastics (11%), wood waste (9 %), and metal 2%.

Table 4-8 Average waste composition of all boreholes in City of Denton Landfill

Bore Hole.	**Physical Composition (% by Weight)**									
	Paper	**Plastic**	**Food waste**	**Textile and Leather**	**Yard Waste and Wood**	**Metals**	**Glass**	**Styrofoam and Sponge**	**C & D Debris**	**Others (Soils and Fines)**
BH-X	14.41	11.08	3.29	12.62	7.69	2.81	0.50	0.00	1.65	45.94
BH-Y	13.71	5.54	0.00	1.70	4.32	0.99	0.24	0.00	0.86	72.63
BH-Z	5.64	11.41	0.00	2.43	15.20	1.36	0.00	1.01	0.25	63.90
Average	11.25	9.34	1.10	5.58	9.07	1.72	0.25	0.34	0.92	60.82
Standard Deviation	3.98	2.69	1.55	4.99	4.55	0.79	0.20	0.48	0.57	11.11
Maximum	14.41	11.41	3.29	12.62	15.20	2.81	0.50	1.01	1.65	72.63
Minimum	5.64	5.54	0.00	1.70	4.32	0.99	0.00	0.00	0.25	45.94

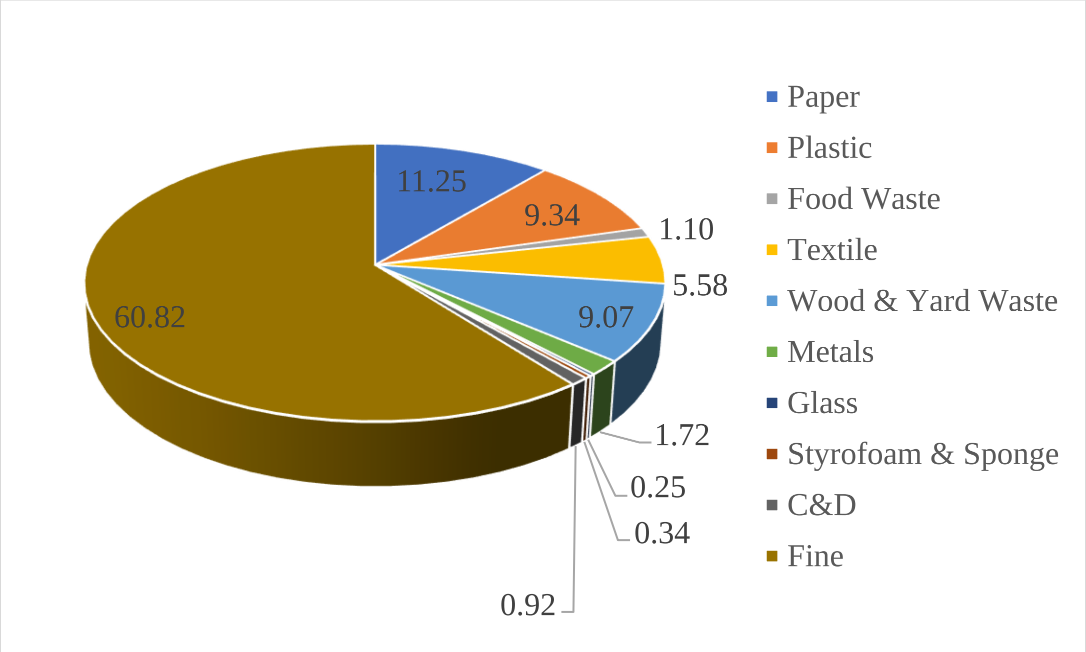


Figure 4-15 Average waste composition of mined waste from City of Irving landfill.

4.2.1.4 Comparison between Fresh and Mined Waste

The average composition of mined and fresh waste from two different landfills was compared, and the results are listed in Table 4-9.

Table 4-9 Comparison between fresh and mined solid waste

Waste Fractions	Waste Composition (%) (Weight Basis)		
	Mined Waste (City of Denton Landfill) 2010-2015	Mined Waste (City of Irving Landfill) 2019	Fresh Waste (City of Denton Landfill) 2016-2018
Paper	16.45	11.25	38.02
Plastic	13.34	9.34	22.09
Food Waste	0.00	0.00	9.37
Textile+ Leather	2.66	5.58	4.69
Yard+ Wood	8.44	9.07	10.82
Metals	5.33	1.72	4.58
Glass	0.53	0.25	2.49
Styrofoam	0.48	0.34	1.75
C&D	3.26	0.92	1.09
Others/Fine	47.95	60.82	5.1

Figure 4-16 shows the comparison of all waste component between mined and fresh solid waste

Waste gradually degrades with time and the presence of moisture. Most (75%) of the boreholes in this study were from Cell 0 in the City of Denton landfill, which was operated conventionally. Twenty-five (25%) of the boreholes were from Cell

2, which was operated by an ELR operation. Cell 0 was 10-30 years old, whereas Cell 2 was 9-15 years old. The City of Irving landfill has only one conventional cell, which was 10-30 years old.

The main difference between the mined and fresh waste was the paper and fine fractions. The paper fraction was 16.45% and 11.25 % at the City of Denton and City of Irving landfills, respectively. The amount of mined paper was significantly less than that of fresh paper (38.02%). Most of the paper (60 - 70%) experienced degradation with time. Plastic was found in 22% of the fresh waste, whereas the mined waste contained 9-13%. The use of plastic was not as common from 1980 – 1990 as it is now; however, the plastic percentage might have increased due to the degradation of the other materials. Food waste was degraded completely, as expected, in the mined waste. No differences were exhibited between mined and fresh waste for yard waste, metal, glass, etc. The fine/degraded fraction was found to be 48 % and 61 % for the City of Denton landfill and the City of Irving landfill, respectively, and was an indicator of the level of degradation. Based on Table 4-9, the waste at the City of Irving landfill experienced more degradation than that at the City of Denton landfill.

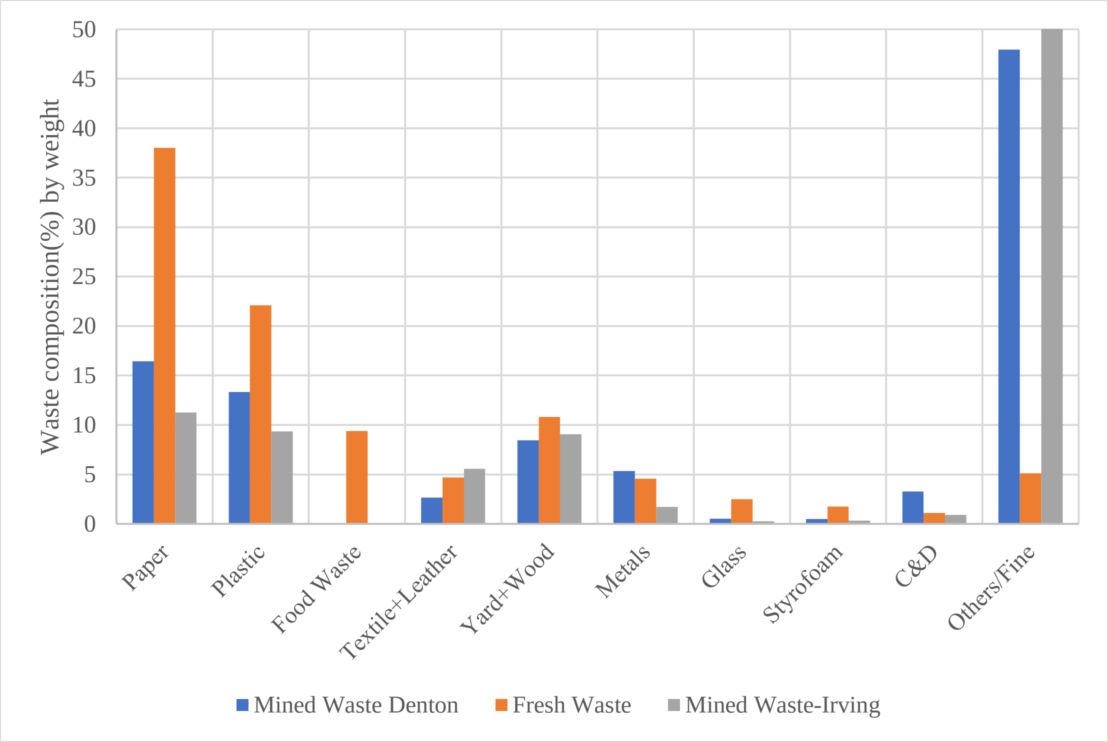


Figure 4-16 Comparison of waste component between mined and fresh waste

4.2.1.5 Comparison with previous studies

Numerous studies have been conducted to determine the composition of excavated waste, and some of the more important ones were featured in Chapter 2. The current study was compared with three different mining projects from three continents, and the results are presented in Table 4-10.

Table 4-10 Comparison of mined waste composition between current study and literature.

	Chen et al.,2010 in China	Hogland et al.,2004 in Sweden	Gabr and Valero, 1995 USA	Samir et al.,2010 Koganti et al.,2015 (City of Denton)	Present Study (City of Irving)
Age (Year)	10	17-22	15-30 Years	10-30	10-30
Paper	0	9.72	0	16.45	11.25
Plastic	7.02	4.94	13	13.34	9.34
Food Waste		1.9		0	0
Textile+ Leather	1.98	2.85	9	2.66	5.58
Yard+ Wood	13.85	11	23	8.44	9.07
Metals		1.73	10	5.33	1.72
Glass	12.08(Stone /Glass Tile)	.28	10	0.53	0.25
Styrofoam				0.48	0.34
C&D		13.7		3.26	0.92
Others/Fine	75.48	54.5	33	47.95	60.82

From the comparison with literature, it is evident that fine/degradation materials consist mostly of mined material. The soil fraction was found higher (75%) in developing countries, like China, due to the high presence of the organic fraction. Paper was found lower in the literature, compared with the current mined waste. Plastic was found lower in excavated waste outside the USA, and yard and wood waste, and glass had higher contributions in the literature.

It should also be noted that at different times of the year, the materials in the waste vary. The year of deposition also plays a very important role in the composition of the landfill. Hence, the fresh waste composition of 2016 - 2018 might be different than the initial composition of the landfilled waste in 1985. Therefore, the changes of waste composition due to degradation may not be reflected when compared to the fresh waste collected in 2009-2010, but the compared data provides a good understanding of changes in the composition of waste with depth, age and degradation of MSW.

4.2.2 Moisture Content

4.2.2.1 Moisture Content of Fresh Waste from City of Denton Landfill

The moisture content of fresh waste from the City of Denton Landfill is presented in Table 4-11. The average moisture content was 26.35% (wet weight basis) and 37.93 % (dry weight basis). Twenty-two bags of samples were collected at different times of the year, with the majority of them being collected in the summer.

Table 4-11 Moisture content of fresh waste from City of Denton landfill.

Sampling Time	Moisture Content (%) (Wet Wt. Basis)	Moisture Content (%) (Dry Wt. Basis)
March 2016	27.22	37.93
November	37.09	60.31
May 2017	21.79	28.65
February	19.28	24.83
Average	26.35	37.93

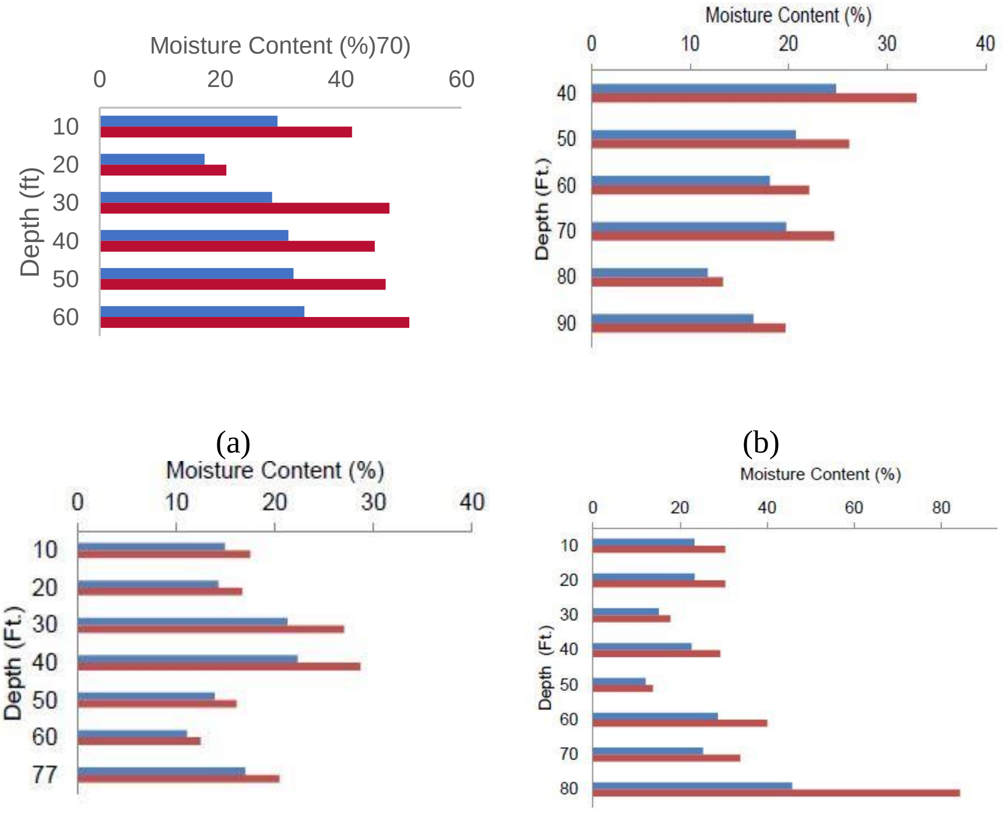
4.2.2.2 Moisture Content of Mined Waste from City of Denton Landfill

The average moisture content of mined waste from the City of Denton Landfill was found to be 19.12 % (wet weight basis) and 24.82 % (dry weight basis) (Table 4-12.) It varied from 11-42% (wet basis). However, the samples were collected from both conventional and ELR-operated cells. The average moisture content from the conventional cell and ELR-operated cell was 19.65 % and 17.56 % (wet weight basis), respectively. The moisture content was expected to be higher in the ELR-operated landfill, due to the addition of moisture. Moisture content was found to be similar for both of the cells.

Table 4-12 Moisture content of mined waste from City of Denton landfill.

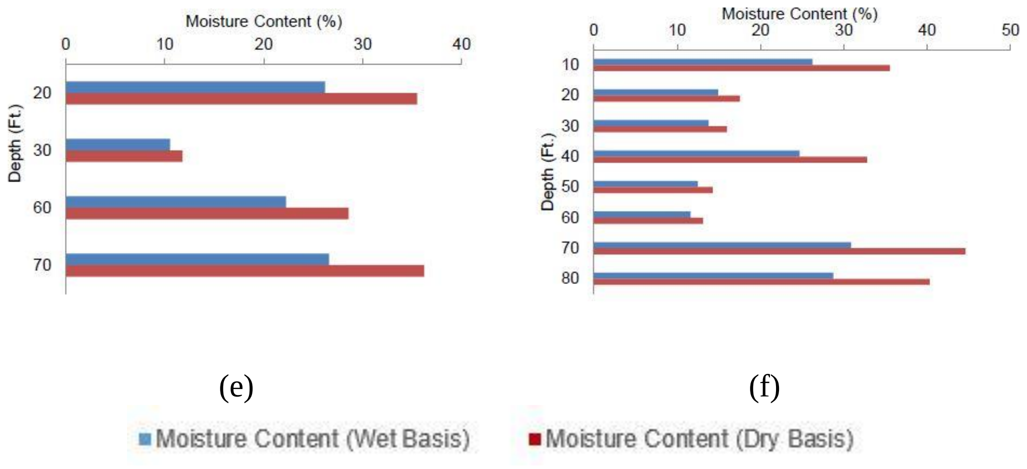
Bore Hole	Moisture Content (Wet Basis)	Moisture Content (Dry Basis)
BH-70	28.82	42.56
BH-72	20.27	26.15
BH-D	20.70	26.1
BH-E	18.60	23.14
BH-F	15.09	17.94
BH-G	16.38	19.85
BH-5	22.08	30.1
BH-6	19.06	23.77
BH-7	15.81	19.26
BH-A	16.14	21.11
BH-B	16.14	21.11
BH-C	20.39	26.74
Average	19.12	24.82
Std Deviation	3.66	6.35
Maximum	28.82	42.56
Minimum	15.09	17.94

The moisture content of all of the borings from the City of Denton landfill, with variations of depth, are presented in Figures 4-17 and 4-18. Waste was anticipated to be degraded with the increase of depth. According to Landva and Clark (1990), the presence of high organic content in MSW increases the moisture content of the waste. Therefore, with degradation, the moisture content might be reduced; however, no significant trend was found in this landfill that supported that idea.



(a) (b)

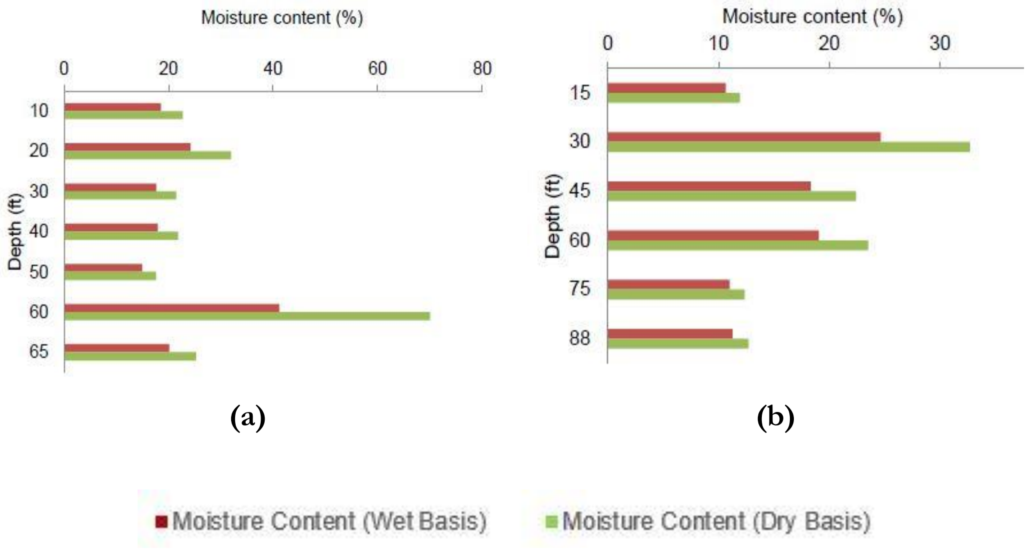
(c) (d)



(e)

(f)

Figure 4-17 Depth wise moisture content profile in a) BH-70 b) BH-E c) BH-G d) BH-A



(a)

(b)

Figure 4-18 Depth wise moisture content profile in a) BH-5 b) BH-6

4.2.2.3 Moisture Content of Mined Waste from City of Irving Landfill

The average moisture content of mined waste from the City of Irving landfill was 25.32 % (wet weight basis) and 35.13% (dry weight basis), as presented in Table 4-13. It varied from 8-39% (wet basis). Based on visual inspection, the samples from BH-Y were dry (17% wet basis). The moisture content ranged from 8-25%, as shown in Table 4-13.

Table 4-13 Moisture content of mined waste from City of Irving landfill.

Bore Hole	Moisture Content (Wet Basis)	Moisture Content (Dry Basis)
BH-X	28.43	39.90
BH-Y	17.38	21.63
BH-Z	30.15	43.86
Average	25.32	35.13
Std Deviation	5.66	9.68
Maximum	30.15	43.86
Minimum	17.38	21.63

The moisture content of boring X was 28.43% (wet weight basis) and 39.9% (dry weight basis). The moisture content of boring Y averaged 17.38% (wet weight basis) and 21.63% (dry weight basis). The moisture content of boring Z averaged 30.15% (wet weight basis) and 43.86% (dry weight basis). Like the City of Denton landfill, the City of Irving's mined waste did not follow any trend of moisture increasing with depth.

(a)

(b)

(c)

Figure 4-19 Depth wise moisture content profile in a) BH-X b) BH-Y c) BH-Z

4.2.2.4 Comparison of Moisture Content between Fresh and Mined Waste

Based on our study, the average moisture content from the City of Denton's mined waste was 19.12 % (wet basis) and 24.84 % (dry basis). The moisture content of the City of Irving landfill's excavated waste was 25.32 % (wet basis) and 35.13% (dry basis). The moisture of the fresh waste from the City of Denton landfill was 26.35% (wet basis) and 37.93% (dry basis). A comparison of the results of this study is shown in Figure 4-20.

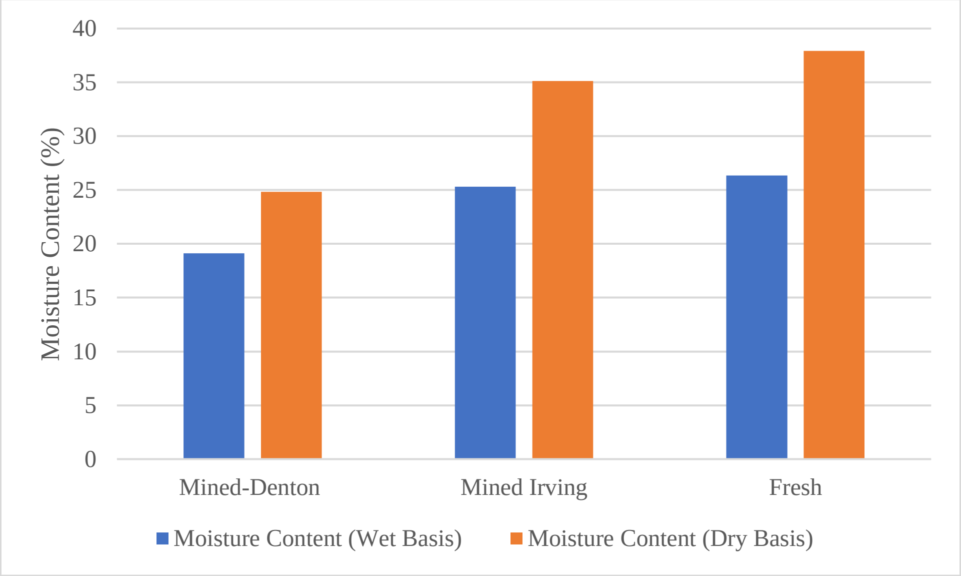


Figure 4-20 Comparison between fresh and mined moisture content

4.2.2.5 Comparison with previous studies

Table 4-14 shows a comparison of the moisture content from this study and that discussed in the literature.

Table 4-14 Comparison of moisture content with literature

Source	Moisture Content (%)	Condition	Remarks
Hull et al.2005	28.3%	9-11 years	USA
Zanetti et al.1997	23.9%		
Zornberg et al.1999	21.9%		
Baumler et al.2004	24%		
This Study	25.32%	10-30 years	USA
Samir,2010 & Koganti ,2015	19.12%	10-30 years	USA
Hogland et al., 2004	29.3%	17-22 years	Sweden
Zekkos et al.,2006	10-50	1-6 years	Portugal

4.2.3 Volatile Solid (Proximate Analysis)

4.2.3.1 Volatile Solid Fresh Waste from City of Denton Landfill

Volatile test results revealed the degradation level of the waste mass. The volatile solid results of fresh waste from the City of Denton landfill are presented in Table 4-15 and Figure 4-19. The average volatile solid was found as 63.87% in the fresh waste. The samples were collected from different times of the year. The highest volatile solid (84.58%) was found in February 2018.

Table 4-15 Volatile solid results from fresh waste of City of Denton landfill.

March 2016		November 2016		May 2017		February 2018	
Sample No.	Volatile Solids (%)	Sample No.	Volatile Solids (%)	Sample No.	Volatile Solids (%)	Sample No.	Volatile Solids (%)
A-1	58.51	N1	20	M-1	-	D-4-1	90.96
A-2	-	N2	30.7	M-2	91.49	D-4-2	91.25
A-3	71.77	N3	44.1	M-3	55.78	D-4-3	71.25
A-4	78.70	N4	48.6	M-4	40.54	D-4-4	92.17
A-5	-	N5	34.42	M-5	74.93	D-4-5	85.71
A-6	-					D-4-6	76.12
Average	69.66	Average	35.56	Average	65.69	Average	84.58
Standard Deviation	10.26	Standard Deviation	11.29	Standard Deviation	22.23	Standard Deviation	8.87
Maximum	78.70	Maximum	48.6	Maximum	91.49	Maximum	92.17
Minimum	58.51	Minimum	20	Minimum	40.54	Minimum	71.25

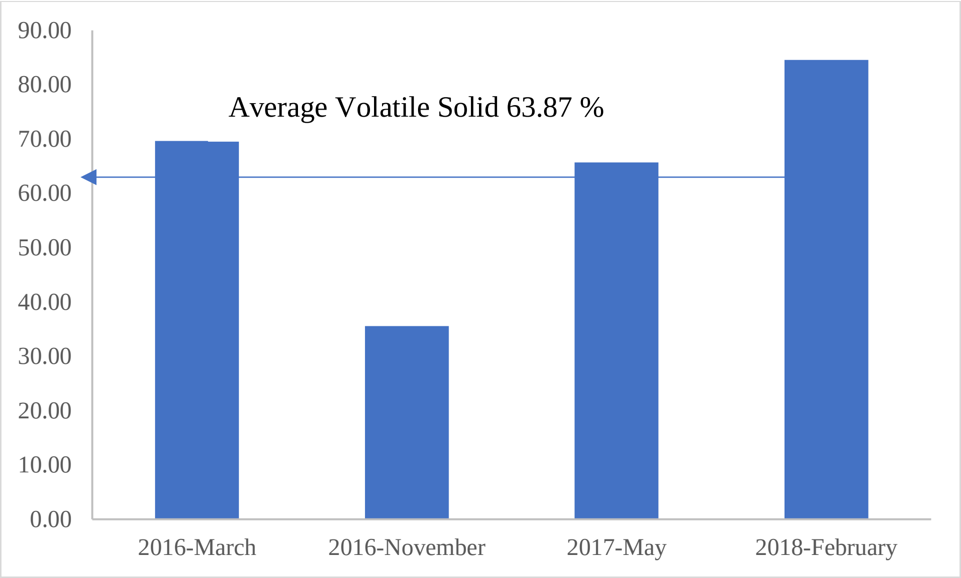


Figure 4-21 Average volatile solid of fresh waste from city of Denton landfill

4.2.3.2 Volatile Solid of Mined Waste from City of Denton Landfill

The average volatile solid from the City of Denton landfill was 33.34% and varied from 8 – 86%, as presented in Table 4-16. The samples were collected from both conventional and ELR-operated cells. The average volatile solids from the conventional cell and ELR-operated cell were 35.61% and 31%, respectively. The volatiles were expected to be lower in the ELR-operated landfill, due to earlier degradation. There were volatile solids in the ELR landfill (31%) than in the conventional landfill (36%), indicating higher degradation due to the addition of moisture.

Table 4-16 Volatile solid of mined waste from City of Denton landfill

Bore Hole	Volatile Solid (%)
BH-70	72.29
BH-72	61.44
BH-D	17.71
BH-G	20.53
BH-5	25.17
BH-6	29.44
BH-7	22.71
BH-A	28.5
BH-B	29.44
BH-C	25.14
Average	33.237
Std Deviation	17.37
Maximum	72.29
Minimum	17.71

As shown in Figure 4-22, the volatile solids in the mined waste did not follow any significant trend.

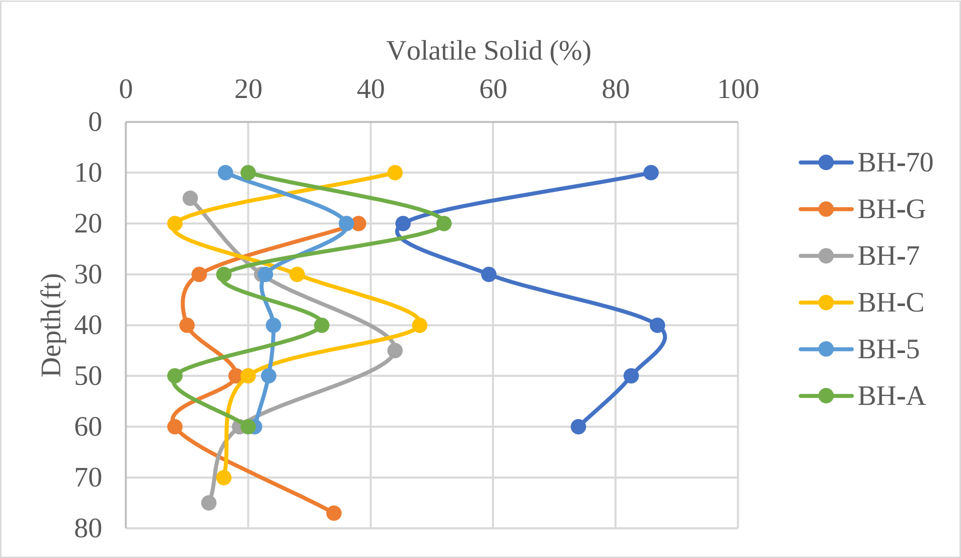


Figure 4-22 Volatile solid (%) from City of Denton landfill with depth

4.2.3.3 Volatile Solid of Mined Waste from City of Irving Landfill

The average volatile of mined waste from the City of Irving Landfill was found to be 32.56%, as presented in Table 4-17. It varied from 15-61%, as presented in Figure 4-23.

Table 4-17 Volatile solid of mined waste from City of Irving landfill

Bore Hole	Volatile Solid (%)
BH-X	32.53
BH-Y	29.91
BH-Z	35.24
Average	32.56
Std Deviation	2.17
Maximum	35.24
Minimum	29.91

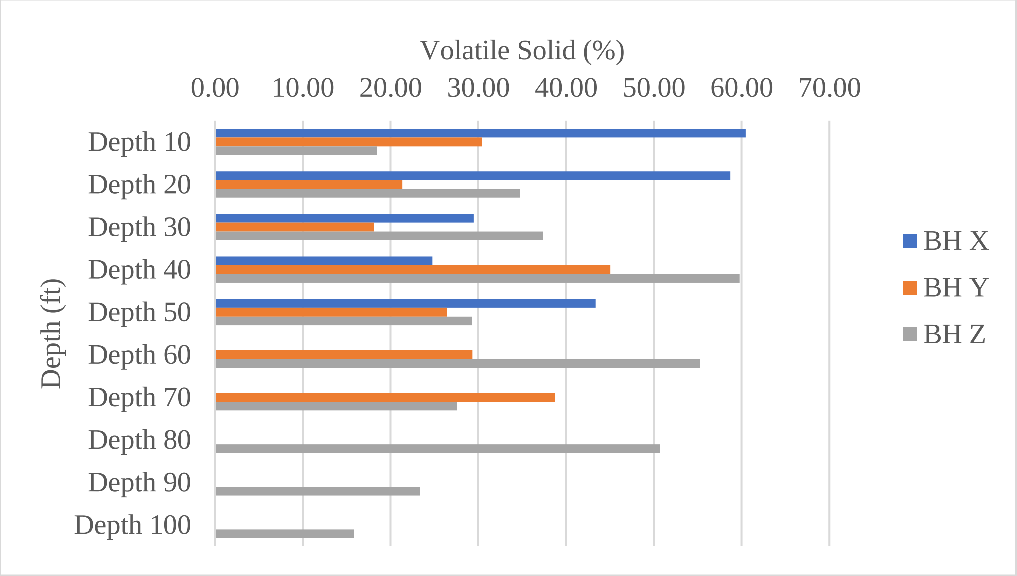


Figure 4-23 Volatile solid (%) from City of Irving landfill with depth

4.2.3.4 Comparison of Volatile solid between Fresh and Mined Waste

Based on our study, the average volatile from the City of Denton's mined waste was 33.24 %. In the City of Irving landfill, the excavated waste had 32.56% of volatile solids. For the fresh waste from the City of Denton landfill, the percent of volatile solids was 63.87%. A comparison of the results from this study is shown in Figure 4-21. Based on the current volatile solid results, the mined waste from both landfills experienced 50% more degradation than the fresh waste from the City of Denton landfill.

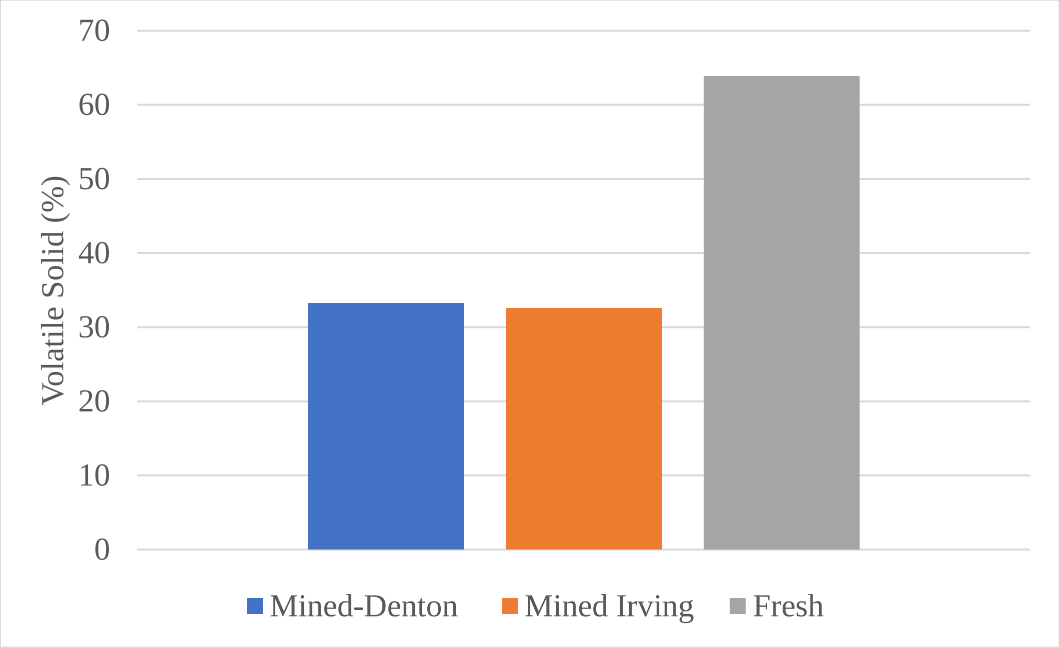


Figure 4-24 Comparison of volatile solid (%) between fresh and mined waste

4.2.3.5 Comparison with previous studies

Table 4-18 compares the volatile solid results with those cited in literature.

Table 4-18 Comparison of volatile solid with literature

Source	Volatile Solid (%)	Condition	Remarks
Kathirvale et al.,2003	31.36 %	Fresh	Malaysia
Kalantarifard, 2011	79-85	Fresh	Malaysia
Tiwari, 2014	76.54 %	Fresh	USA
This Study	32.56%	10-30 years	USA
Samir,2010 & Koganti ,2015	33.24%	10-30 years	USA
Sapkota, 2017	86.71%	Fresh	USA
This Study	63.87%	Fresh	USA

4.3 Energy potential of solid waste

4.3.1 Energy potential of Paper Waste

Based on the waste composition, other than the fine fraction, the paper fraction was found to be highest in the fresh waste and mined waste. The closed landfill section (Cell 0) was operated conventionally, without adding any moisture during operation; therefore, the decomposition rate was slow. The energy potential (calorific/heating value) of mined paper from different depths, collected from conventional Cell 0, was found to be 3756.23 Btu/lb. to 7162.95 Btu/lb. in this study. This reflects the lower degradation rate of recovered paper waste that was 14 - 30 years old. Paper waste included newspaper, cardboard, tissue paper, Kraft paper, etc. Cell 2 was operated with enhanced leachate recirculation (ELR) to expedite the waste composition. The mined paper from the ELR-operated landfill, which was 8 – 15 years old, had an average calorific value of 6067.89. The fresh paper waste from Cell 2 of the Denton landfill had a heating value from 5250.81 Btu/lb. to 7531.97 Btu/lb., with an average calorific value of 6209.66 Btu/lb., which is slightly higher than the value of mined paper (6032.31 Btu/lb.). Mined paper waste was supposed to have a lower calorific value; however in this study, the recovered mined paper waste had energy potential similar to that of the fresh paper, even after the degradation of around 50%. The ELR operation did not affect the energy potential of the paper. All of the experimental results are shown in Table 4-19.

Table 4-19 Calorific value of Paper waste

No of Samples	Conventional	ELR	Fresh
1	6975.43	6792.04	7062.37
2	6531.99	7972.85	6625.73
3	3756.53	5295.04	5642.94
4	6644.68	5803.04	6649.3
5	5539.47	6349.75	6294.83
6	6354.49	6309.04	5250.81
7	5805.87	5762.94	5859.41
8	6248.98	6394.93	7060.46
9	5896.35	5394.95	5892.54
10	7112.66	5662.12	7531.97
11	6478.38	6293.93	6175.2
12	5250.81	6593.95	7114.47
13	6857.81	4193	5598.93
14	6382.67		6593.2
15	5385.98		5980.3
16	5859.41		5739.48
17	6294.96		5835.84

18	6954.03		6329.4
19	7162.95		5490.4
20	5493.95		5305.7
21	7060.46		6450.3
22	5892.54		6128.9
23	7531.97		
24	6175.2		
25	7114.47		
26	5598.93		
27	5683.05		
28	5295.92		
29	6584.27		
30	6284.95		
31	5697.95		
32	6355.39		
Average	6195.703125	6218.72	6209.66
Standard Deviation	749.4099474	860.164	610.646
Maximum	7531.97	7972.85	7531.97
Minimum	3756.53	4193	5250.81

Few studies have focused on the energy potential of solid waste, or have measured the energy potential of individual components of mined waste. Based on the previous studies, the energy potential of paper waste from this study lies within a pretty good range. However, paper waste from a mined landfill in Belgium had lower calorific values that were calculated from a mathematical model. Table 4-20 compares the calorific value of paper and fresh waste from landfills with some of the studies described in the literature.

.

Table 4-20 Comparison of energy from paper waste with literature

Calorific Value (Btu/lb)	Location	Reference	Waste Type
6032.31	Texas, USA	This Study	Mined
6067.89	Texas, USA	This Study	Mined (ELR operated)
6209.66	Texas, USA	This Study	Fresh
5590	Belgium	Quaghebeur et al.,2012	Mined
3439.381	New Jersey, USA	Hull et al.,2005	Mined (Determined using mathematical model)
3525.365	New Jersey, USA	Hull et al.,2005	
6698.1943	Canada	Shi et al.,2015	Non recycled fresh paper
6018.92	Italy	Giugliano et.al. (2008).	Fresh Paper and cardboard

4.3.2 Energy potential of Plastic Waste

Plastic waste has been an integral part of a circular economy due to its non-degradability. Different types of plastics (PET, HDPE, LDPE, LLDPE, PP, PVC) have been considered for measuring its energy potential. Plastic that has a calorific value 9797.45 -11880.2 Btu/lb. is PET or PVC. The rest of the plastic types had a calorific value between 14977.8 and 19856.7 Btu/lb. In this study, the calorific value of mined plastic from different depths was found to be between 9797.45 Btu/lb. and

18946.97 Btu/lb., whereas the values of virgin plastic varied from 9906.08 Btu/lb. to 19856.7 Btu/lb. The average calorific value of mined plastic waste was measured as 15353.29 Btu/lb., which was similar to the average calorific value of fresh plastic waste (16458.29 Btu/lb.) The difference accounted for the contamination of the plastic waste that was 15 - 30 years old. The increased calorific value can be attributed to the increased percentage of plastic in the mined waste. The mined plastic from the ELR-operated landfill had an average energy value of 16044.54 Btu/lb. All of the experimental results are shown in Table 4-21

Table 4-21Calorific value of Plastic waste

No of Samples	Conventional	ELR	Fresh
1	10446.1	14935.93	16879.5
2	16109.1	12953.8	18649.8
3	15541.43	12378.03	15607.4
4	17299.4	15914.4	17253.5
5	12365.32	17893.04	19856.7
6	11880.2	9831.16	12624
7	16706.9	12522.8	18105
8	17163.8	15607.4	16879.5
9	18593.25	15323.1	17286.5
10	15438.65	15607.4	19651.9
11	13218.2	17253.5	18060.2
12	12697.35	19856.7	18963.7
13	9797.45	12624	17322.5
14	13964.32	18105	16782.7
15	16561		18693.7
16	10680.6		17230.4
17	13084.2		16903.4
18	16893.95		17780.9

19	18739.93		9906.08
20	18946.97		10277.38
21	15036.87		16745.9
22	18936.8		10621.63
23	14977.8		
24	15538.6		
25	17605.8		
26	18049.7		
27	15845.94		
28	17398.94		
29	18716.9		
30	17639.93		
31	14593.94		
32	13999.6		
Average	15452.1544	15057.59	16458.28591
Standard Deviation	2581.27553	2644.037	2851.490652
Maximum	18946.97	19856.7	19856.7
Minimum	9797.45	9831.16	9906.08

Plastic recovery potential is one of the factors that determines the feasibility of landfill mining projects. Therefore, some independent studies were carried out with only excavated plastic waste. Table 4-22 compares the calorific value of plastic from mined and fresh waste with some of the literature.

Table 4-22 Comparison of energy from plastic waste with literature

Calorific Value (Btu/lb)	Location	Reference	Waste Type
15353.29	Texas, USA	This Study	Mined
16044.54	Texas, USA	This Study	Mined (ELR operated)
16458.29	Texas, USA	This Study	Fresh

11983.58	Jordan	Abu-Qudais and Abu-Qdais,1999	Fresh
15356.84	Canada	Shi et al.,2015	Plastic-rigid
18254.51	Canada	Shi et al.,2015	Plastic-film and Styrofoam
12040.00	Belgium	Quaghebeur et al.,2012	Mined
19242.50	China	Zhou et al.2014	Mined

4.3.3 Energy potential of Wood and Yard Waste

Wood and yard waste are the third highest component of fresh solid waste in the US. The calorific value of mined wood waste in this study was found to be from around 3847.06 Btu/lb. to 7812.64 Btu/lb.; the calorific value of fresh wood from the same landfill was found to be from 5736.35Btu/lb. to 7818.99 Btu/lb. The average calorific value of mined wood waste was 6577.13 Btu/lb. in Cell 0, which was almost equal to the average energy of wood from fresh waste (6813.332 Btu/lb.). Hull et al. (2005) reported the higher heating value of mined wood from 2837.5 Btu/lb. to 5202.06 Btu/lb., having an average of 3826.31 Btu/lb. in the Burlington County Landfill in New Jersey. Hull et al. (2005) used the mathematical formula derived by Dulong. Wood waste in the Denton landfill experienced slower degradation than the waste in New Jersey, probably because of slower degradation of materials, like wood, containing a high lignin content, under anaerobic conditions. Furthermore, numerous parameters, such as moisture content, age of the cell, the nature of wood, etc., affected the decomposition process of individual landfills. All of the experimental results are shown in Table 4-23.

Table 4-23 Calorific value of Wood waste

No of Samples	Conventional	ELR	Fresh
1	7440.21	6767.61	7493.94
2	6300.25	5007.93	6493.76
3	3847.06	5503.56	5893.9
4	5326.55	4994.03	6915.93
5	6395.64	7193.54	6587.26
6	6970.56	6890.94	6589.32
7	6578.94	4059.02	6330.56
8	6129.56	5294.74	7450.27
9	6156.32	6827.71	7529.19
10	6912.52	5184.94	7683.92
11	6348.19	7237.74	7334.76
12	5893.64	6314.55	7562.47
13	6983.65	5512	6338.74
14	7569.32	6845.94	5866.09
15	4640		6840.24
16	6894.67		5640.58
17	7194.56		6589.32
18	6194.86		6382.19
19	7294.83		7618.26
20	5004.6		7628.64
21	6793.94		7159.23
22	6230.54		5924.76
23	7706.43		
24	7812.64		
25	7476.65		
26	7334.76		
27	6739.94		
28	6396.74		
29	7397.68		

30	7348.87		
31	6145.93		
32	5938.84		
Average	6543.71531	5973.875	6811.52
Standard Deviation	897.7735	972.4613	647.413
Maximum	7812.64	7237.74	7683.92
Minimum	3847.06	4059.02	5640.58

Table 4-24 compares the calorific value from mined and fresh wood and yard waste with some of the literatures

Table 4-24 Comparison of energy from wood waste with literature

Calorific Value (Btu/lb)	Location	Reference	Waste Type
6577.13	Texas, USA	This Study	Mined waste
6813.33	Texas, USA	This Study	Mined waste
6030.36	Texas, USA	This Study	Mined waste (ELR)
7738.61	Spain	Montejo et al. (2011).	Fresh
7919.1745	Canada	Shi et al.,2015	Fresh

4.3.4 Energy potential of other fractions of waste

According to the waste composition, the other potential source of energy is food waste, and textiles and leather. As was expected, food waste was not found in mined waste. Textile and leather waste was found in very low fractions in both fresh and mined waste, due to the recycling industry of textile waste. Table 4-25 compares the calorific value of food and textile/leather waste with similar fractions of mined waste.

Table 4-25 Calorific value of other fraction of waste with literature

Waste Type	Average Calorific value (Btu)	Location	Reference
Food Waste	1961.68	Texas, USA	This Study
Organic Fraction	859.845	Taiwan	Chang et al. (2008).
Organic Fraction	1719.69	Spain	Montejo et al. (2011).
Textile & Leather	6513.65	Texas, USA	This Study

4.3.5 Energy potential of Mixed Waste

The overall energy potential of mixed waste was calculated by applying the individual waste composition to the individual calorific value. The overall calorific value of fresh waste from the City of Denton landfill was found to be 6843.7 Btu/lb., ranging from 4882.23 Btu/lb. to 8449.29 Btu/lb., as presented in Table 4-26.

Table 4-26 Calorific value of mixed waste

	Conventional	ELR	Fresh
1	6895.68	3609.87	6611.40
2	3791.95	5272.79	6759.97
3	1189.57	2188.51	4935.33
4	6513.73	2889.55	6062.19

5	4856.45	887.12	4882.23
6	3029.99	3819.74	6804.79
7	7835.08	6551.55	7581.22
8	4665.61	5479.60	7621.50
9	6555.83	2300.97	6536.48
10	4420.03	7091.98	7564.79
11	1372.23	2381.82	7147.88
12	4560.06	3797.33	6243.23
13	402.94	1604.40	7153.60
14	2651.99	2095.21	7641.88
15	3248.93		7503.43
16	4808.33		8449.30
17	954.15		
18	6011.38		
19	1906.22		
20	1328.52		
21	5185.44		
22	3903.90		
23	4062.23		
24	2572.63		
25	2188.70		
26	2389.92		
27	2234.20		
28	2460.67		
29	3800.31		
30	4636.95		
31	2421.49		
32	2492.77		
Average	3604.62	3569.32	6843.70
	3586.97		
Std Deviation	1847.62	1824.16	939.59
Maximum	7835.08	7091.98	8449.30
Minimum	402.94	887.12	4882.23

Table 4-27 compares the calorific value of fresh mixed waste with that in literature. It is obvious from the table that developing countries like Pakistan, China, and Malaysia have a relatively lower calorific value due to a higher portion of organic waste. Malaysia waste showed a higher energy potential (9888.2201 Btu/lb.) in a study that was conducted in a different region. Waste composition was the key indicator for the energy potential of mixed solid waste. In addition, the type of landfill operation, precipitation, temperature, and moisture affect the energy potential of fresh compounds. Table 4-28 compares the calorific value of fresh mixed waste with some of the literature.

Table 4-27 Comparison of energy from fresh mixed waste with literature

Waste Type	Average Calorific value (Btu)	Location	Reference
Mixed MSW	4941.293	Jordan	Abu-Qudais and Abu-Qdais,1999
Mixed Waste	3433.902	Pakistan	Korai et al.,2015
Mixed Waste	3583.202-3763.082	China	Abdul et al.,2003
Mixed Waste	2698.194-4676.87	Malaysia	Chunming et al.,2013
Mixed Waste	5159.07	Tanzania	Omanri et al.,2014
Mixed Waste	7407.5666	Nigeria	Amber et al.,2012
Mixed Waste	4472	New York, USA	Chin and Franconeri,1980

MSW	5576	National Average	GAA,1997
MSW	8186.322	Texas, USA	Change and Davila,2007
MSW	5159.07	India	Mboowa et al.,2017
MSW	9888.2201	Malaysia	Kalantarifard and Yang,2011
MSW	2698.194- 4676.87	Malaysia	Kathirvale et al.,2003
MSW	6838.9	Texas, USA	This Study

The overall calorific value from mined waste was found to be 3665.88 Btu/lb., ranging between 887.122 Btu/lb. to 7835.84 in this study. The upper value of the range indicates the lower degradation of 10 - 30 year old waste. Table 8 compares the calorific value of mined waste from this study with some of the literature. Very few studies measured the energy potential of excavated waste experimentally. Hogland et al. (2003) measured the energy value according to the fraction size. In this study, the excavated waste (>50 mm larger fraction) had a heating value of 3000.46 Btu/lb. in the Masalycke Landfill, Sweden. Quaghebeur et al., 2012 considered two types of waste, municipal and industrial, for energy values, which were found to be 10210.662 Btu/lb. and 10748.1 Btu/lb., respectively. Plastic was found as the highest fraction (around 25%) in that landfill, subsequently contributing to the higher calorific value. Kaartinen et al. (2013) considered two types, mechanically sorted and manually sorted, to determine the higher heating value of a Finnish landfill. In this study, no classification was used for energy potential. Table 4-28 compares the calorific value of mined mixed waste with some of the literature.

Table 4-28 Comparison of energy from mined mixed waste with literature

Waste Type/Age	Average Calorific value (Btu)	Range (Btu)	Location	Reference
14-29 yeras	10210.66	8168.53-12037.8	REMO Landfill,Belgium	Quaghebeur et al.,2012
14-29 yeras	10748.10	9458.30-12037.8	REMO Landfill,Belgium	Quaghebeur et al.,2012
17-25 yeras		3009.46	Masalycke and Gladsax Lnadfill,Sweden	Hogland et al.,2003
Excavated Waste	1934.65	1461.74-3740.33	Italy	Cossu et al.,1995
Excavated Waste (Fine)		2966.47-3396.39	Fiborna Landfill,Sweden	Hogland et al.,2003
	4729.15			Obermeier and Saure,1995
		2579.54-5588.99	Germany	Brammer et al.,1995
	Up to 8598.45			Cossu et al.,1995 Rottenberger G(1Thsi 950

15-20 years	3084.00		Lancaster County, Pennsylvania,USA	Forster G,1995
5-10 years		9030-10320	Finland	Kaartinen et al. (2013)
10-30 years	3665.88	887.12-7835.08	Texas,USA	This Study

4.3.6 Comparison of energy potential between fresh and mined solid waste

The energy values from individual combustible fractions (paper, plastic, and waste and wood) in fresh and mined (conventional and ELR-operated) landfills were calculated, using the experimental method (calorimeter) shown in Figure 4-25. It is evident from the figure that excavated waste exhibited an energy value similar to that of fresh waste. Food waste was completely degraded in the mined waste. The overall energy value of excavated waste was compared with fresh waste from the same landfill in Figure 4-26.

The overall energy found in excavated waste was 3665.88 Btu/lb.; the overall energy in fresh waste was 6838.9 Btu/lb. The mined waste retained 53% more of the energy, even after 10 - 30 years of degradation compared with the energy from the fresh waste. The higher calorific value of the recovered solid waste combustible fraction has made landfill mining a potential energy source.

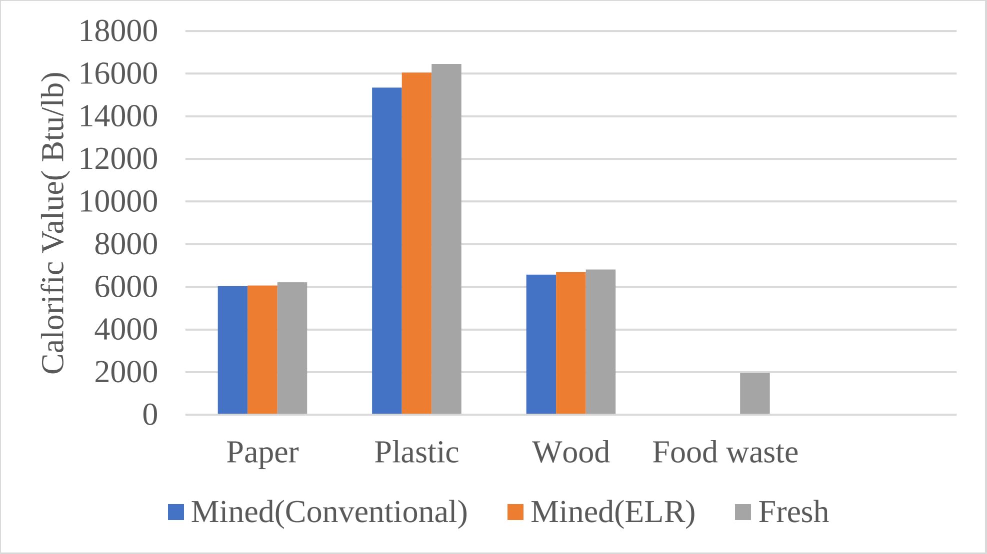


Figure 4-25 Comparison among individual waste fraction

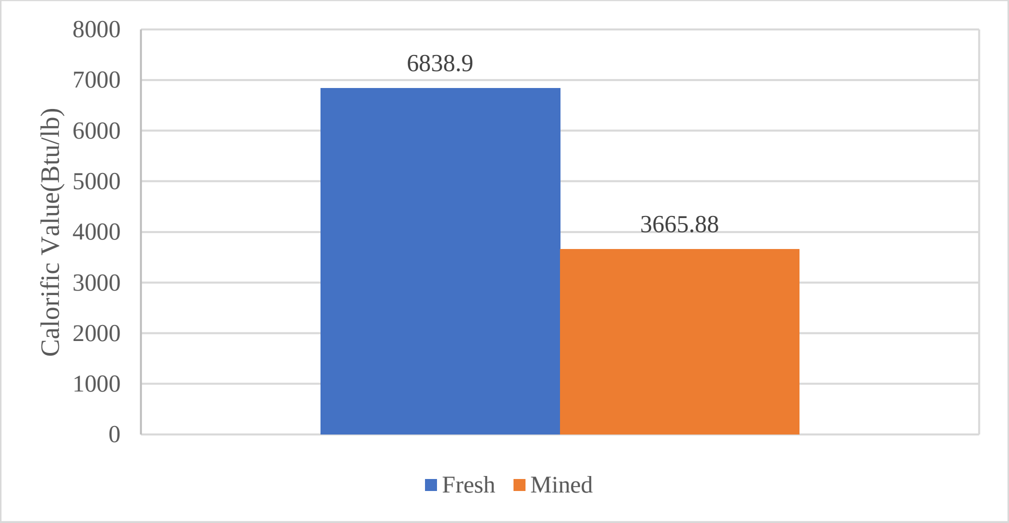
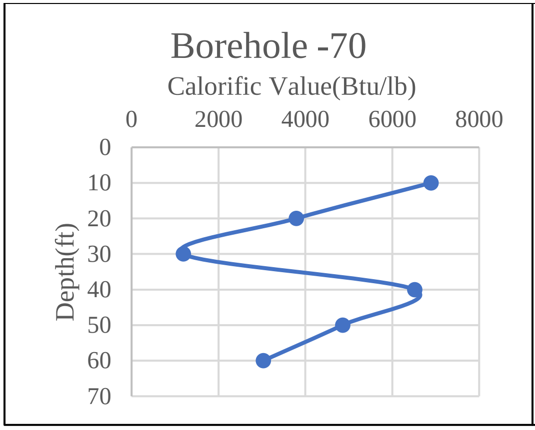
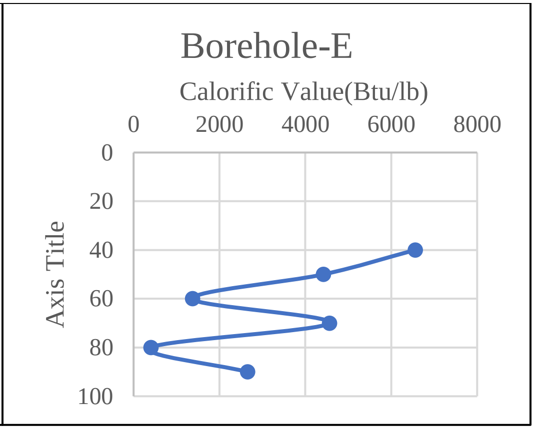


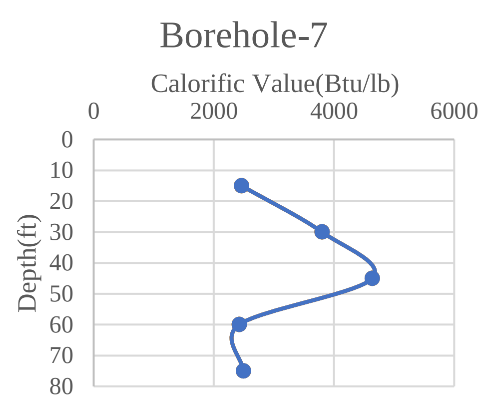
Figure 4-26 Comparison between energy potential of mined waste and fresh waste

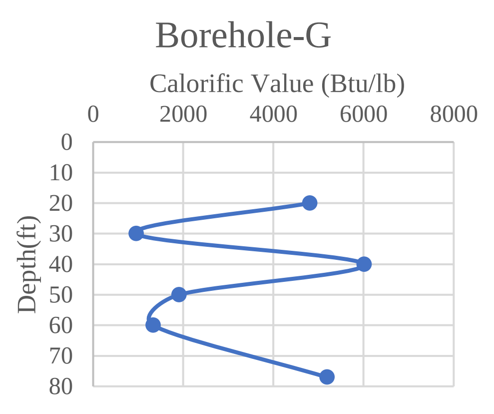
4.3.7 Effect of depth on Energy Potential in Conventional landfill

The energy profile, created according to the depths of different boreholes of Cell 0, is shown in Figure 4-27. Some boreholes were excluded for their random point data from different depths. The cover soil was approximately 8 ft. Samples collected from 10 ft. depth were relatively fresh. The energy value was found as 6895.68 Btu/lb. in 10 feet depth of Borehole 70, whereas it was 3903.91 Btu/lb. for Borehole 5. The energy gradually decreased at 30 feet in Borehole 30. Borehole G and Borehole 5 had calorific values of 1189.57 Btu/lb., 954 Btu/lb., and 2572.63 Btu/lb. In 40 feet depth, three boreholes (BH-70, BH-E, and BH-G) had energy values over 6000 Btu/lb., and Borehole 7 had over 4500 Btu/lb. However, borehole 5 had 2188.69 Btu/lb. at the same depth. Based on the energy profile, 35-45 feet of depth had the potential for higher energy. After 40-45 feet, the energy decreased up to 60 feet. The range was 1328.52-2421.49 Btu/lb. in 4 boreholes. Only Borehole 70 had a heating value of 3029.99 Btu/lb. Based on the energy profile, 55 - 65 feet depth had the potential to have the least energy. Borehole 6 and Borehole E showed an increased energy value after 60 feet.


Borehole -70
Calorific Value(Btu/lb)
0
2000
4000
6000
8000
Depth(ft)
0
10
20
30
40
50
60
70


Borehole-E
Calorific Value(Btu/lb)
0
2000
4000
6000
8000
Axis Title
0
20
40
60
80
100


Borehole-7
Calorific Value(Btu/lb)
0
2000
4000
6000
Depth(ft)
0
10
20
30
40
50
60
70
80


Borehole-G
Calorific Value (Btu/lb)
0
2000
4000
6000
8000
Depth(ft)
0
10
20
30
40
50
60
70
80

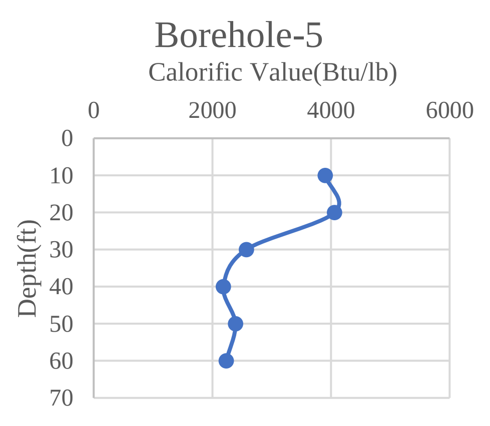

Borehole-5
Calorific Value(Btu/lb)
0
2000
4000
6000
Depth(ft)
0
10
20
30
40
50
60
70

Figure 4-27 Energy profile of Individual boreholes in Conventional Landfill

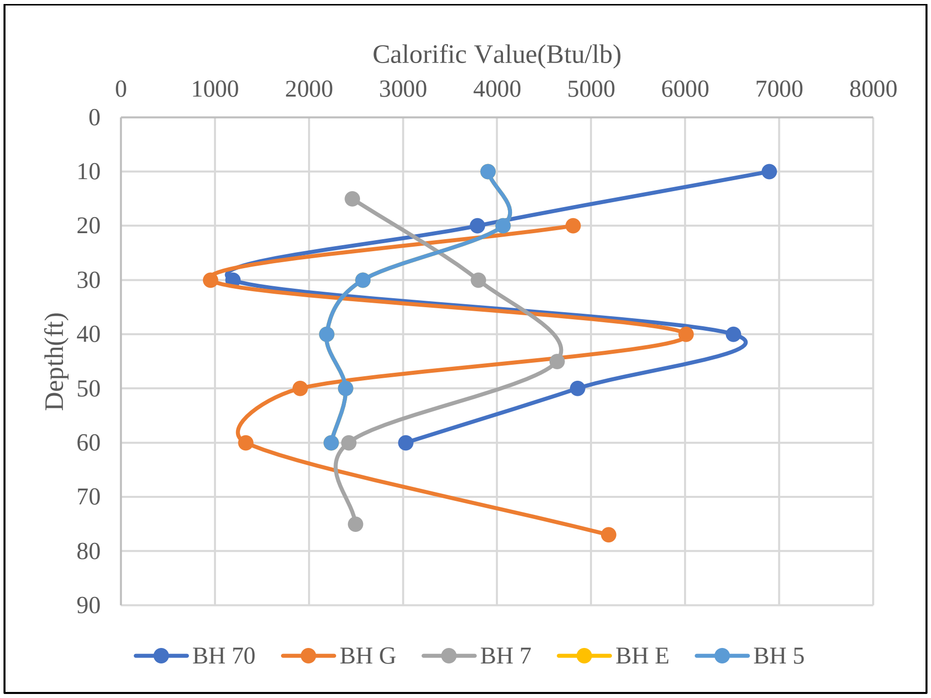
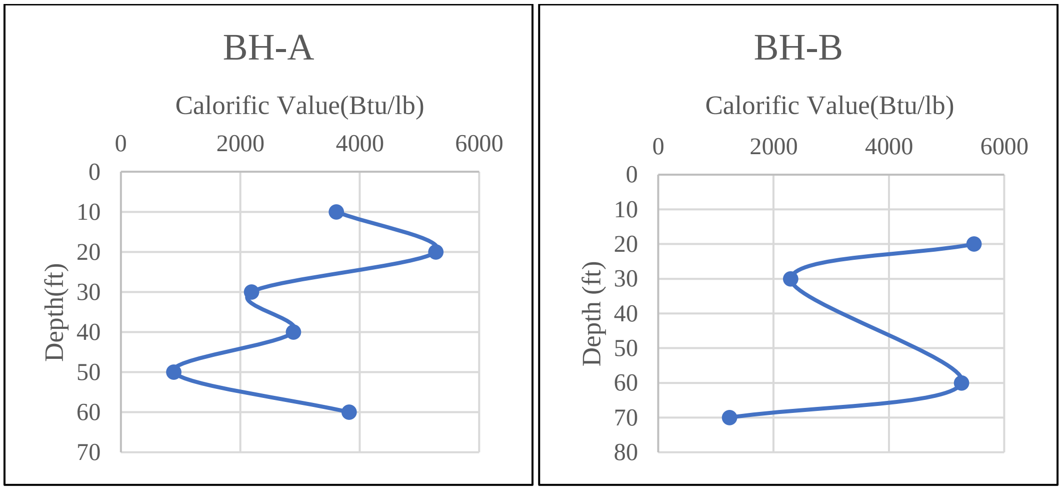


Figure 4-28 Energy profile in conventional landfill.

Figure 4-28 summarized the effects of depth on energy potential in conventional landfills. It was anticipated that the energy potential would decrease with the depth due to the higher degradation with time; it did not follow this trend, as illustrated in Figure 4-28. The energy profile had a zigzag pattern. Samples collected from 10 ft. depth were relatively fresh, resulting in a higher energy value. The degradation of MSW is enhanced by the presence of moisture in the waste. The closed landfill section was operated as a conventional landfill; therefore, no water was added to the landfill. There was no permanent cover on top of the closed section of the landfill, except for cover soil. The higher degradation at 25- 35 ft. might have been be due to water intrusion from the top, through the cover soil. From the composition, it was observed that the percentage of paper was low and the percentage of soils and degraded fines was high at these depths. However, the absence of a final cover in the landfill might also have led to unanticipated water intrusion in the waste mass. Hence the presence of fewer degraded samples after 30 ft. of the landfill may have been due to the absence of moisture in the landfilled waste. It can be summarized that the unavailability of moisture in landfilled waste may result in less-to-no degradation.

4.3.8 Effect of depth on Energy Potential in ELR landfill

In the ELR-operated landfill, moisture was added to expedite the waste decomposition. Hence, the energy potential of excavated waste from the ELR landfill was supposed to be lower than that of the conventional landfill. The energy profile for an ELR landfill is shown in Figure 4-29.



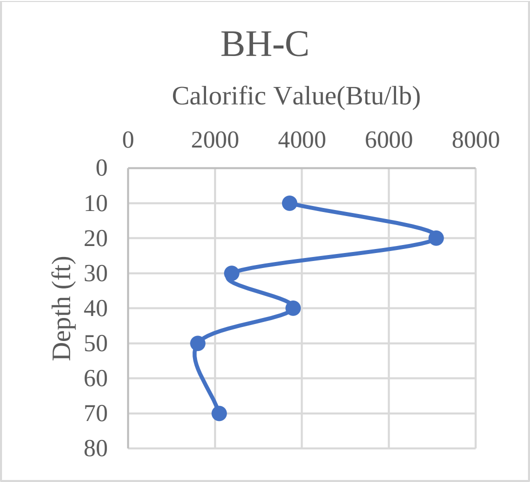


Figure 4-29 Energy profile of individual boreholes in ELR landfill

The age of the excavated waste from the ELR landfill (8-15 years) was different from the excavated waste from the conventional landfill (15-30 years). At 20 feet, the energy value was found as 5272.79 Btu/lb., 5479.603 Btu/lb., and 7091.97 Btu/lb. for Boreholes A, B, and C, respectively. The excavated waste from 20 feet was 7- 8 years old. The energy value decreased to 2188.51 Btu/lb., 2300.97 Btu/lb., and 2381.82 for the three boreholes, respectively, experiencing a higher level of degradation. The same trend was also found for the conventional landfill. After 30 feet, the energy profile was erratic, as was expected. However, a gradual decreasing trend was found by the ELR energy profile, as shown in Figure 4-30, indicating the enhancement of degradation at a greater depth.

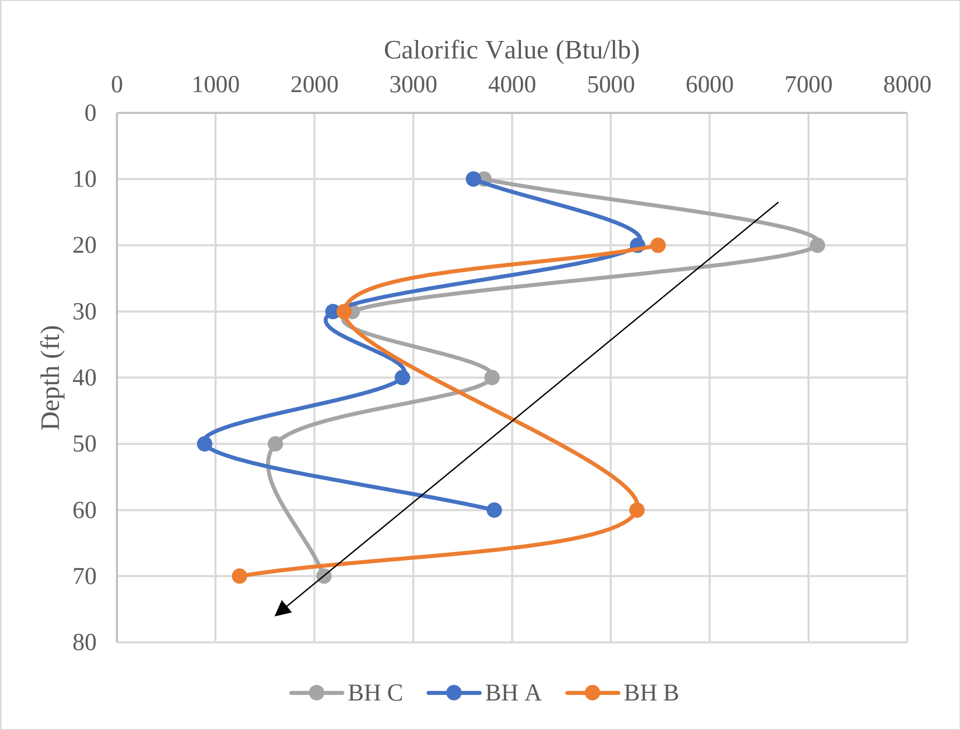


Figure 4-30 Energy profile in ELR landfill.

4.3.9 Effect of Fine/Degraded Material on Energy Potential

Fine/degraded material was found to be a very good indicator of the energy potential of mined waste, and was inversely proportional to the energy value, as shown in Figure 4-31. Fine material increased with the decrease of the energy value, regardless of the depth of the mined sample. The age of the excavated waste was 8-30 years. The R^2 was found to be 0.7108 of the relation between fine material and the calorific value of the mined waste, and is a very good value, considering the heterogeneity of solid waste. The lower degradation indicated the lower amount of fine/degraded material resulting from the higher portion of paper, and wood and yard waste in the excavated waste. Similarly, a higher amount of fine/degraded material indicated the higher degradation of the combustible fraction, resulting from the lower energy value of the excavated waste. Based on the figure, the excavated waste, which was 0- 20% fine, had an average calorific value of 5000-7000 Btu/lb. If the fine material increases up to 40- 50 %, the energy value will decrease to 3000-4000 Btu/lb. Seventy to eighty percent (70-80%) of fine contributes to an energy value of 1500- 2000 Btu/lb. Hogland et al. (2003) reported the average fine fraction of the Masalycke Landfill, Sweden as 54.54%, with a calorific value of mixed waste (>50 mm) as 3010 Btu/lb. This value clearly complies with our study.

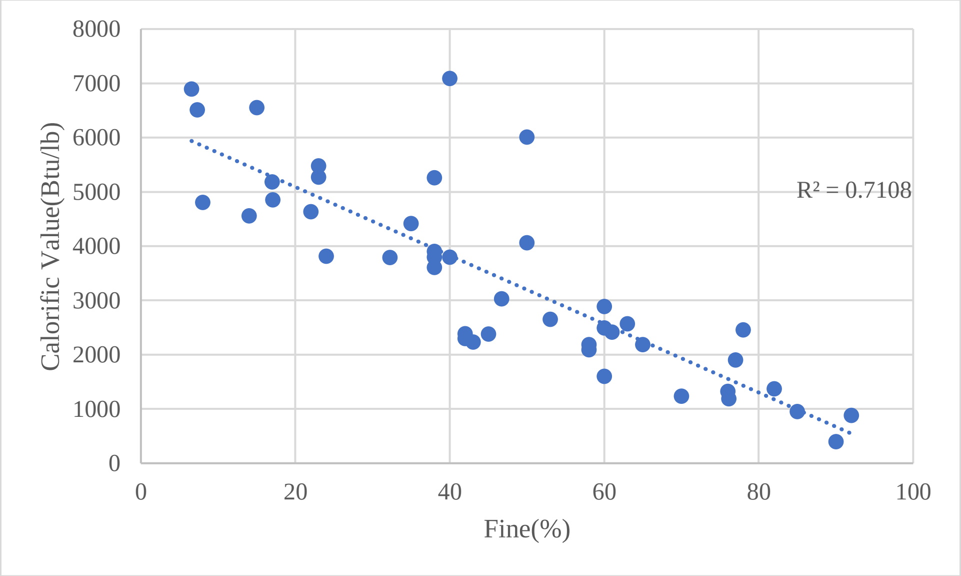


Figure 4-31 Effect of fine/ degraded material on energy potential of mined waste.

Even though fine material is a very good predictor of energy value, it did not follow any trend with depth in the conventional landfill, as shown in Figure 4-32. On average, the fine material was found to be around 50%. However, it varied from 10% to 90%, depending on the state of the degradation. Fine material was found to be 6.58-38% within 10 feet, representing comparatively lower degradation of waste that was 25-30 years old. At 30 feet depth, the fine material that was 20-25 years old was 63- 84%, indicating higher degradation. This was in very good agreement with the energy profile of the boreholes. The same zigzag pattern was found after 30 feet depth, similar to that of the energy profile.

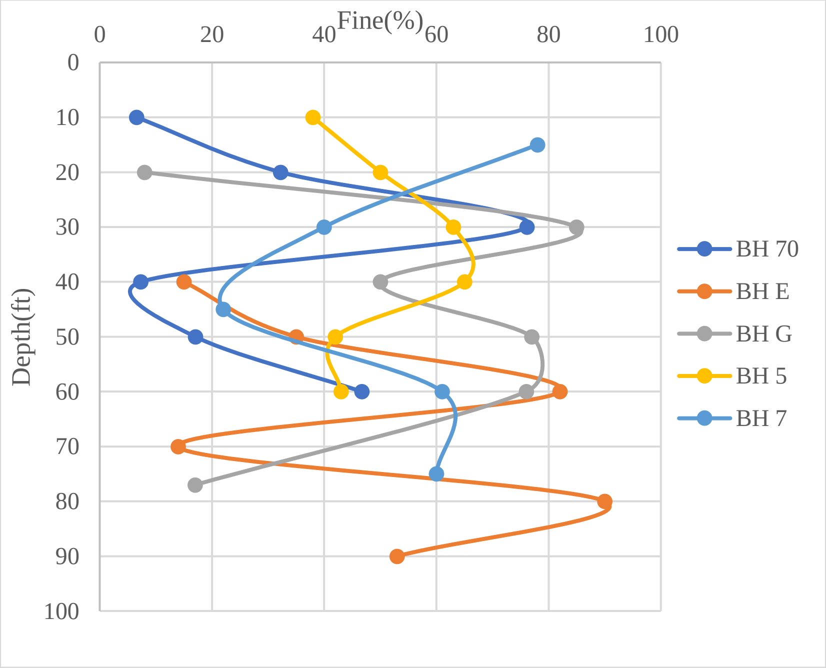


Figure 4-32 Fine material in different depth in conventional landfill

The gradual increase of fine material with depth in the ELR-operated landfill is depicted in Figure 4-33. The fine material was 20-40% within 20 feet depth. Three boreholes (A, B, and C) had fine fractions of 23%, 23%, and 40%, respectively. The age of the excavated waste in 20 feet was 7-9 years. The fine material was 70 % and 58 % for Borehole B and Borehole C, respectively, in 70 feet. The age of the excavated waste in this depth was 13-15 years. The gradual increase of fine fraction with depth was a good indicator of the ELR operation. Due to the presence of additional moisture, the degradation increased, resulting in a higher fraction of fines at a deeper depth.

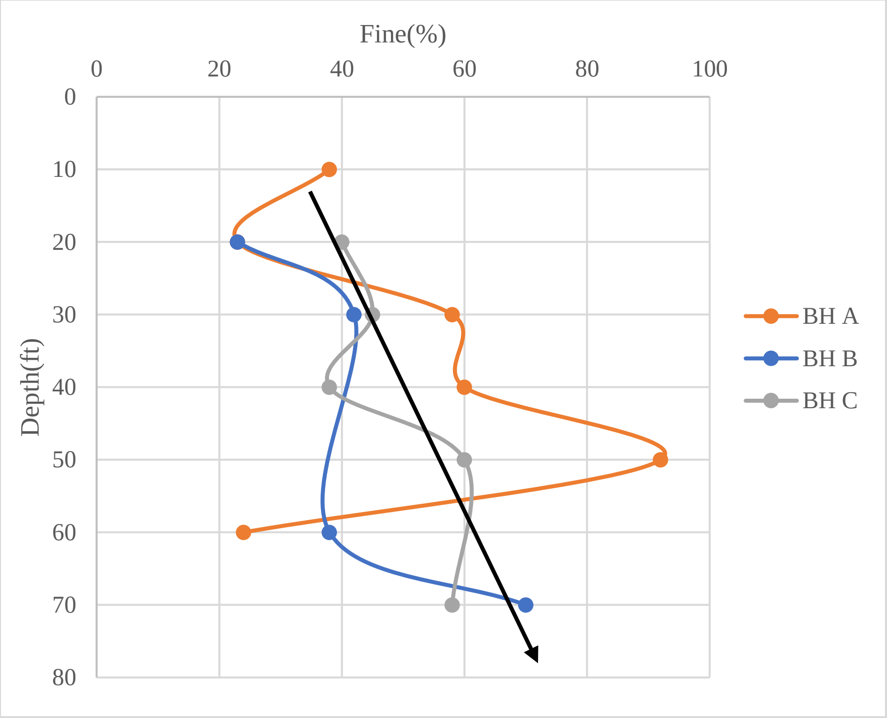


Figure 4-33 Fine material in different depth in ELR landfill

The effect of storage time on the fine fraction of excavated waste is illustrated in Figure 4-34 (Chen et al., 2009).

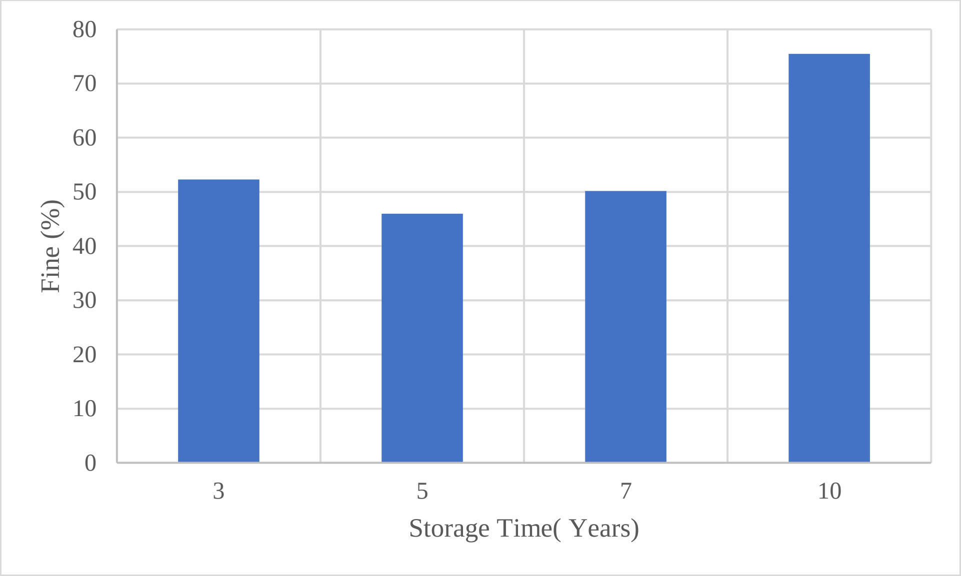


Figure 4-34 Effect of storage time in fine fraction of mined waste (Chen et al., 2009)

4.3.10 Effect of Moisture content on Energy Potential in Conventional Landfill

The moisture content of MSW is extremely important, as it influences the decomposition behavior and all other engineering properties. The variations of the calorific value with the moisture content (wt. basis) for individual boreholes are presented in Figure 4-35. Forty to seventy percent (40-70%) of moisture is required for optimum biological activity (Barlaz et al, 1990). The moisture content was below 40% in every borehole. According to Landva and Clark (1990), the presence of high organic content in MSW increases the moisture content of the waste.

Therefore, the moisture content is higher in the waste of developing countries, due to the presence of a higher food waste fraction. The moisture content was 11- 41%, having an average of 20% in the excavated waste, as shown in Figures 4-35 to 4-39, due to the comparatively lower degradation within 10-20 feet. The energy value was found higher (2460.67-6869 Btu/lb.) with a moisture content of 10.64 -29.51 % throughout the boreholes. At 30 ft. depth, the degradation was higher, resulting in lower energy values in the waste with a moisture content of 17.66-28.61%. Moisture content followed similar changes with the change of energy values in some of the depth intervals in different boreholes BH-70(10-20 feet), BH-7(20-30 feet), BH-G (40-70 feet), BH-5 (10-50 feet), and BH-E (70-90 feet). Paper, cardboard, food waste, yard waste and fine material can absorb moisture (Hull et al. 2005).

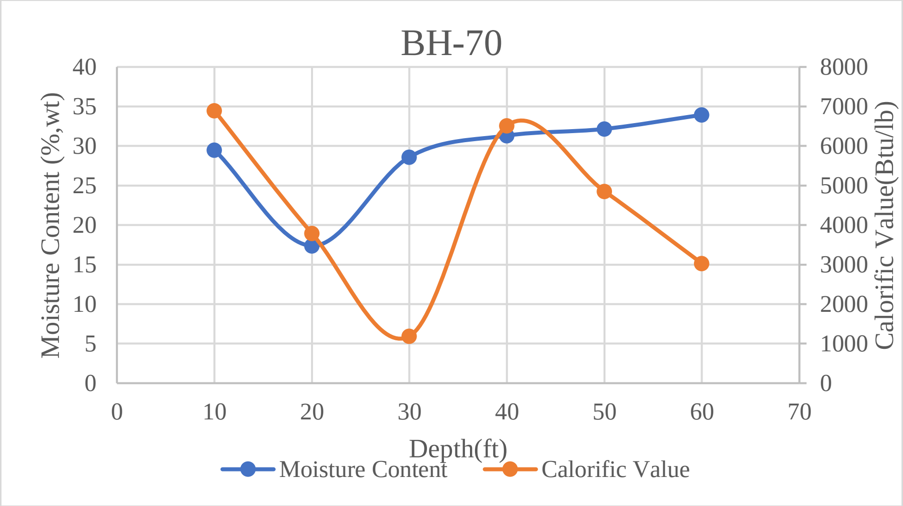


Figure 4-35 Effect of moisture content on calorific value in borehole 70

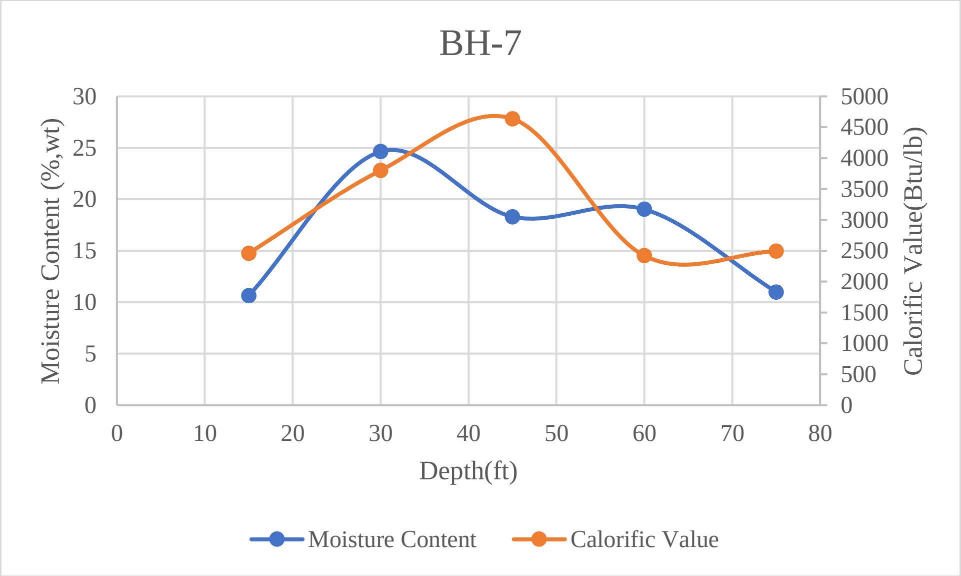


Figure 4-36 Effect of moisture content on calorific value in borehole 7

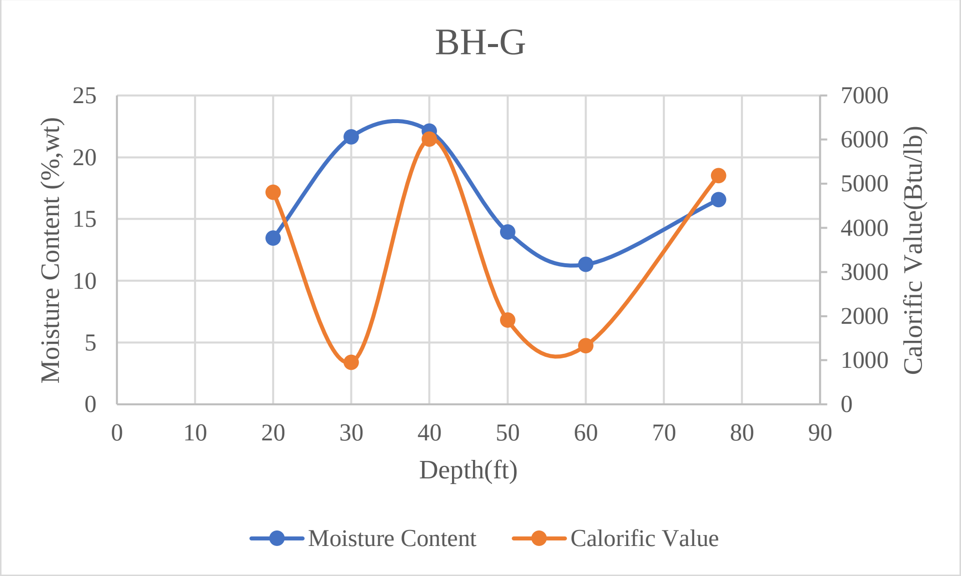


Figure 4-37 Effect of moisture content on calorific value in borehole G

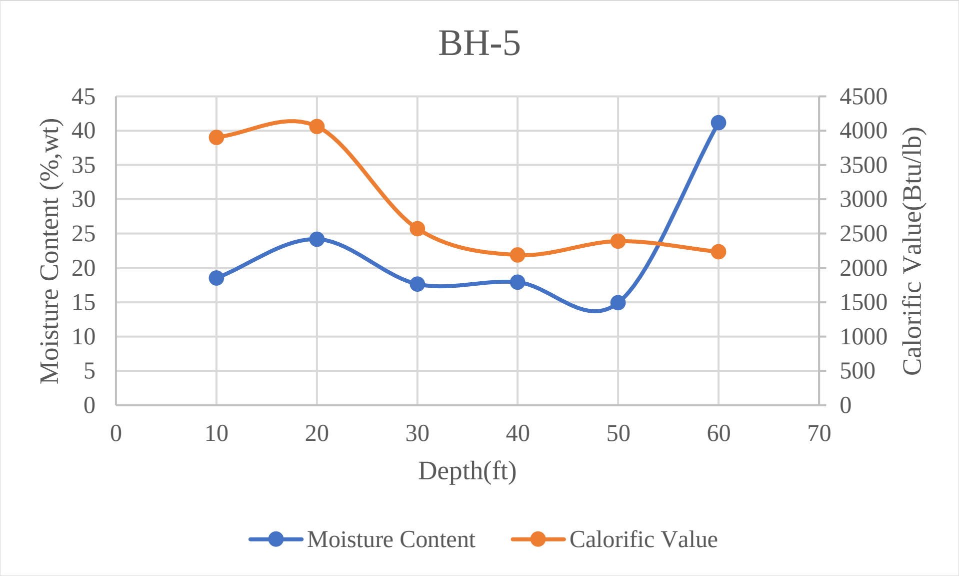


Figure 4-38 Effect of moisture content on calorific value in borehole 5

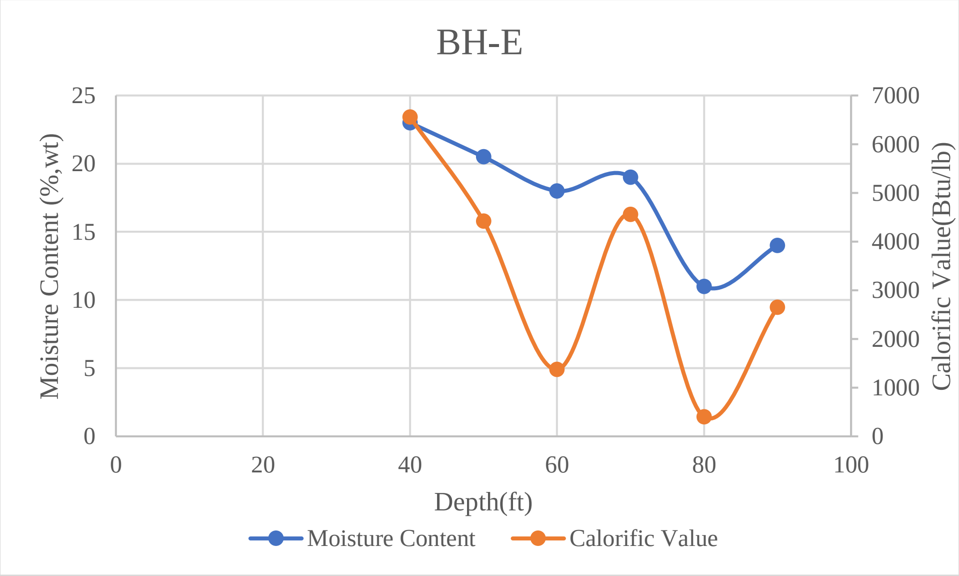


Figure 4-39 Effect of moisture content on calorific value in borehole E

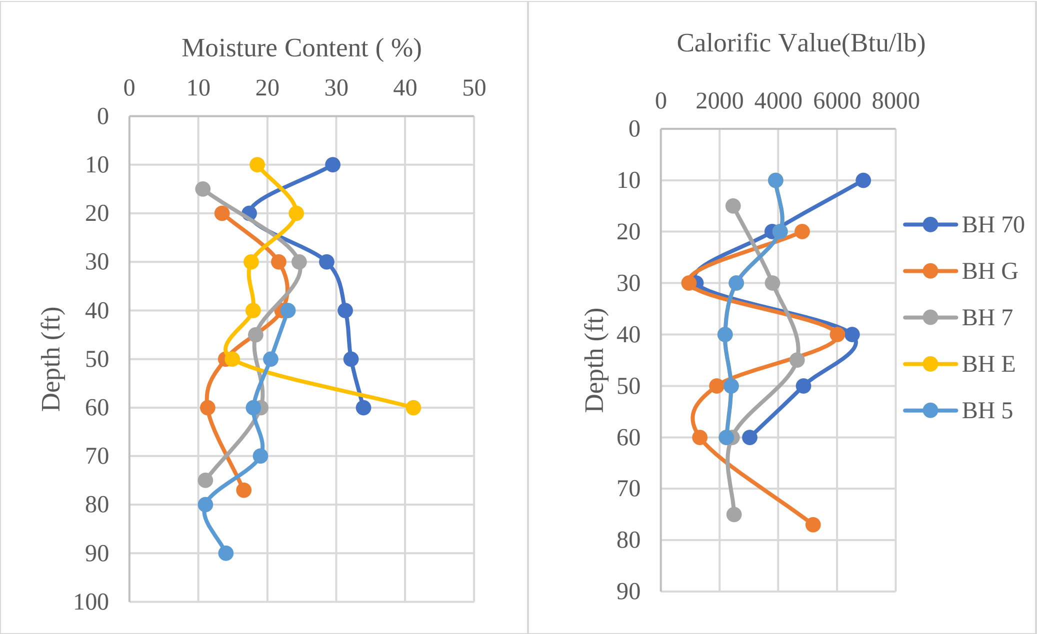


Figure 4-40 Effect of moisture content on calorific value in conventional landfill

Based on the moisture profile shown in Figure 4-40, no significant trend was found between the moisture content and depth. This finding is similar to other landfill mining projects reported in the literature (Hull et al. 2005; Hoagland et al., 2003; and Chen et al., 2010).

4.3.11 Effect of Moisture content on Energy Potential in ELR Landfill

The effect of moisture content on the energy potential from ELR-operated boreholes is shown in Figures 4-41 to 4-43. A higher moisture content was anticipated in the excavated waste from an ELR operation; however, the moisture content was 12.5 - 30.5%, having an average of 21%. The moisture content followed the same trend with the energy profile in some of the depth intervals in three boreholes, like BH-A (30-60 feet), BH-B (20-60 feet), and BH-C (30-70 feet). The energy potential was found to have the highest calorific value in all three boreholes (5272.79 Btu/lb., 5479.603 Btu/lb., and 7091.98 Btu/lb., for BH-A, B, and C, respectively).The moisture content was 14.65-23.64% at 20 feet depth; however, it increased to 25-30% at 60-70 feet depth. At this greater depth, the energy value was low, 1240.59 Btu/lb. and 2095.205 Btu/lb. in Boreholes B and C, respectively, indicating the higher degradation level. Twenty percent (20%) of the paper fraction was found at 60 feet of Borehole A.

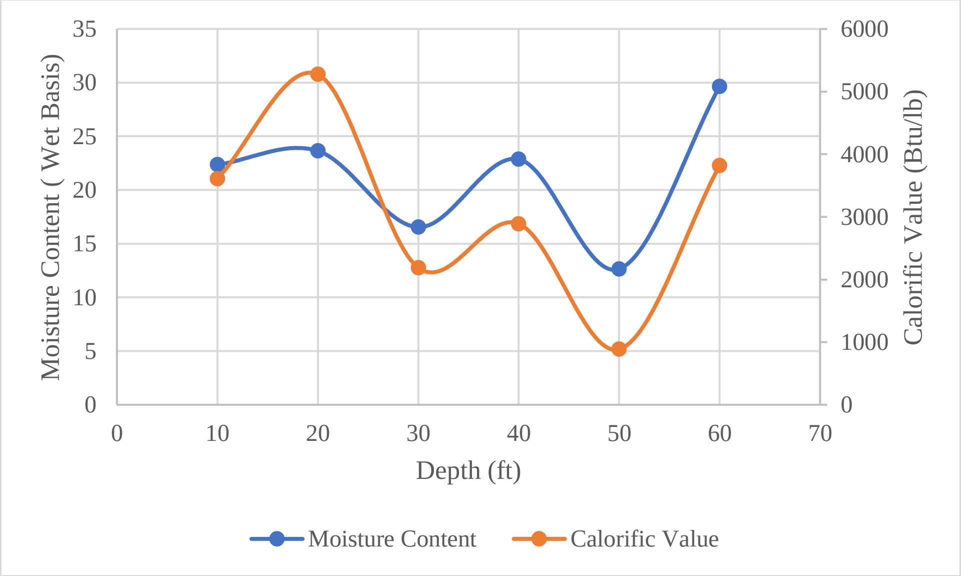


Figure 4-41 Effect of moisture content on calorific value in borehole A

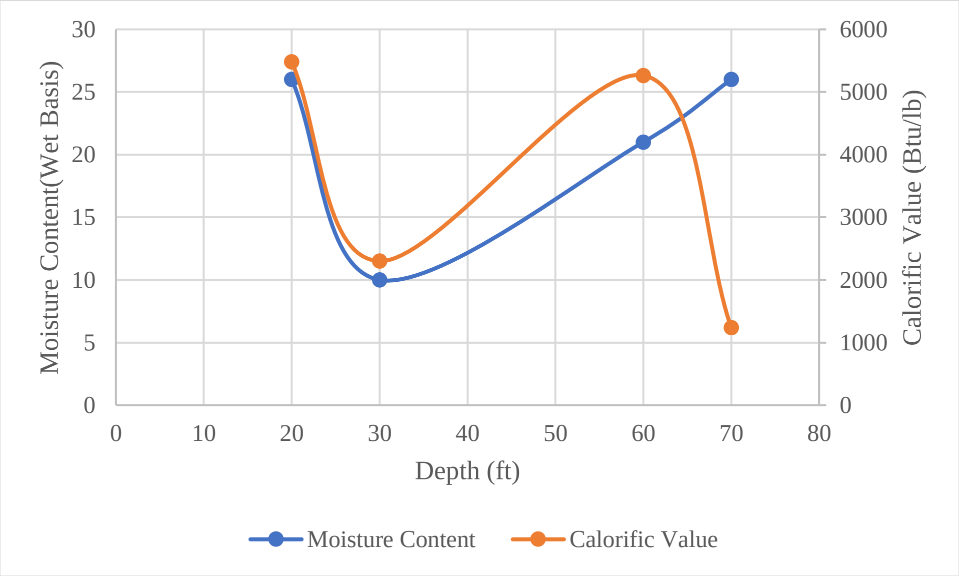


Figure 4-42 Effect of moisture content on calorific value in borehole B

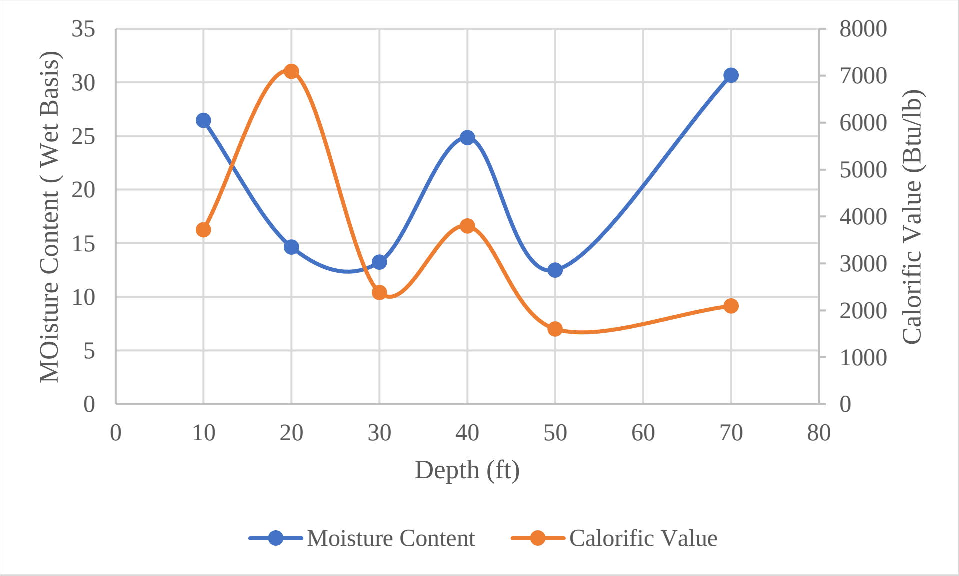


Figure 4-43 Effect of moisture content on calorific value in borehole C

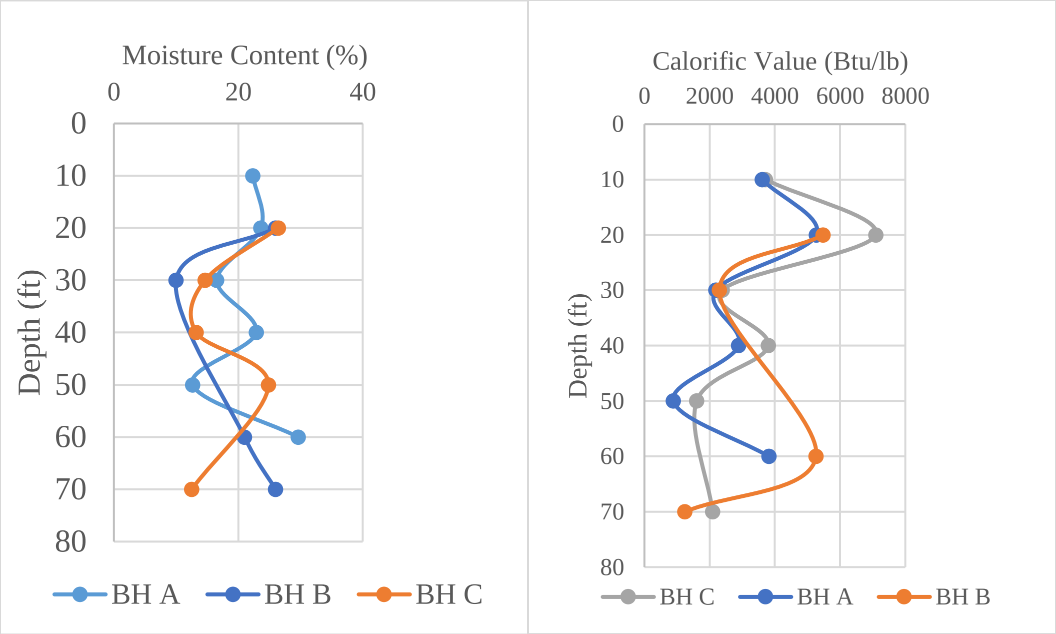


Figure 4-44 Effect of moisture content on calorific value in ELR landfill

It can be seen, from the moisture profile shown in Figure 4-44, that no significant trend was found between the moisture content of an ELR-operated landfill and depth. Overall, moisture content of mined waste has a tendency to increase with the increase of calorific value, as illustrated in Figure 4-45.

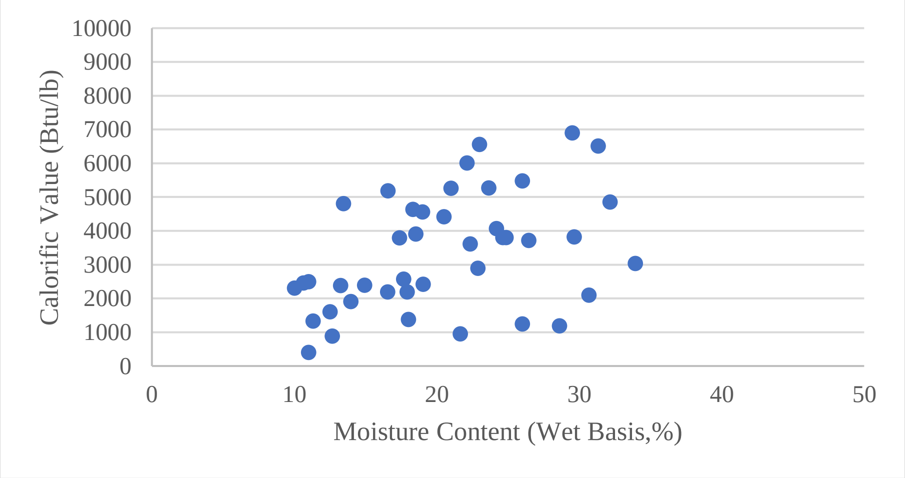


Figure 4-45 Effect of moisture content on calorific value of landfill mined waste

4.3.12 Effect of Volatile Solid on Energy Potential in Conventional Landfill

According to ITRC (2006), the volatile solid test is the most inexpensive method of measuring the amount of biodegradable material that remains in the waste mass. However, the volatile solid test is not an accurate measure of available biodegradable material (Hull et al., 2005).The effect of volatile solids on the energy potential of each borehole is shown in Figures 4-46 to 4-49. The volatile solids were 85.79% and 76% within 10 feet of Borehole 70 and Borehole G, indicating a higher potential of remaining degradability. On the other hand, less of the volatile solids was found in Borehole 5 (16.27%) and Borehole 7 (10.5%), indicating the lowest potential of degradability of waste. Volatile solids decreased to 59.3 % and 24% in 30 feet for Borehole 70 and Borehole G. The degradation level was high in 30 feet, which was also found in the fine fraction graph. Borehole 5 and Borehole 7 had volatile solids of 22.83 % and 22.2%, respectively. The volatile solid graph did not follow any trend; however, the volatile solids maintained a similar trend with the energy value in all of the boreholes. BH-70, BH-5 and BH-7 had similar trends between the volatile solid and energy value up to 75 feet. In BH-G, only one point (40 depth) exhibited an unexpected reverse trend between the energy value and volatile solids. Overall, the volatile solids were 8-86.56%, with an average of 34.5%.

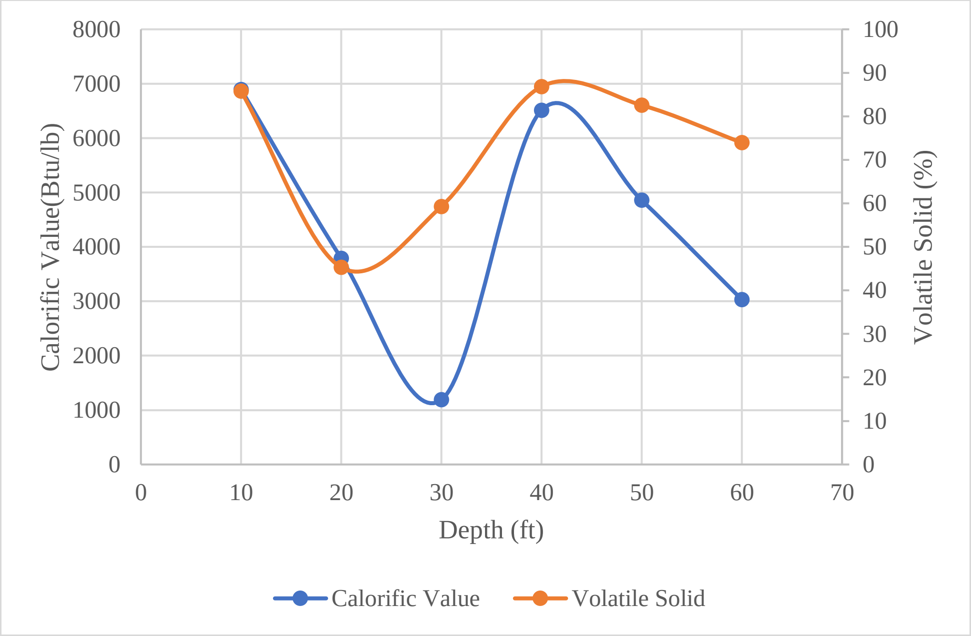


Figure 4-46 Effect of volatile solid on calorific value in borehole 70

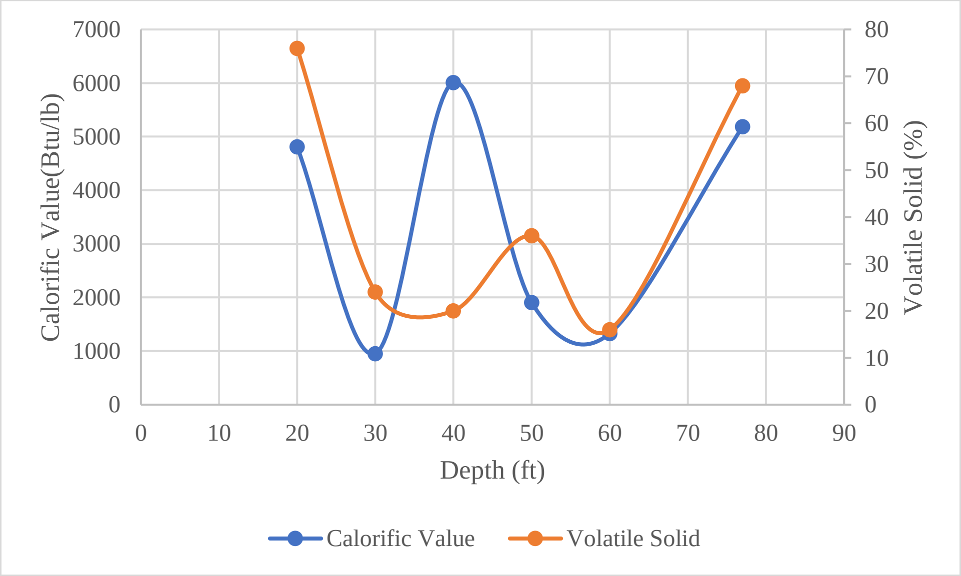


Figure 4-47 Effect of volatile solid on calorific value in borehole G

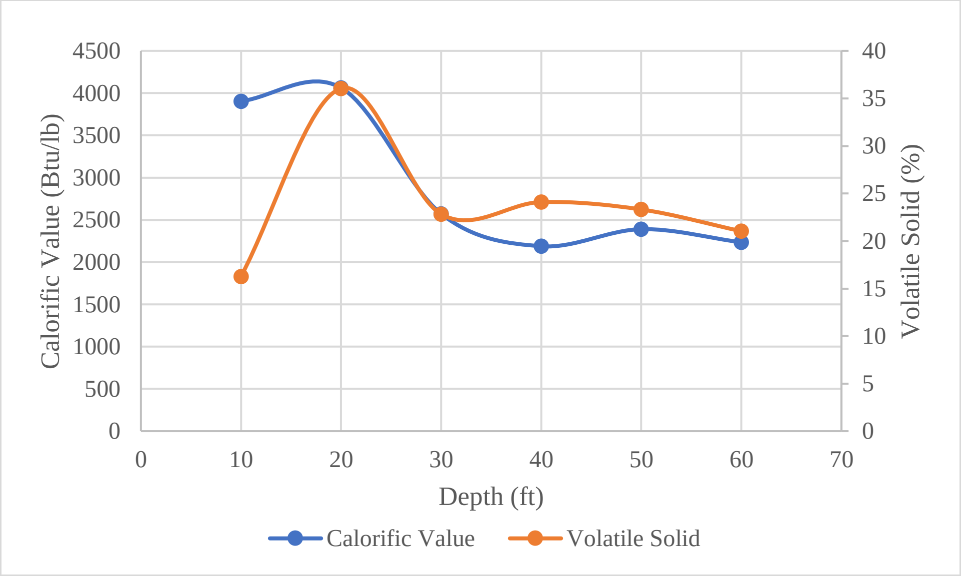


Figure 4-48 Effect of volatile solid on calorific value in borehole 5

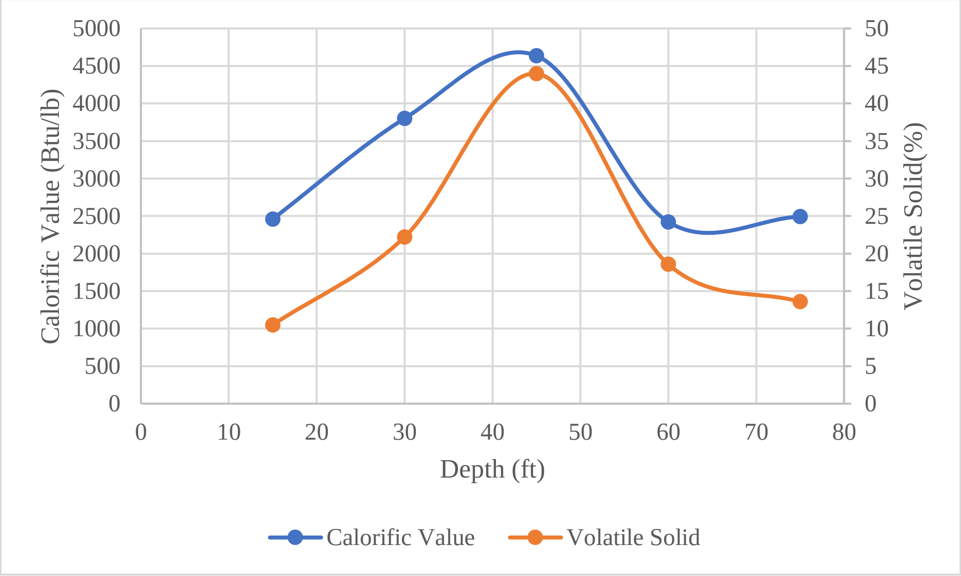


Figure 4-49 Effect of volatile solid on calorific value in borehole 7

4.3.13 Effect of Volatile Solid on Energy Potential in ELR Landfill

The effect of volatile solids on the energy potential in an ELR landfill is shown in Figures 4-50 and 4-51. A lower value of volatile solids was expected, due to the addition of moisture to enhance the decomposition. However, the volatile solids had values ranging from 8 - 48%, with an average of 26%, which was lower than the volatile solids from the conventional landfill (34.5%). This indicates a lower energy potential for the excavated waste. The volatile solids were 20% and 44% in the first 10 feet of depth in BH-A and BH-C, respectively. The energy value was 3609.87 Btu/lb. and 3715 Btu/lb. for the boreholes, respectively. The paper fraction (50%) in Borehole C contributed to the higher volatile solid, in spite of having similar energy value. In 30 feet depth, the volatile solid results, 16% and 28%, indicated a higher level of degradation than the upper layer. The decomposition trend was similar in the conventional landfill in the first 30 feet. This zigzag degradation trend continued, even after adding the moisture to enhance the decomposition. The age of Cell 2 (ELR operated), which was supposed to have a higher energy value than the conventional landfill, was 6 - 13 years. The average energy value from an ELR-operated landfill was found to be 3376.33 Btu/lb. (volatile solids - 26%), compared with the calorific value from conventional landfills of 3425 Btu/lb. (volatile solid - 34.5%).Therefore, the ELR- operated landfill enhanced the decomposition, lowering the energy value of 6 - 13 year old waste, compared with the 10 - 30 year old waste.

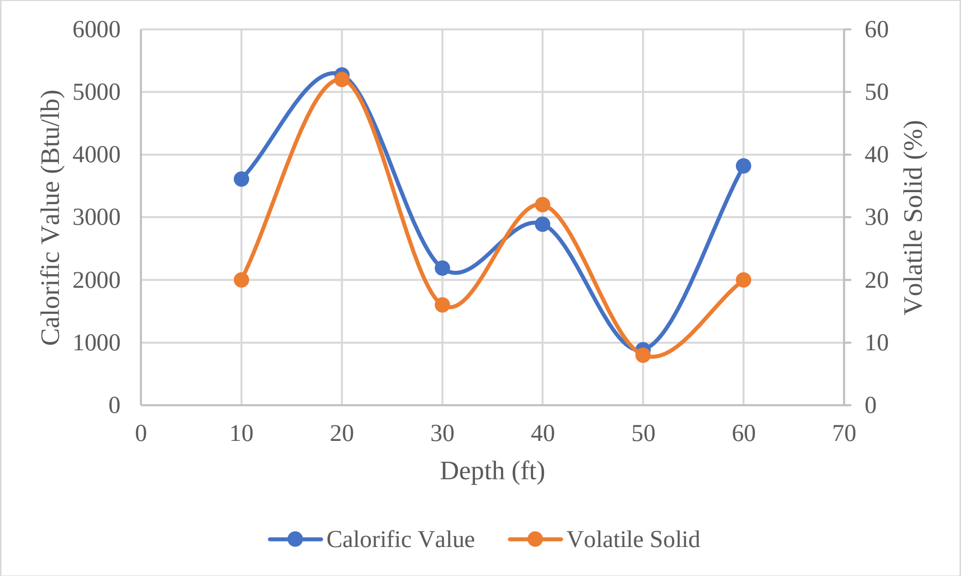


Figure 4-50 Effect of volatile solid on calorific value in borehole A

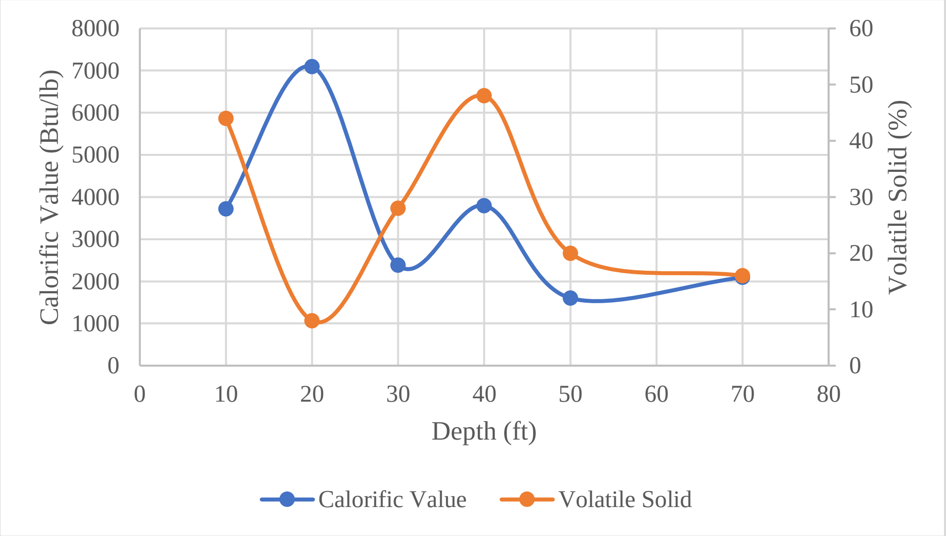


Figure 4-51 Effect of volatile solid on calorific value in borehole C

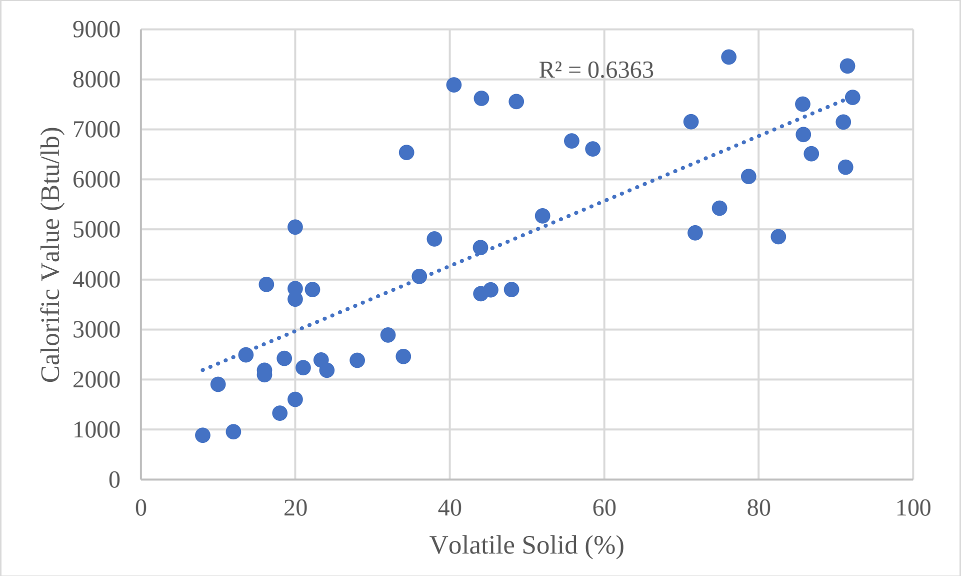


Figure 4-52 Effect of volatile solid on calorific value of municipal solid waste (Fresh and mined)

As is shown in Figure 4-52, volatile solids were in good agreement with the energy value at all depths, even though it is not an accurate measure of available biodegradable material (Hull et al., 2005). However, volatile solids give a good indication of the potential energy remaining in any kind of waste (fresh and mined).This graph contained a wide range of data from fresh waste to be degraded and partially degraded waste.

4.3.14 Effect of age and precipitation in energy potential of solid waste.

The age of the excavated waste is a crucial parameter for assessing the energy potential of mined waste. The energy value is supposed to be lower with the increase of the storage time of the waste; however, decomposition of solid waste is pretty complex inside the landfill. It includes different interconnected parameters, like microbes, moisture, temperature, waste composition, and precipitation. Age was calculated from the date of the newspapers.

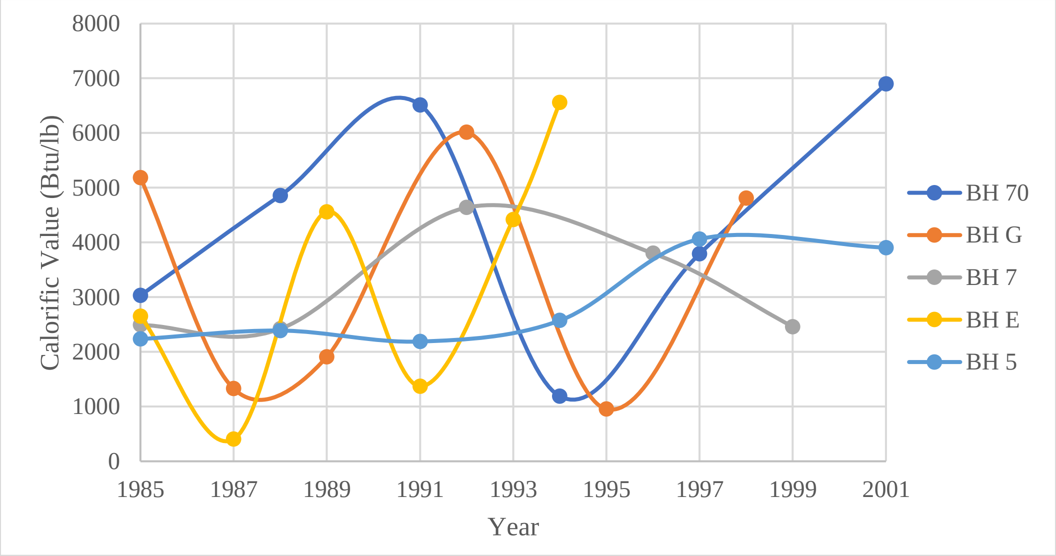


Figure 4-53 Effect of age in energy potential in conventional landfill

As is shown in Figure 4-53, the energy value followed a sinusoidal trend with age, and was found to be 2234.19 – 5185 Btu/lb. in 1985. Three of the boreholes had paper fractions of more than 40%, indicating relatively lower degradation. After the RCRA 1991 act, the energy value increased significantly. The City of Denton landfill probably accepted more waste due to the closing of a significant number of landfills. BH-70, BH-G, BH-5 and BH-7 had combustible fractions of 77.46%, 44%, 24%, and 63%, respectively, resulting in higher calorific values at that time. The 1994-95 energy value was relatively lower, having a fine fraction of more than 50%. In the closing year, 2001, the energy value was found to be 6898.68 Btu/lb.

and 3903.91 Btu/lb. for BH-70 and BH-5, respectively. Waste with higher storage time was found to have more energy in China (Chen et al., 2010) and Belgium, (Quaghebeur et al., 2012), as shown in Figure 4-54

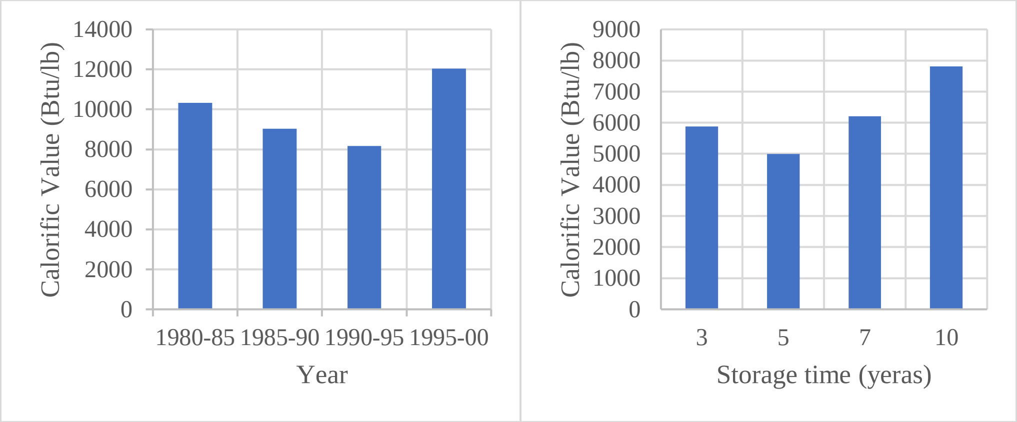


Figure 4-54 Effect of age in energy potential in other countries (a) Belgium (Quaghebeur et al., 2012) (b) China (Chen et al., 2010)

As depicted in Figure 4-55, the energy potential of excavated waste had a decreasing trend with the increase of storage time. The energy value in 2001 was found to be 1204.59 Btu/lb. and 3819.735 Btu/lb. for BH-A and B, respectively. The average energy value was 2512.17 Btu/lb. The energy value from the conventional landfill during the same time (2001) was 5401.29 Btu/lb. Due to the ELR operation, the excavated waste from Cell 2 experienced more degradation, resulting in a lower remaining energy value. The paper fraction was over 30% in conventional landfill in 2001; in the ELR landfill, it was almost degraded at the time of disposal. The energy value increased with the decrease of storage time.

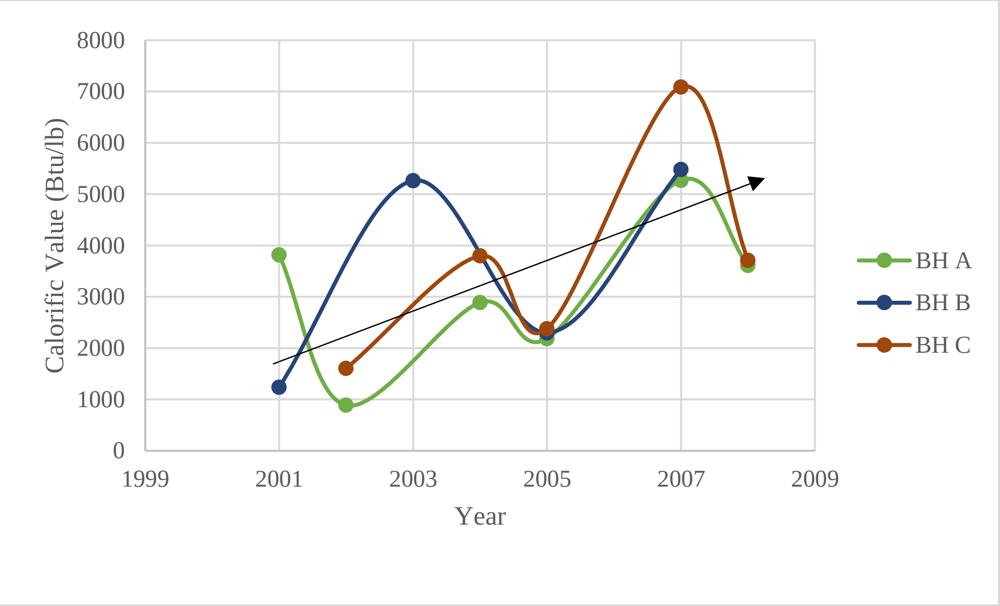


Figure 4-55 Effect of age in energy potential in ELR landfill

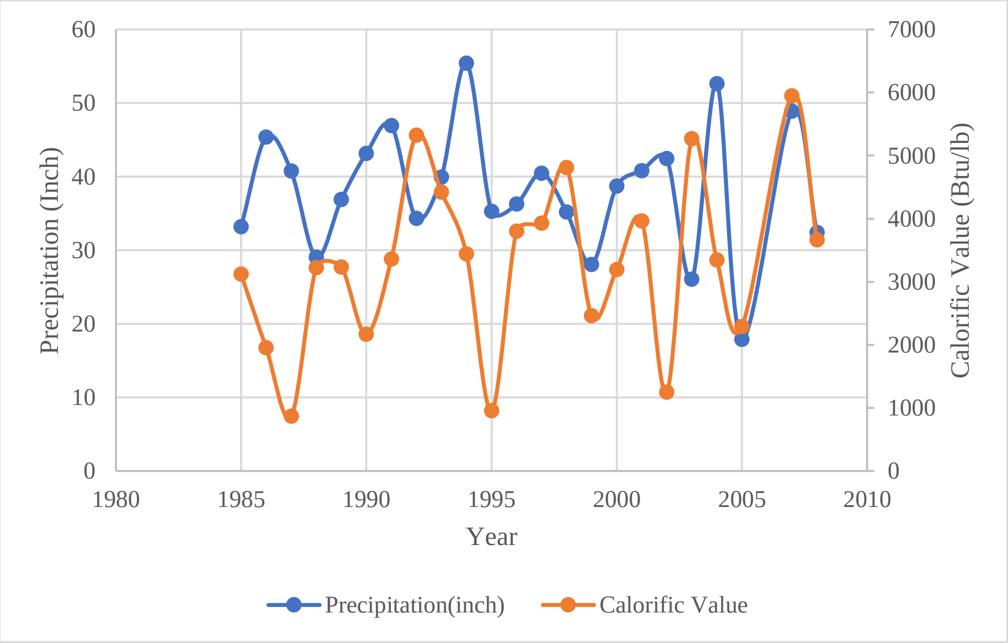


Figure 4-56 Effect of precipitation in energy potential of excavated waste

The effect of weather on energy values are shown in Figure 4-56. National Weather Service volunteer cooperative observer data, which began in 1913, was used to include precipitation. Based on the figure, higher precipitation enhanced the decomposition rate of the solids. The energy value was 865.73 Btu/lb. in 1987, immediately after a 45.37 inch rain in 1986. Similarly, a 55.4 inch rain was .recorded in 1994, and the energy value decreased to 954.15 Btu/lb. from 3439.34 Btu/lb. This exact trend was observed after the precipitation of 2004 (52.61 in). Forster, 1995 evaluated the effect of precipitation on the energy potential in one mining project shown in Figure 4-57.

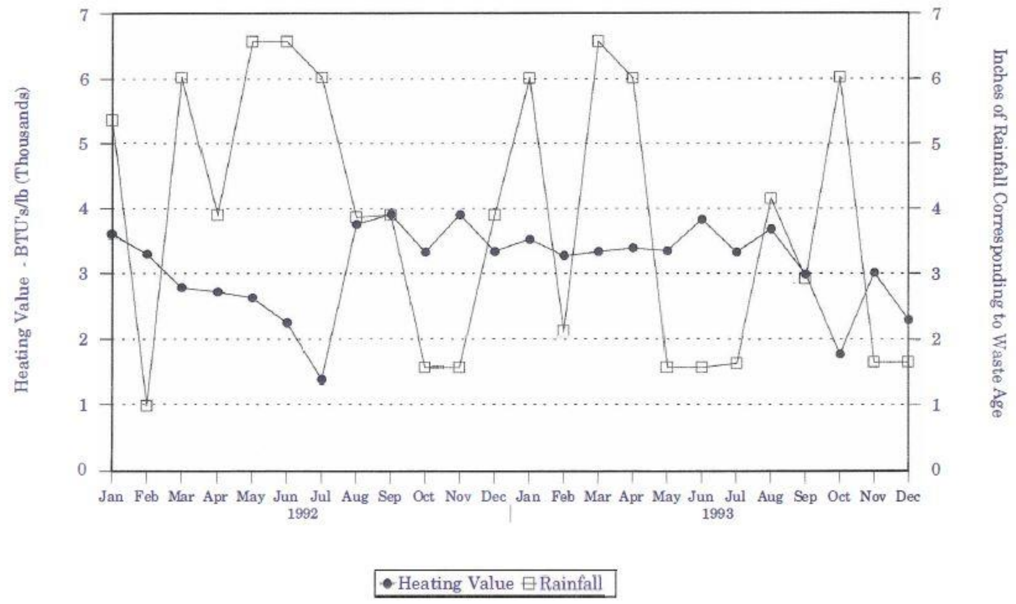


Figure 4-57 Effect of precipitation in energy potential of excavated waste in Pennsylvania (Forster, 1995)

4.3.15 Effect of waste composition in energy potential of solid waste.

Generally, in landfills, food waste, yard waste, cardboard, and paper fractions are considered biodegradable (Eleazer et al., 1997). The effects of waste composition are shown in Figures 4-58 to 4-62. The percent of plastic ranged from 0.38 - 32.82 in the conventional landfill, with an average of 9.13 %. The recovery of plastic plays an important role in assessing the energy potential of excavated waste. The plastic fraction had the almost similar trend as the energy value in BH-E, BH-G, BH-5, and BH-7. Generally, the plastic fraction was higher (weight basis) in waste composition in the higher degraded regions. A likely reason is that as the relative proportions of readily degradable organics, such as paper, cardboard, food, and yard waste declined due to degradation, the proportion of non-biodegradable fractions relative to the overall composition of the waste increased. The energy value was 3903.91-6895.68 Btu/lb. within 10 feet, of waste which was 9-15 years old. The paper fraction was 32-49.52 %, followed by 10-15.16% of plastic. The energy value was found comparatively less (954.152 Btu in BH-G, 1189.56 Btu/lb. in BH-70, 2572.63 Btu/lb. in BH-G) in 30 ft. depth, due to higher degradation. The paper fraction was 3-19% followed by 2-8% plastic, and 1.17-7 % wood and yard waste. The energy value of excavated waste from 40 feet of BH-G was 6011.38 Btu/lb., having higher plastic fraction of 30 %. Forty-seven percent (47%) wood in BH-E (70 feet) contributed the overall energy value of 4560 Btu/lb.

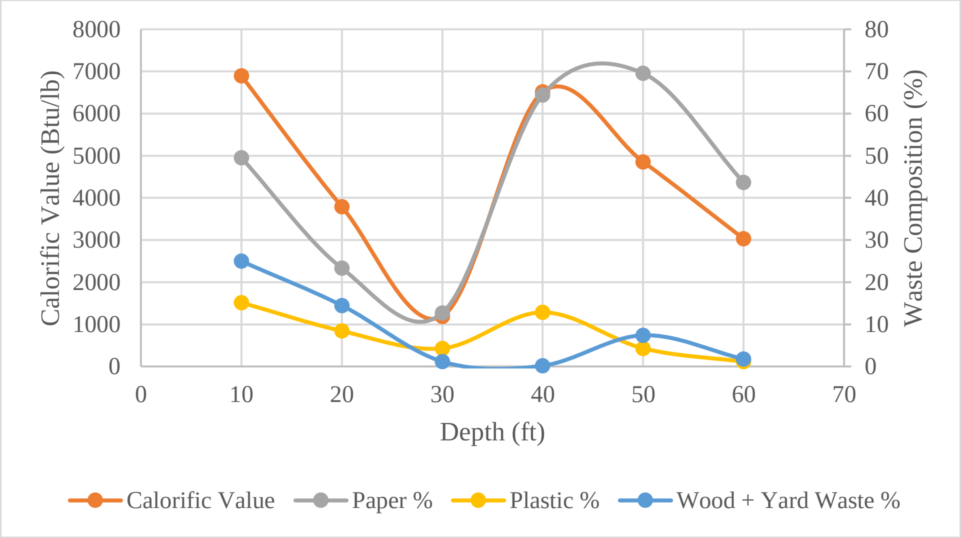


Figure 4-58 Effect of waste composition on energy potential of mined waste in borehole 70

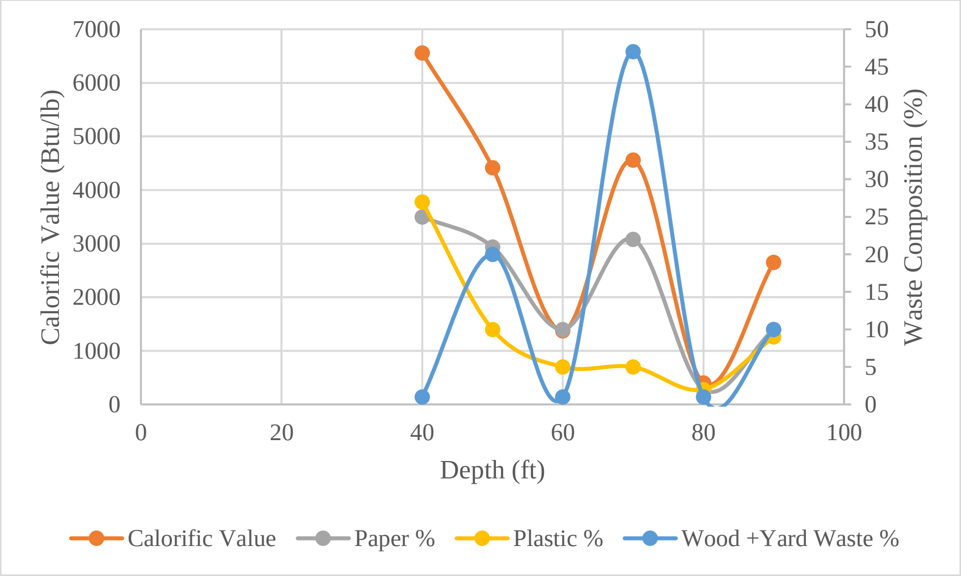


Figure 4-59 Effect of waste composition on energy potential of mined waste in borehole E

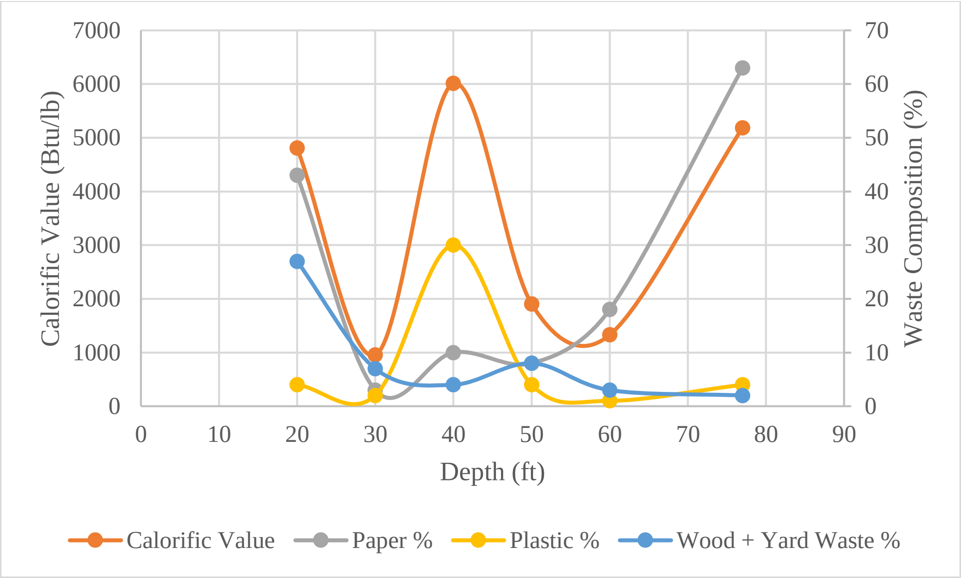


Figure 4-60 Effect of waste composition on Energy potential of mined waste in borehole G

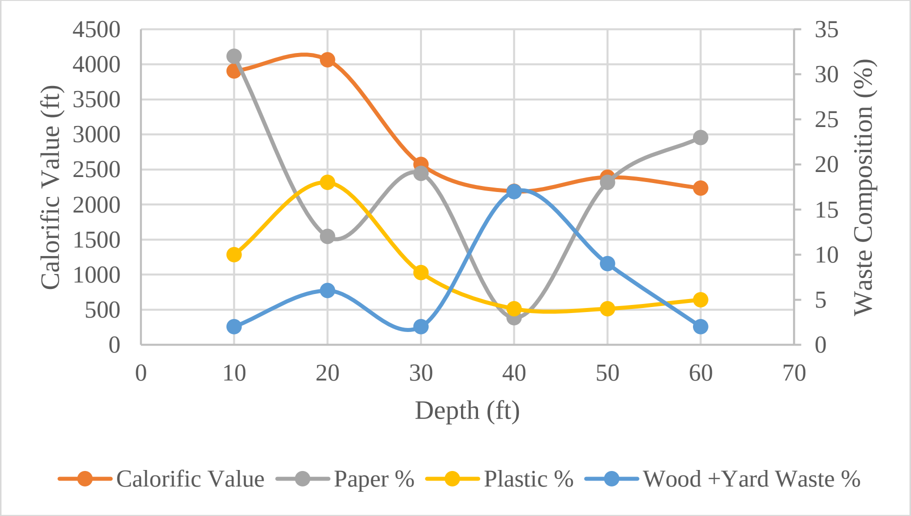


Figure 4-61 Effect of waste composition on energy potential of mined waste in borehole 5

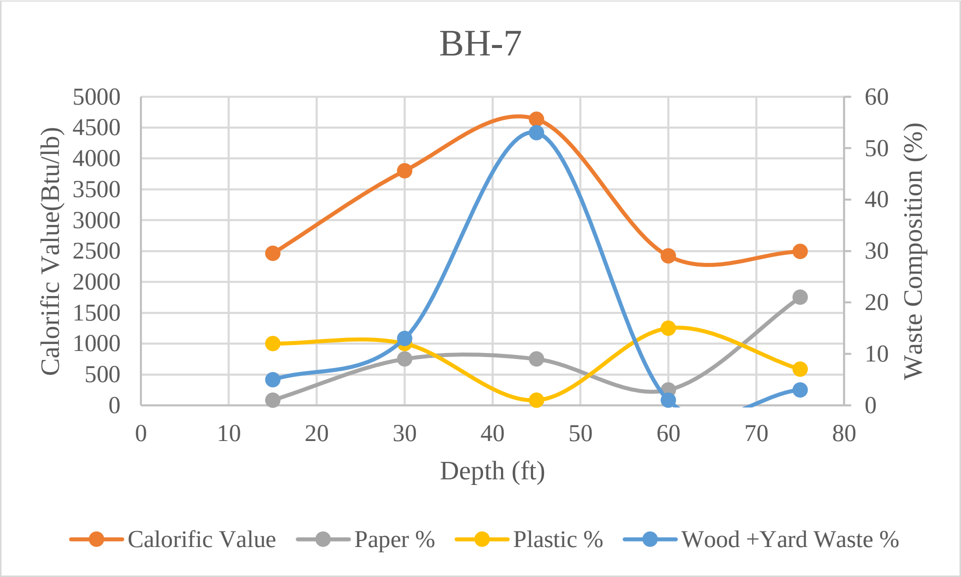


Figure 4-62 Effect of waste composition on energy potential of mined waste in borehole 7

4.3.16 Effect of waste composition in energy potential of solid waste in ELR landfill

The effects of waste composition on the energy potential of solid waste in ELR landfills are shown from in Figures 4-63 to 4-65. The paper fraction decreased from 40% and 50% to 4% and 9% for BH-B and BH-C, respectively, with an interval to 10 ft. depth. Due to the ELR operation, the paper fraction was degraded almost completely after 30 feet. Therefore, the plastic fraction maintained similar trends in each of the boreholes. Plastic was found unexpectedly high in two boreholes, 37% in 60 feet depth of Borehole B, and 41 % in 20 feet depth of Borehole C. Overall, the average paper, plastic, and wood waste fractions were 11.7% , 15.6%, and

9.175%, respectively, in the ELR-operated landfill. The average energy potential was 3540. 604 Btu/lb. in this type of landfill. In the conventional landfill, the average paper, plastic, and wood fractions were 20%, 9.13%, and 8.38%, respectively. The average calorific value from the conventional landfill was 3604.621 Btu/lb.

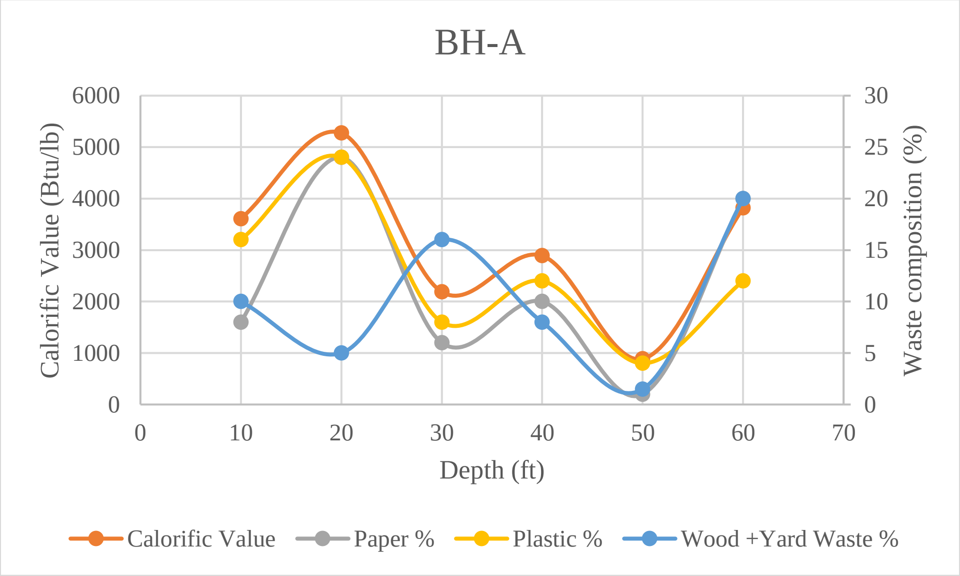


Figure 4-63 Effect of waste composition on energy potential of mined waste in borehole A

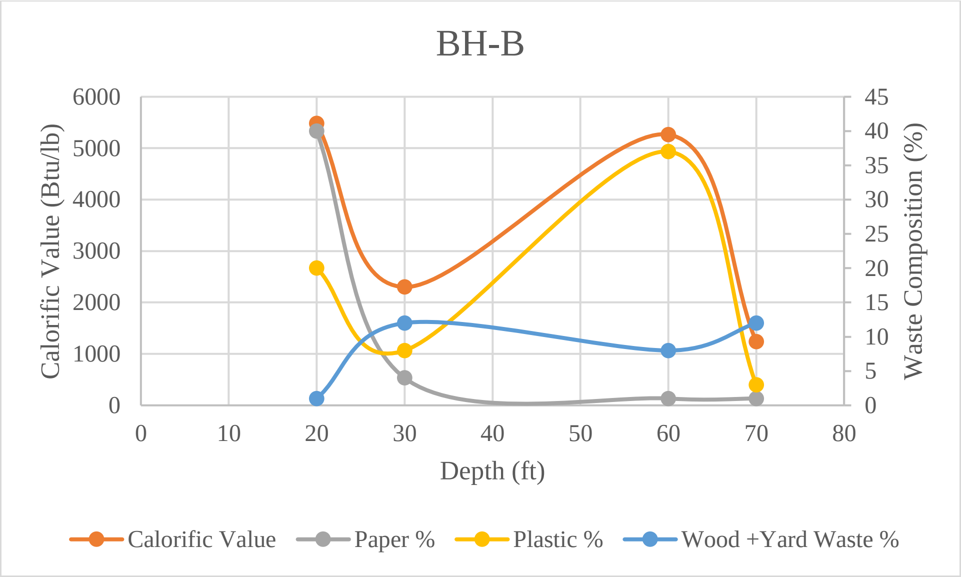


Figure 4-64 Effect of waste composition on energy potential of mined waste in borehole B

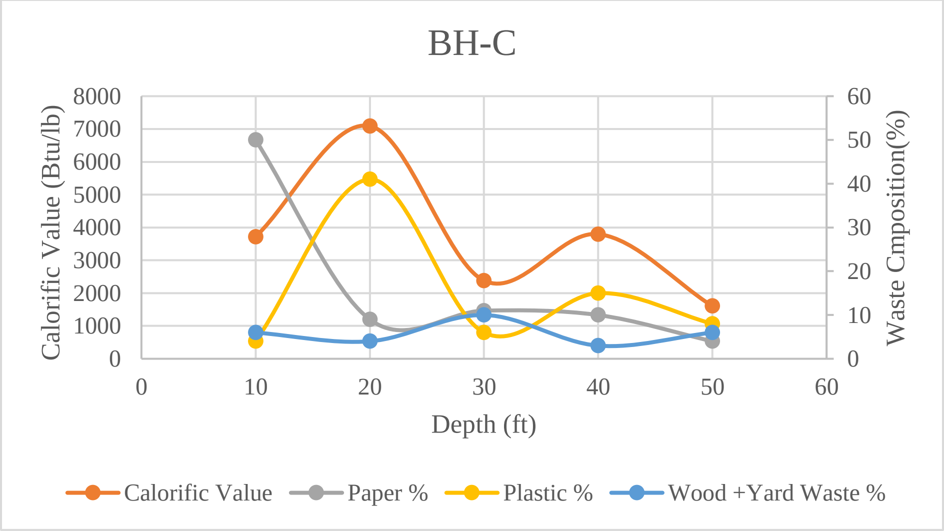


Figure 4-65 Effect of waste composition on energy potential of mined waste in borehole C

A comparison of the effects of waste composition on energy potential in this study and with literature are presented in Table 4-29

Table 4-29 Comparison of effect of waste composition on energy potential with literature.

		Paper	Plastic	Food	Wood	Calorific Value	Reference
Fresh	Jordan	11	16	63	0	4917.13	Abu-Qudais and Abu-Qdais,1999
	Italy	44	15	20	5	5430.9	Giugliano et al.,2008
	Taiwan	13	18	36	7	3672.2	Chang et al.,2008
	Spain	15	11	56	6	3288.64	Montejo et al.,2011
	Srilanka	6.47	5.9	56.57	12.39	4032	Menikpura and Basnayake et al.,2008
	NY	31.2	3.8	36.6	3.5	4600	Chin and Franconeri,1980
	FL	16.8	12.2	35.8	16.8	5254	
	NY	51.2	5.03	13.3	2.17	4867	Chin and Franconeri,1980
	NY	32.2	8.81	23.36	3.83	4112	Chin and Franconeri,1980
	Nigeria	25	10	59.38		4923.86	Amber et al.,2012
	NY	31.3	8.9	12.7	5.6	5000	
Mined	Belgium	14	25		4.1	7740	Quaghebeur et al.,2012
Mined	Sweden	9.72	4.94		9.93	3182	Hogland et al.,2003
Fresh	This Study	38.14	21.68	12.29	12.75	6838.9	
	This Study	23.27	9.07		7.89	3665.88	

4.3.17 Energy Index of Municipal Solid waste

Energy potential in the landfill clearly depends on the waste composition and the rate of degradation; however, it is very difficult to predict the exact state of degradation. Waste composition can be carried out in every country very easily by hand sorting. As waste composition varies country to country, there is no universal index to predict the energy potential of solid waste. Generally in landfills, paper, cardboard, yard waste, and wood degrade with the time. In addition to these components, food waste degrades very quickly. Plastic remains non-degradable inside the landfill. On the other hand, fine/soil, like degraded materials, keep increasing with time. Based on the degradation nature of the solid waste components, a universal energy index can be introduced, regardless of the waste composition. The experimental value of the energy index of municipal solid waste is shown in Table 4-30.

Energy Index (EI) = (Paper %+Cardboard %+Yard waste %+Wood %+Plastic)/ (Food Waste %+Fine%)

Table 4-30 Energy index of the municipal solid waste

	Conventional	ELR	Fresh
1	13.67	0.89	7.42
2	1.43	2.30	2.44
3	0.24	0.52	7.63
4	10.60	0.50	4.87

5	4.76	0.07	1.63
6	1.00	2.17	2.32
7	0.34	3.90	4.90
8	3.53	2.65	9.51
9	1.46	0.57	9.69
10	0.20	1.35	2.68
11	5.29	0.60	5.46
12	0.06	0.74	7.18
13	0.55	0.30	6.88
14	0.08	0.43	13.94
15	9.25		14.40
16	0.14		12.18
17	0.88		
18	0.26		
19	0.29		
20	4.06		
21	1.16		
22	0.72		
23	0.46		
24	0.37		
25	0.74		
26	0.70		
27	2.23		
28	0.23		
29	0.85		
30	2.86		
31	0.31		
32	0.52		
Average	2.16	1.21	7.07
Max	13.67	3.90	14.40
Min	0.06	0.07	1.63

Based on the calorific value of fresh and mined solid waste, a nonlinear trend was found to predict the energy potential of waste, as shown in Figure 4-68. R^2 of 77.49 % indicated a good correlation, considering the heterogeneity of the excavated and fresh waste. This curve was developed based on the calorific value for both fresh and mined waste at any depth. Based on Table 4-11, the average energy index of mined waste 10-25 years old was 2.10, ranging from .006 to 13.67, which indicates a higher decomposition and lower remaining energy potential of excavated waste (Figure 4-67). The excavated waste (6- 13 years old) from the ELR-operated landfill had an average energy index of 1.60, indicating the expedited decomposition of excavated waste. The fresh waste was found to have an energy index of 7.07, indicating the lower state of degradation (Figure 4-66). The energy index of excavated waste was usually less than 1, regardless of the type of operation of the landfill. The energy index was usually greater than 4 for fresh waste.

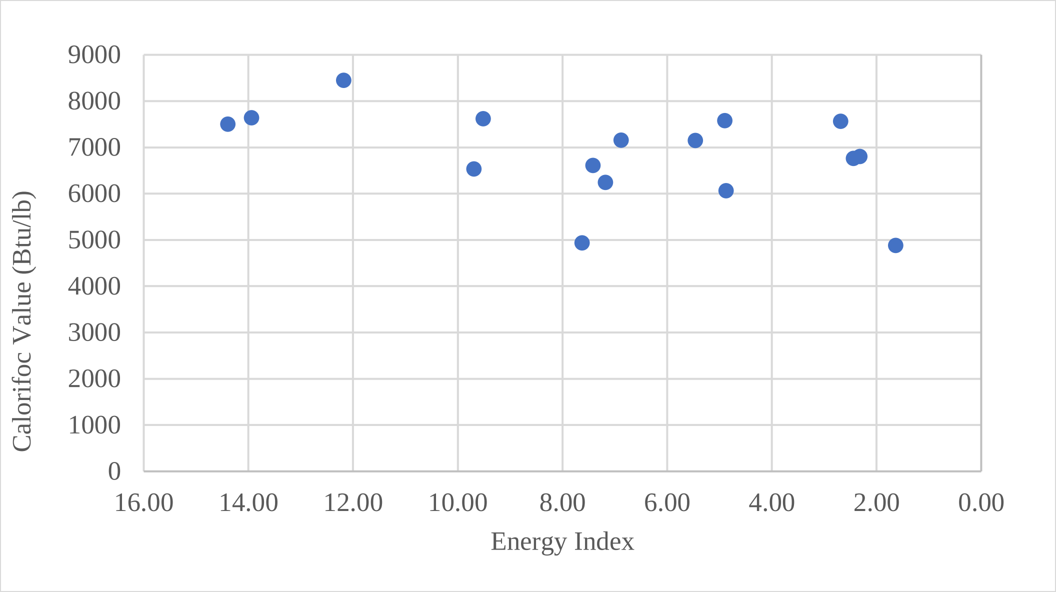


Figure 4-66 Energy index of fresh municipal solid waste

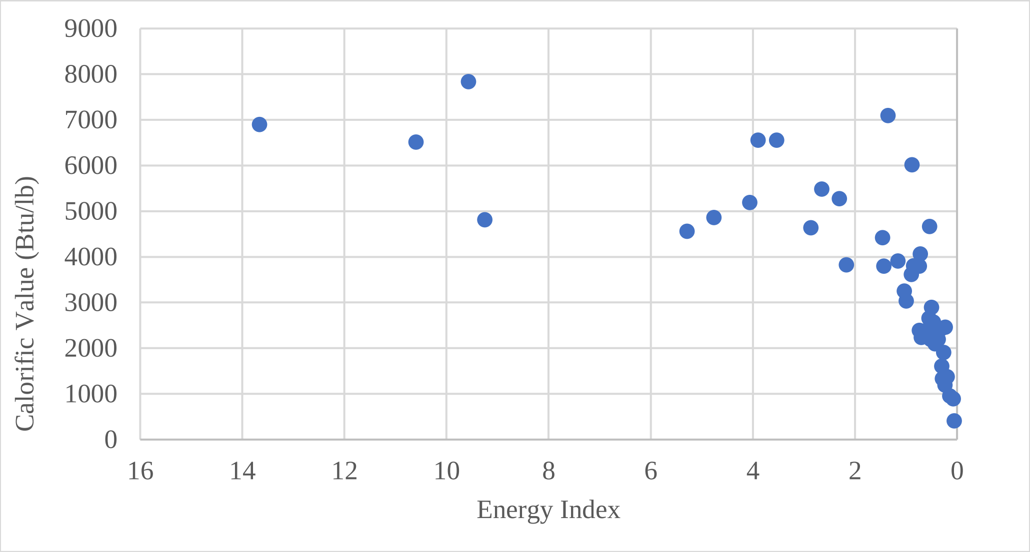


Figure 4-67 Energy index of mined solid waste

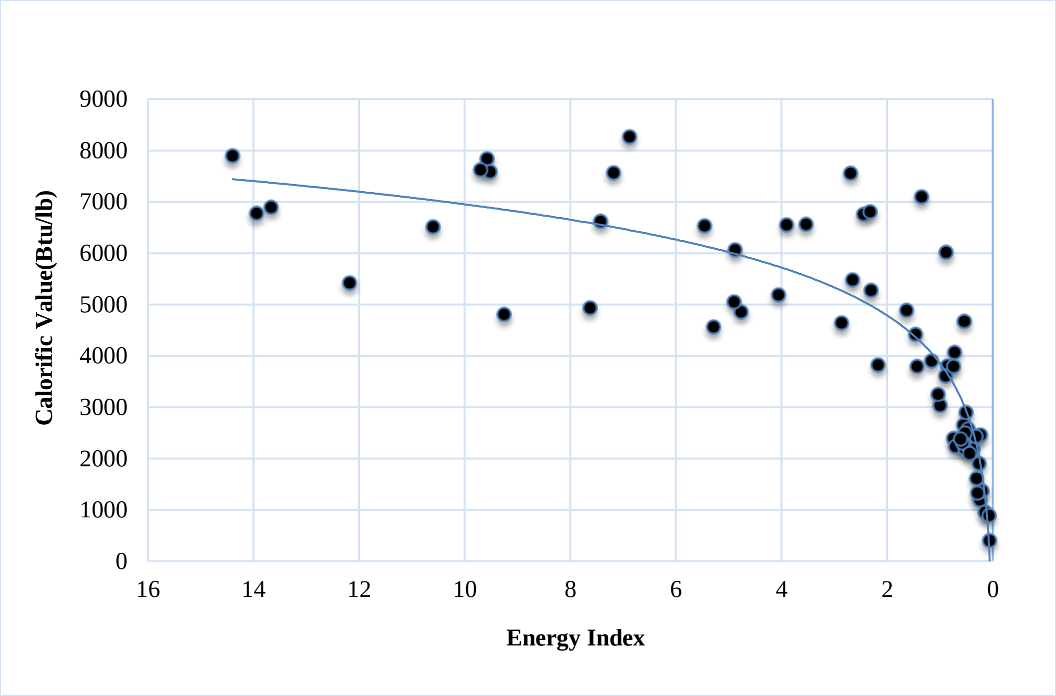


Figure 4-68 Effect of energy index on energy potential in municipal solid waste

4.4 Elemental Analysis of Solid waste

4.4.1 Elemental Composition from Municipal Solid Waste

The elemental composition of the solid waste was measured by an elemental analyzer. Both the fresh and mined waste were considered, and the results are presented in Tables 4-31 to 4-34. The percentage of carbon ranged from 28.86-43.6% in the mined paper, and 33.8-48.27% in the fresh paper. The average carbon content was 36.48 % and 41.03 % for mined and fresh waste, respectively. The paper waste mainly consisted of newspaper, cardboard, and mixed paper. The highest percent of carbon was found in the plastic waste (65.39-91.69%, with an average of 77.63% for fresh plastic.) Mined plastic had 43.6-88.44% of carbon, with an average of 68.61%. Usually, carbon was found highest in the plastic fraction, except PETE and PVC. In mined wood and yard waste, 42.4-51.37% carbon was found. On the other hand, fresh wood had 40.77-52.32% of carbon.

Hydrogen was found highest in plastic: 4.43-15.88% in mined plastic, and 8.13-18.28% in fresh plastic. Plastic had 68.61% and 77.63%, on average, for mined and fresh plastic, respectively. The hydrogen content was higher with an increase of the percentage of carbon in the waste.

Paper products had nitrogen less than 0.5% in both fresh and mined waste. Similarly, nitrogen was found less than .5% in the plastic and wood waste. However, the variability of the nitrogen content was high.

Table 4-31 Elemental composition of Paper waste

	Mined Paper			Fresh Paper		
Sample	C	H	N	C	H	N
1	43.60	6.20	0.19	48.27	7.62	0.37
2	37.00	5.60	0.36	41.65	6.92	0.06
3	26.62	2.34	0.05	33.18	5.52	0.04
4	26.65	4.58	0.06			
5	56.15	9.03	0.05			
6	28.86	3.80	0.12			
Average	36.48	5.26	0.14	41.03	6.69	0.16

Table 4-32 Elemental composition of Plastic waste

	Mined Plastic			Fresh Plastic		
Sample	C	H	N	C	H	N
1	46.20	8.30	0.38	70.36	8.13	0.23
2	43.70	6.20	0.24	83.10	15.92	0.10
3	64.20	4.43	0.05	91.69	18.28	0.03
4	79.26	9.13	0.05	65.39	11.23	0.36
5	88.44	9.63	0.07			
6	84.89	12.80	0.02			
7	79.71	15.88	0.03			
8	43.53	5.18	0.04			
9	85.90	15.65	0.02			
10	70.27	12.26	0.09			
Average	68.61	9.95	0.10	77.63	13.39	0.18

Table 4-33 Elemental composition of Wood waste

	Mined Wood			Fresh Wood		
Sample	C	H	N	C	H	N
1	47.00	6.70	0.23	48.20	7.10	0.12
2	46.90	6.62	1.14	52.32	8.29	0.12
3	51.37	7.25	0.15	40.77	5.30	0.21
4	42.40	6.52	0.08			
5	48.02	7.52	0.07			
6	45.22	6.12	0.14			
7						
8						
9						
10						
Average	46.82	6.79	0.30	47.10	6.90	0.15

Table 4-34 Elemental composition of Textile waste

	Fresh Textile		
Sample	C	H	N
1	46.75	3.26	0.41
2	36.84	5.03	1.26
3	58.16	3.60	0.03
Average	47.25	3.96	0.57

4.4.2 Comparison of elemental composition between Fresh and Mined Waste

Based on the Figures 4-69 to 4-71, it is evident that the percentage of elemental composition of mined waste is very similar to that of fresh waste. Due to contamination and degradation, the elemental composition of mined waste was found to be about 10% less than that of fresh waste. The average carbon content in fresh paper was found to be 41.03%, which supports the carbon content found in the literature (41.44% - Siang and Zakaria, 2006; 44.49% - Gidarakos et al., 2006; and 32.8-43.2% - Komillis et al., 2011). The average carbon content of mined paper waste was 36.48% in the City of Denton landfill. Quaghebeur et al., 2012 found that the carbon content in a mining project in Belgium was 23-34%. Very few studies from mining projects determined the elemental composition experimentally.

The carbon in the mined plastic fraction was 43-88%, with an average of 68%. In China, the mined plastic was 88% carbon (Zhou et al., 2018), and was 77.21% carbon in a 10-year old landfill (Chen et al., 2010). Mined plastic has impurities, which consist of soil type fractions, sands, and waste papers. The carbon from fresh plastic was determined as 65-91%, having an average of 77%, which supports the previous literature percentages of 85.9% (Shi et al., 2015); 66.72% (Chen et al., 2009) and 63-85% (Baawain et al., 2017). The excavated wood had a carbon content (46%) similar to that of fresh wood (47%). The carbon contents of different types of wood are available through numerous biomass studies. Shi et al., 2015 reported that the carbon content of wood waste from different studies was 36-52%. The hydrogen content followed a trend similar to that of carbon. Hydrogen was found highest in plastic waste.

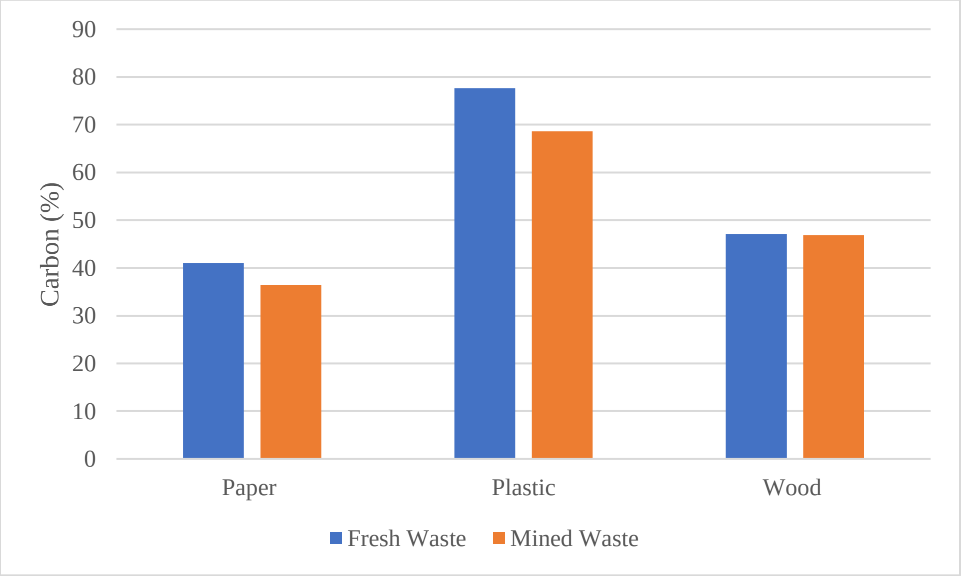


Figure 4-69 Comparison of Carbon (%) between fresh and mined waste

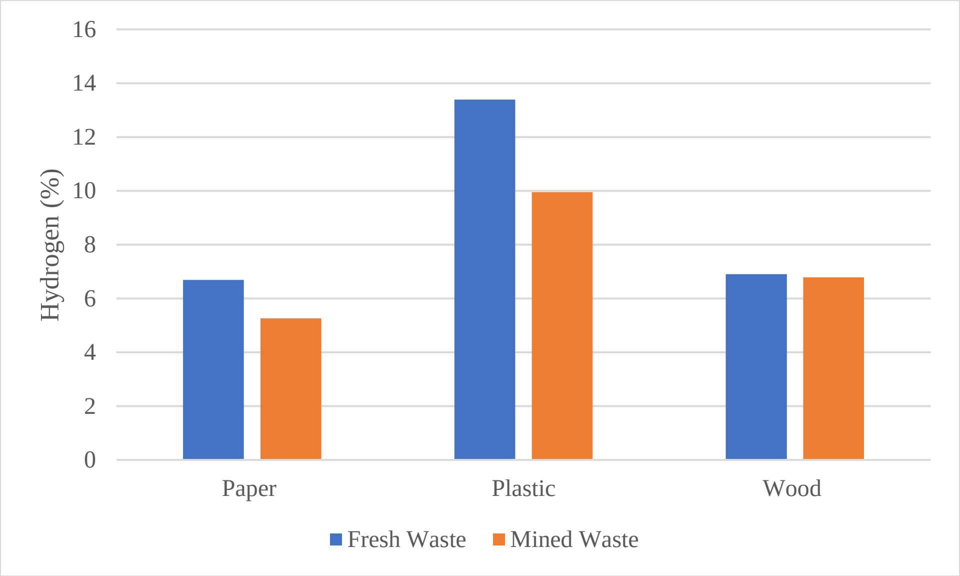


Figure 4-70 Comparison of Hydrogen (%) between fresh and mined waste

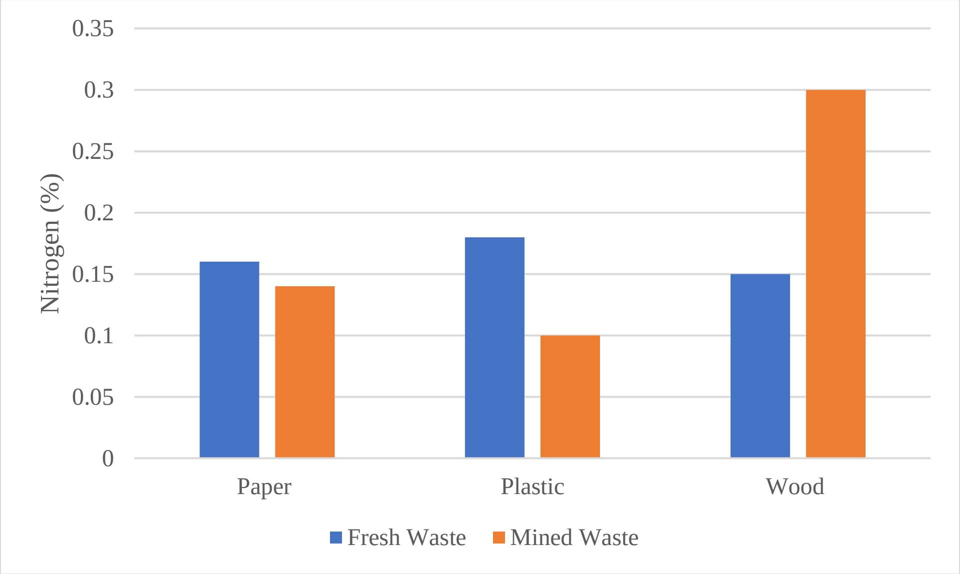


Figure 4-71 Comparison of Nitrogen (%) between fresh and mined waste

4.4.3 Effect of elemental composition on Calorific Value

The effects of different elemental compositions are presented in Figures 4-72 to 4-74. Carbon and hydrogen have a linear effect on caloric value, but nitrogen did not demonstrate any significant trend with it. A similar linear trend was found in literature (Komillis et al., 2011; Garces et al., 2015); however, carbon was not found significant in some literature (Liu et.al, 1996) and Chang model reported in Kathirvale et al., 2003. Liu et al., 1996 found it difficult to explain since organic matter is expected to be the main source of energy. Kathirvale et al., 2003 found the negative effect of hydrogen in the calorific value. In summary, carbon and hydrogen were found positively correlated with most of the models cited in the literature.

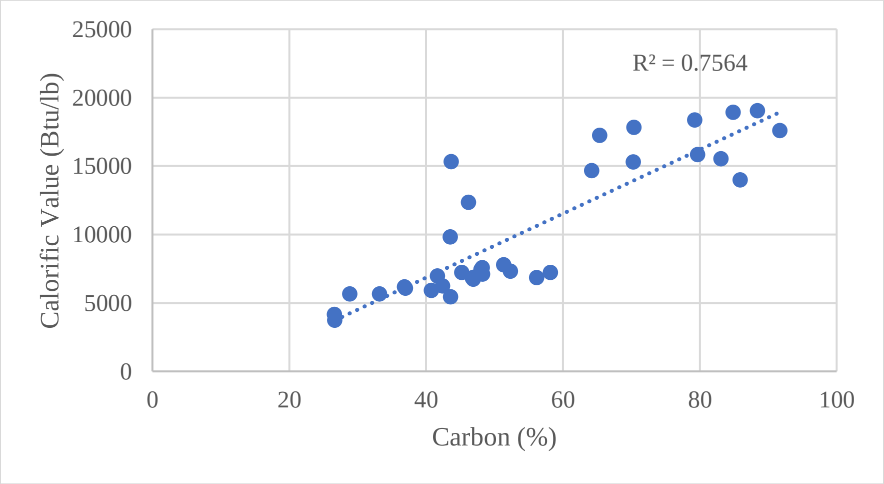


Figure 4-72 Effect of Carbon on calorific value of solid waste

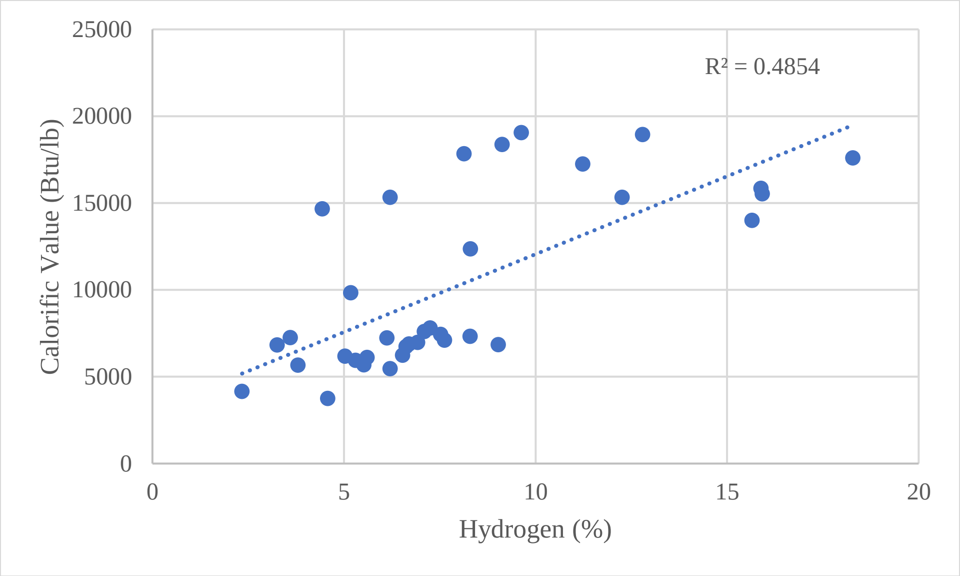


Figure 4-73 Effect of Hydrogen on calorific value of solid waste

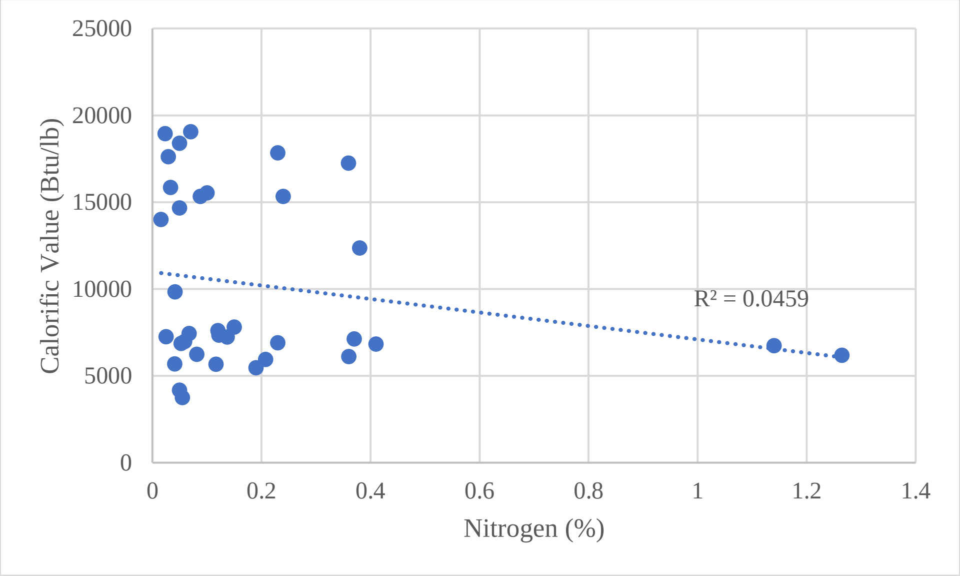


Figure 4-74 Effect of Nitrogen on calorific value of solid waste

5 Chapter: Modelling the calorific value of municipal solid waste

5.1 Introduction

Energy potential of municipal solid waste depends on different variables. The heterogeneity of the solid waste creates an uncertain situation for predicting the energy potential from the landfills. The current available energy prediction models are mainly elemental analysis-based models where the energy potential of solid waste from the landfills is predicted, using the elemental composition. Models based on physical composition are also available in different countries. However, the prediction of energy potential of MSW based on waste composition is best suited in its own area (Kathirvale et al., 2003). Therefore, models based on physical composition are not found universal. The direct effect of decomposition is not incorporated in the models. In addition, no model has evaluated the effect of mined waste energy potential. Therefore, the objective of this chapter is to develop three different universal models to predict the energy potential of solid waste including mined waste.

This chapter describes in detail the statistical procedures for developing the proposed energy prediction model, based on three different analyses of the City of Denton landfill: Physical waste composition, proximate analysis, and elemental analysis). It is divided into three sections, and each section describes the assumptions made in the development of the model, including the procedure for developing the simple regression equation for predicting the energy potential, based on the physical waste composition, volatile solids, and elemental composition obtained during the lab investigation.

5.2 Model based on physical waste composition

5.2.1 Model Development

Simple linear regression (SLR) analysis was conducted, using a statistical modelling tool, R, and the model assumptions were investigated to satisfy the model assumptions. The steps followed to develop the SLR model for energy potential are presented in Figure 5.1.

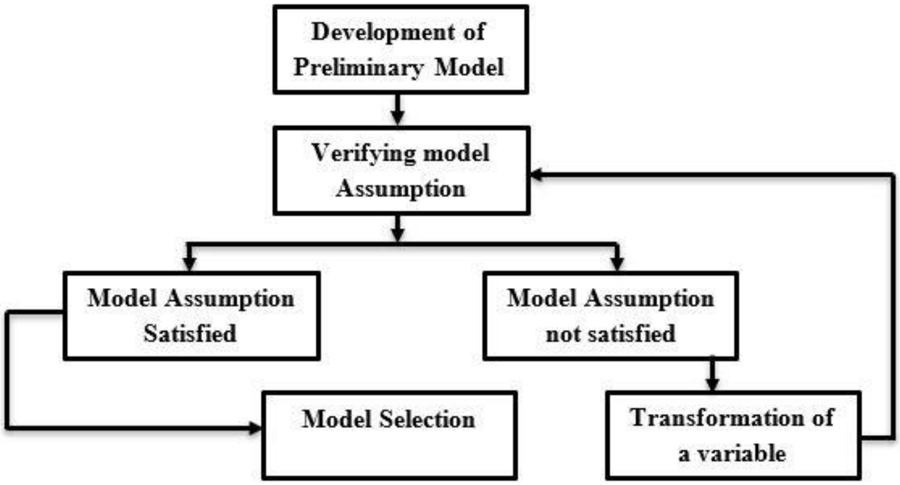


Figure 5-1 Steps to develop model using R software

5.2.2 Model Assumption

(i) Parameters

The preliminary goal for the model development was to generate a universal energy prediction model, considering the effect of the mined waste composition. Therefore, the composition of both fresh and mined waste was used to develop the energy-predicting model. The only predictor considered for energy potential was the energy index.

(ii) Data Collection

The mined solid waste was collected from Cell 0 and Cell 2, from 12 different boreholes, at different depths. Physical waste composition was calculated for each waste sample; hence, the energy index was calculated against each type of waste. The calorific value was measured for each possible combustible component. The overall energy potential was measured, considering the fresh waste collected from the City of Denton landfill during 2016-2018. Altogether, 63 data points were used to develop the model. Mined waste data from the City of Irving landfill was used to validate the developed model, and 22 data points were considered to validate the model. Moreover, 16 data points from 8 different countries from literature were considered to validate the model and to assess its applicability globally.

5.2.3 Simple Linear Regression Analysis

This section includes a detailed description of the simple linear regression analysis. Based on the lab investigation, a SLR equation was developed to predict the energy potential of solid waste as a function of energy index.

5.2.3.1 Scatter plot of the response variable vs. predictor variable.

The response vs. predictor plot is used to observe whether a simple linear regression form would be suitable for fitting the data. The response vs. predictor plot is presented in Figure 5-2.

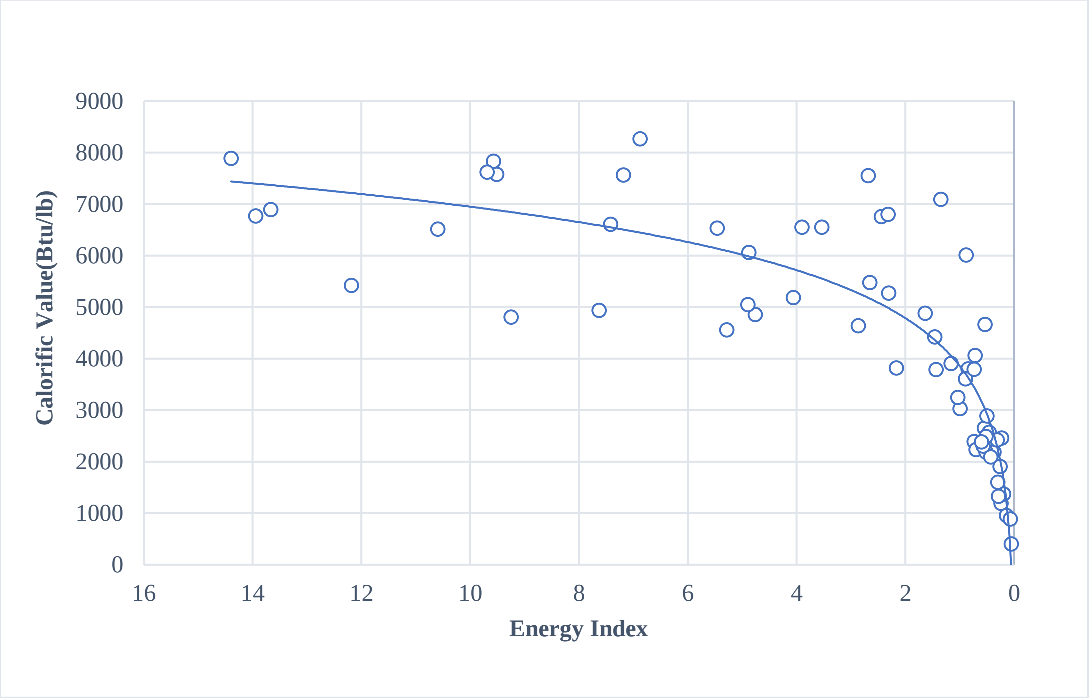


Figure 5-2 Calorific value vs Energy index

It was observed from the scatterplot that a non- linear relationship exists between the energy index and the calorific value Btu/lb. The relationship indicates that the calorific value increases nonlinearly with an increase of the energy index.

5.2.3.2 Residual plot and Normality Plot

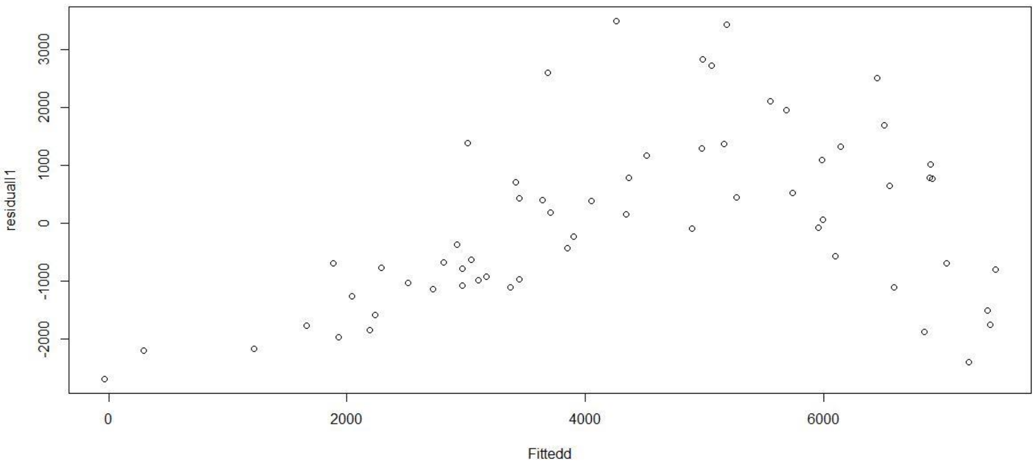


Figure 5-3 Residual plot of fitted value

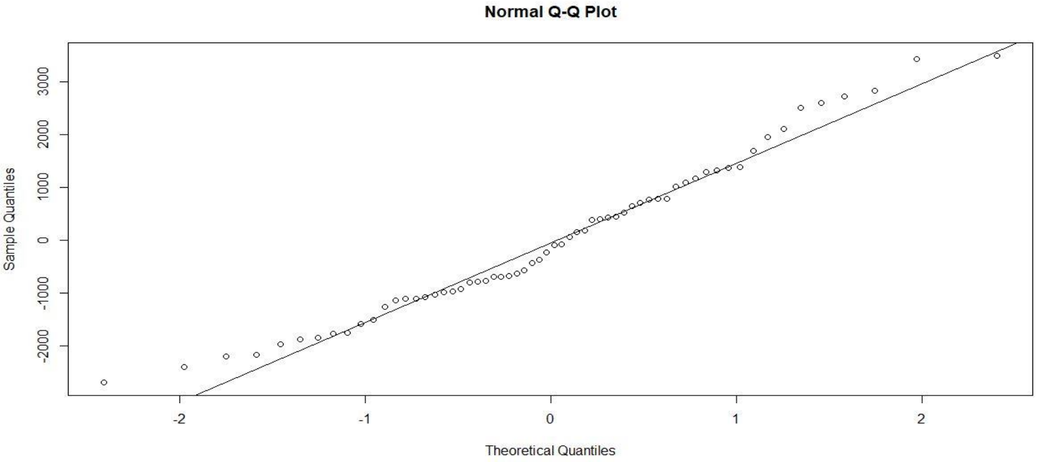


Figure 5-4 Normal probability plot of residuals

Figure 5-3 represents the residual plots of fitted values of calorific values. Clearly, it shows a downward curvature, and does not reflect any funnel shape. Therefore, the variance is not constant. It clearly violates the assumption of the linear model.

Figure 5-4 shows the Q-Q plot for the residuals. The plot shows a left and right tail; therefore, the plot is not straight. Normality is clearly violated, but even though normality is not satisfied here, it is close to normal distribution.

5.2.3.2 Transformation

The nonlinear regression relationship between the energy index and the calorific value needs linearizing. As the distribution of error terms is reasonably close to normal distribution and the error terms have approximately constant variance, transformation of the predictor variable should be attempted. Scatter plot and residual plot are two key plots for determining the type of transformation. Therefore, the energy index value has been transformed logarithmically, like Figure 5-5. The value of response variables (calorific values) are kept the same.

New predictor = ln (energy index)

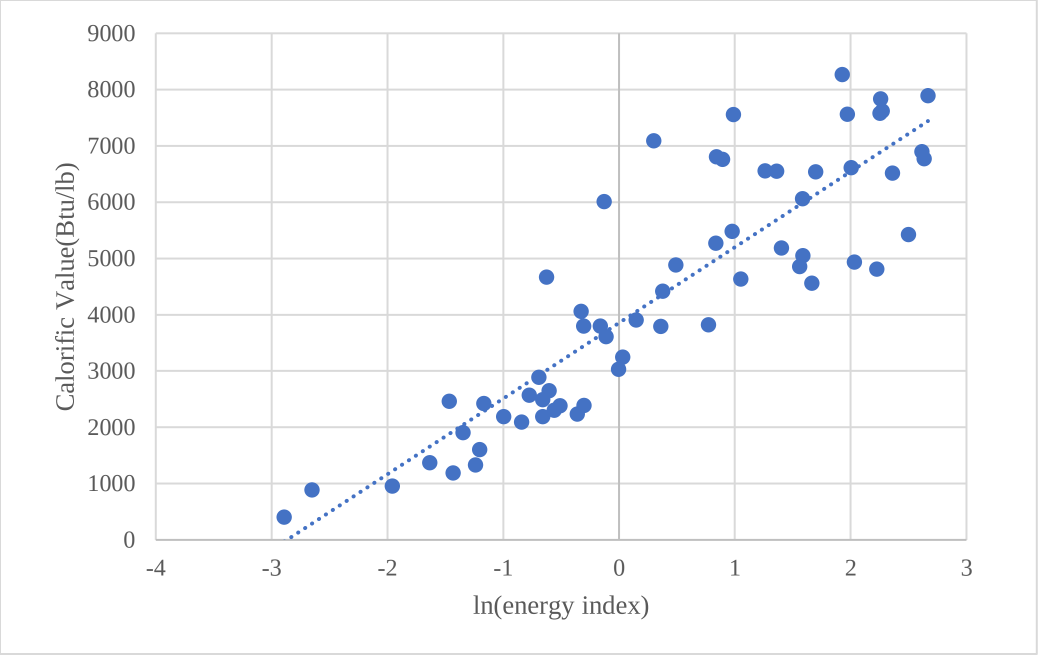


Figure 5-5 Transformation of predictor variable

The scatter plot was recreated, based on the transformation of the predictor variable (energy index) (Figure 5-5). This figure shows a clear linear relationship between the transformed predictor and the response variable.

5.2.3.3 Simple Linear Regression Model

The calorific value data was modelled, using a first order basic regression model, where ln (energy index) was the predictor variable, and the calorific value in Btu/lb. was the response variable. The basic regression model is

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$

Where

Y_i is the value of the response variable for the ith trial. For the energy model it represents the expected number of calorific value in solid waste

β_0 is the y − intercept.

β_1 is the slope. For the model, it represents the impact of energy index for the calorific value in the solid waste.

x_i is the value of the predictor for the ith trial. This term represents the known quantities of energy index when calculating the number of calorific values in the model.

ε_i is the random error term for the ith trial

R was used to calculate the least squares and the parameter estimates using 63 data points

Table 5-1 Parameter estimate for the preliminary SLR model

Parameter Estimates					
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	**1**	3854.46	136.24	28.29	<.0001
ln (Energy Index)	**1**	1344.67	93.57	14.37	<.0001

Based on the preliminary analysis, the fitted SLR equation is presented

$$HHV = 3854.46 + 1344.67 \ln x$$

Where

HHV= Higher Heating Value/Calorific Value of Solid Waste

X= Energy Index of the solid waste

The estimated total calorific value of solid waste is 3854.46 plus 1344.67 of ln (energy Index). The coefficient of energy index 1344.67 means the mean calorific value change 1344.67 when the energy index increases by one.

Looking at the results of our t-test shown in Figure 5, $|t^*| > t\ (0.975;\ 63)$ and $p << \alpha$ so we reject H_o and confirm that our regression is significant

Table 5-2 Analysis of variance of the SLR model

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	1	220458082	220458082	206.52	<.0001
Error	60	64048147	1067469		
Corrected Total	61	12657817.57			

R-Square	0.7749
Adj R-Sq	0.7711

The ANOVA results shown in Table 5-2 also confirm the results of our regression analysis. The R-Square value of 0.7749shows that the calorific values varies by

77.49 % with the energy index. Also the F-value of 206.52 confirms the linear association of ln (energy index) and calorific value as F*> F(0.90;1,63).

5.2.3.4. Inferences on the Parameters

The calculation for a 95% confidence interval for the intercept is shown below.

$$b_0 = 3854.46$$

$$s\{b_0\} = 136.29$$

$$n = 63$$

$$\alpha = 0.05$$

Confidence interval (CI) = $b_0 \pm t\left(1 - \frac{\alpha}{2}; n - 2\right) s\{b_0\}$

$$CI = 3854.46 \pm t\left(1 - \frac{0.05}{2}; 61\right) 136.24$$

$$where \;\; t(0.975; 61) = 1.99$$

$$CI = (3581.94\,, 4126.97) \text{ with 95\% confidence}$$

This range represents the calorific value solid waste without energy index with 95% confidence.

The calculation for a 95% confidence interval for the slope is shown below.

$$b_1 = 1344.67$$

$$s\{b_1\} = 93.57$$

$$n = 63$$

$$\alpha = 0.05$$

Confidence interval (CI) = $b_1 \pm t\left(1 - \frac{\alpha}{2}; n - 2\right) s\{b_1\}$

$$CI = 1344.67 \pm t\left(1 - \frac{0.05}{2}; 61\right) 93.57$$

$$where\ \ t(0.975; 257) = 1.99 \text{ (using Excel T. INV)}$$

$$CI = (1157.50\ , 1531.83) \text{ with } 95\% \text{ confidence}$$

5.2.3.5 Inferences on the True Line and Prediction

In developing countries, municipal solid waste consists mainly of food waste. Similarly, in the landfill mining project, fine material dominates the mined waste composition. Therefore, it is crucial to assess the calorific value that has an energy index less than 1. For this reason, we analyzed the calorific value of solid waste when the energy index was 0.5. We considered a 95% confidence interval to estimate the mean number of calorific values in this situation.

$$b_0 = 3854.46$$

$$b_1 = 1344.67$$

$$Calorific\ value\ \hat{Y}\ |_{x=1} = b_0 + b_1(.5) = 3854.46 + 1344.67\ln(.5) = 2922.54 \text{ Btu/lb}$$

$$Y_h = 2922.54$$

$$n = 63$$

$$\alpha = 0.05$$

$$\textstyle\sum_{n=1}^{i}(X_i - \bar{X})^2 = 121.93$$

$$(X_H - \bar{X})^2 = (.25 - .39)^2 = .0196$$

$$s\{\hat{Y}_H\} = \sqrt{MSE\left[\frac{1}{n} + \frac{(X_H - \bar{X})^2}{\sum_{n=1}^{i}(X_i - \bar{X})^2}\right]} = \sqrt{1067469.12\left[\frac{1}{63} + \frac{.0196}{121.93}\right]}$$

$$= 130.83$$

$$\text{Confidence interval } (CI) = Y_h \pm t\left(1 - \tfrac{\alpha}{2}; n - 2\right) s\{\hat{Y}_h\}$$

$$CI = 2922.54 \pm t\left(1 - \frac{0.05}{2}; 61\right) 130.83$$

$$where\ \ t(0.975; 257) = \ 1.99\ \text{(using Excel T. INV)}$$

$$CI = \ (2662.18, 3182.89)\ \text{with 95\% confidence}$$

Using these values, 95% of energy index with 0.5 results in a calorific value within the range of 2662.18 to 3182.89.

Below, we develop and interpret a 95% prediction interval for the given 0.5calorific value.

$$S\{pred\} = \ \sqrt{\left(S\{\hat{Y}_H\}\right)^2 + MSE} = \sqrt{(130.83)^2 + 1067469.12} = 1041.43$$

$$\text{Prediction interval } (PI) = Y_h \pm \ t\left(1 - \tfrac{\alpha}{2}; n - 2\right) s\{pred\}$$

$$PI = \ 2922.83 \pm \ t\left(1 - \frac{0.05}{2}; 61\right) 1041.43$$

$$where\ \ t(0.975; 61) = \ 1.99\ \text{(using Excel T. INV)}$$

$$PI = \ (589.73, 4734.63)\ \text{with 95\% confidence}$$

We predict with 95% confidence that the energy index of 0.5 will have between 589.73 and 4734.63 This is a wider band than our confidence interval, but the reasonable values of calorific value give energy index support our model.

Below the confidence bands are computed

$$\hat{Y}\ |_{x=.5}\ \pm\ \sqrt{2F(0.95; 2, 61}(s\{\hat{Y}_h\})$$

$$where\ F(0.95; 2, 61) = 3.15$$

$$\text{Confidence band (CB)} = \pm\sqrt{2(3.15)}(130.83)$$

$$CB = (2594.16, 3250.92)\text{ with 95\% confidence}$$

We are 95% confident that the true line for when energy index is equal to .5, lies between 2594.16 and 3250.92 calorific values.

5.2.3.6 Checking Model Assumptions for SLR Equation

We consider the following model assumptions:

1) The data can be represented with a linear model.

2) The residuals in the model are normally distributed and with a constant variance.

3) Serial correlation is not significant.

4) No outliers significantly impact the model’s accuracy.

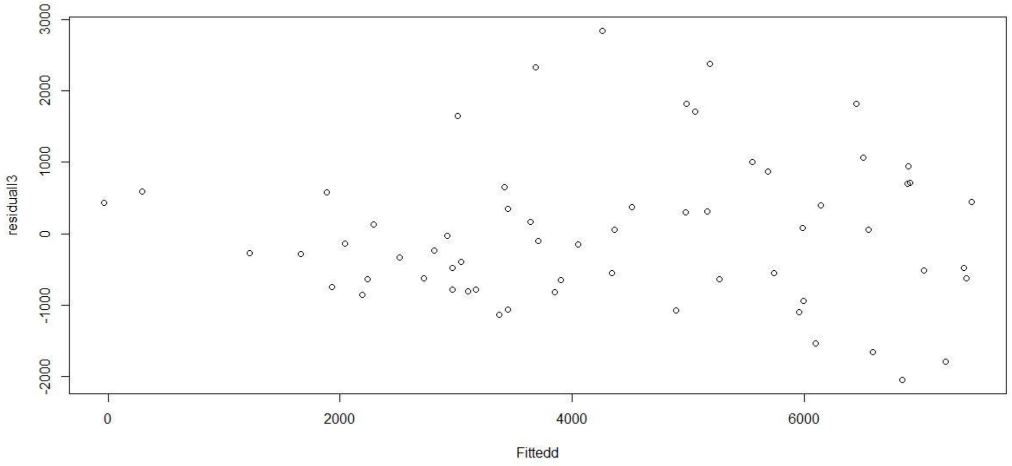


Figure 5-6 Residual vs. fitted plots for the preliminary model

Looking at the residual plot of residual vs fitted value in figure 5-6, the data appears to be random point cloud showing no curvature, no funnel shape (i.e non-constant variance).So linear model is reasonable. While visual inspection of the residuals may indicate a few outliers may exist, we cannot reject any data points since the data was professionally collected.

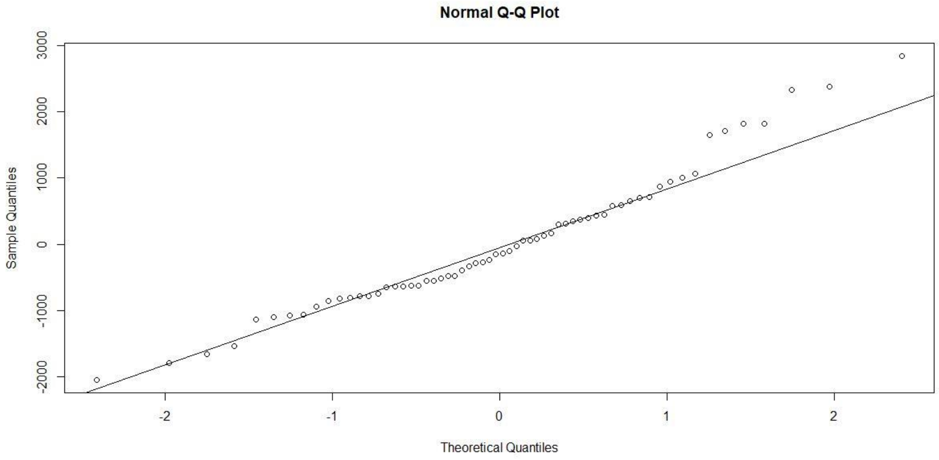


Figure 5-7 Normal probability plot of the residuals

Figure 5-7 shows the normality plot of residuals vs normal scores. On the left tail, there is shorter tail on the normality plot and on the right tail, it has longer tail. Overall, the normality line is not straight. We can conclude that normality is not ok for our model. Serial correlation is not significant here as we did not take any time depended data.

Tests for Normality

$$H_0: \rho = 0; normal\ distribution$$

$$H_1: p \neq 0; not\ a\ normal\ distribution$$

$$if\ p \leq\ c(\propto; 63) then\ reject H_0$$

$$c(\propto = 0.05, n = 63) = 0.9945$$

$$0.7185 < 0.981\ Reject\ H_0, normality\ are\ NOT\ okay\ for\ correlation\ tests$$

Correlation Analysis

Correlation analysis indicates the liner association between two variables. Table 5-3 presents the Pearson’s correlation coefficients between responseand predictors. Pearson’s correlation coefficient “r” ranges from -1 to +1, while -1 indicates strong negative correlation and the +1 indicates a strong positive correlation between the parameters. When r=0, little or no correlation is indicated between the parameters.

Table 5-3 Correlation analysis for raw data

Pearson Correlation Coefficients, N=63		
	Calorific Value	Energy Index
Calorific Value	1.00	0.7185
Energy Index	0.7185	1.00

Breusch-Pagan test

The Breusch-Pagan test was conducted to determine whether or not the error variance is constant for all levels of x. The results support the conclusion of constant variance. Linear regression was performed, and the results are shown in Table 5-4, with analysis of variance.

Table 5-4 Parameter estimate and ANOVA between ln (Energy Index) and residual squared

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	939965.9797	205581.806	4.572223575	2.46558E-05
Ln(Energy Index)	1	237584.1987	141194.3015	1.682675549	0.097635367

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	6.88225E+12	6.88225E+12	2.831397002	0.097635367
Error	60	1.45841E+14	2.43069E+12		

Corrected Total	61	1.52724E+14			

$$H_0: \gamma = 0; variance\ is\ constant$$

$$H_1: \gamma \neq 0; variance\ is\ non - constant$$

$$Test\ statistic: {X_{BP}}^2 = \frac{SSR *}{2} / \left(\frac{SSE}{N}\right)^2$$

$$Reject\ H_0\ if\ {X_{BP}}^2 > \mathcal{X}^2\,(1-\propto; 1) Fail\ to\ reject\ if\ {X_{BP}}^2 \leq \mathcal{X}^2\,(1-\propto; 1)$$

SSR*= 6.88225E+12

SSE=64048147

$${X_{BP}}^2 = \frac{6.88225\text{E} + 12}{2} / \left(\frac{64048147}{63}\right)^2 = 3.32$$

$$\mathcal{X}^2\,(0.95; 1) = 3.84$$

$$3.32 \leq 3.84\ Fail\ to\ reject\ H_0, Variance\ is\ constant$$

The Breusch-Pagan test also demonstrated that there is constant variance in our model. The conclusion is the same with the residual plot. Hence, we conclude that there are linear associations and constant variances from residuals versus the ln (Energy index) plot, and normality is not ok from the Q-Q plot.

5.2.3.6 Final Model

Our goal for regression analysis was to develop a model that can predict the total calorific value in municipal solid waste. In our simple linear regression, the energy index is the indicator for predicting the total calorific value in solid waste. Using 63 data points, our final SLR model is:

$$HHV = 3854.46 + 1344.67\ln x$$

Where

HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb)

X= Energy index based on the waste composition

An Energy Index Chart is developed to predict calorific value in Municipal Solid waste using the SLR model shown in Table 5-4

Table 5-5 Energy index chart

Energy Index	Calorific Value (Btu/lb)
0.1	758.40 +/- 258.7
0.25	1990.35 +/- 258.7
0.5	2922.4 +/- 258.7
1	3854.46 +/- 258.7
2	4786.5 +/- 258.7
3	5331.73 +/- 258.7
4	5718.57 +/- 258.7
5	7548.18 +/- 258.7
6	8250.93 +/- 258.7

5.2.4 Model Validation

Model validation is necessary for evaluating the performance of the developed model. Mined waste data from the City of Irving landfill (2019) was used to predict the overall energy potential from the landfill cell. The predicted energy value, using the model, was compared with the measured calorific value from the landfill to estimate the variation from the model.

The developed SLR equation for estimating the energy potential is

$$HHV = 3854.46+1344.67\ln x$$

Where

HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb)

X= Energy index based on the waste composition

A summary of comparisons between the predicted energy from the model and measured energy from the landfill cell is presented in Table 5-6.

Table 5-6 Summary of comparison between the predicted and measured energy potential

Sample No	Predicted Calorific Value (Btu/lb)	Measured Calorific Value (Btu/lb)	Variation (%)
1	4229.024714	4211.280514	0.41958138
2	3586.748816	2839.587182	20.831167
3	3082.745085	3317.395946	-7.6117504
4	2236.279093	1679.534222	24.896037
5	1926.662638	2049.72957	-6.3875704
6	3533.733754	3312.078378	6.27255453
6	2471.617893	2063.27205	16.5213986
8	1703.143472	1475.626316	13.3586606
9	2876.875732	2202.152444	23.4533345

10	3801.310102	4810.125643	-26.538628
11	2053.890035	1793.190965	12.6929419
12	3639.025884	3615.430143	0.64840816

The comparison between the predicted calorific value and the measured calorific value indicated that the maximum variation was 23.4%. However, the average variation from the estimated results was found to be 6.55% Therefore, we can conclude that the model predicts the overall energy potential within an average variation of 10%.

Figure 5-8 compares the predicted or estimated energy potential from the SLR model, with the actual measurement in the lab.

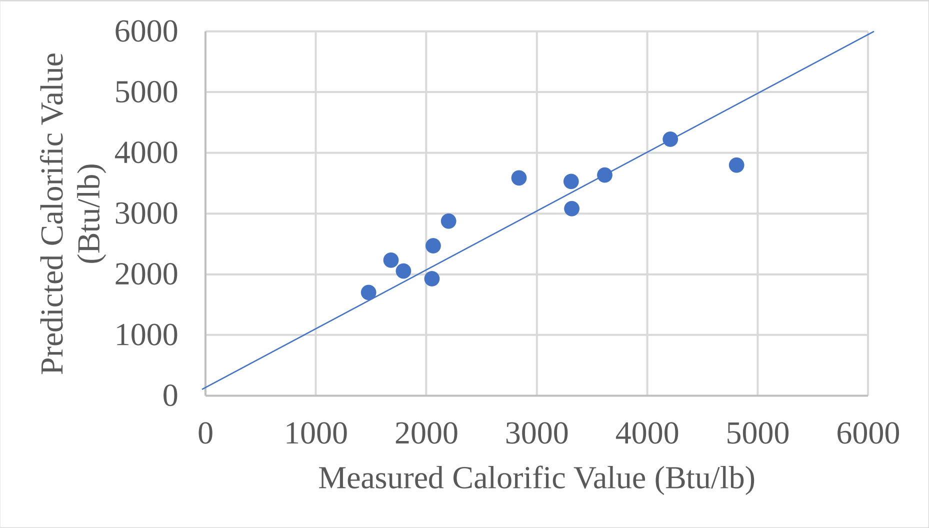


Figure 5-8 Predicted energy value with measured energy value

5.2.5 Model Validation using data from literature

It is vital to evaluate the applicability of this model around the world. Waste composition data from different literatures shown in Table 5-7 was used to predict the overall energy potential. The predicted results were compared with the measured calorific value from the literature to estimate the variation from the model.

Table 5-7 Summary of comparison between the predicted and measured energy potential from literature

Sample No	Predicted Energy Value (Btu/lb)	Measured Energy Value (Btu/lb)	Variation	Country	Reference
1	5065.787668	5430.9	-7.2074	Italy	Giugliano et al.,2008
2	3927.204192	3672.2	6.49328	Taiwan	Chang et al.,2008
3	3031.810468	3288.64	-8.4712	Spain	Montejo et al.,2011
4	3868.543992	4600	-18.908	New York,USA	Chin and Franconeri,1980
5	5690.397073	4867	14.4699	New York,USA	Chin and Franconeri,1980
6	4555.172338	4112	9.72899	New York,USA	Chin and Franconeri,1981
7	4617.686643	4300	6.87978	Malaysia	Kathirvale et al,2003
8	3810.842744	3700	2.90862	Malaysia	Kathirvale et al,2003
9	2806.067434	2700	3.77993	Malaysia	Kathirvale et al,2003
10	3880.823447	4000	-3.0709	Malaysia	Kathirvale et al,2003

11	4768.724752	4676	1.94443	Malaysia	Kathirvale et al,2003
12	5355.499712	5301.8	1.0027	New York,USA	Themelis et. al., 2002
13	2784.305921	3182	-14.283	Sweden	Hogland et al.,2003

The comparison between the predicted energy and the measured energy indicated that the maximum variation of the predicted and measured energy was 25.52%. However, the average variation from the estimated results was found to be 7.5%. Therefore, we can conclude that the model predicts the overall energy potential within an average variation of 10%.

Figure 5-9 presents a comparison of the predicted or estimated energy potential from the SLR model with the literature

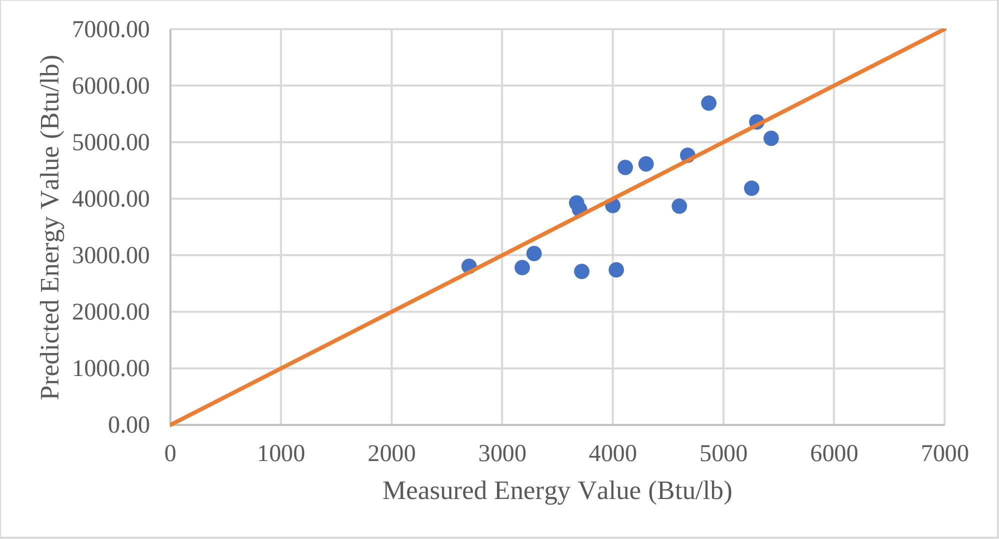


Figure 5-9 Predicted energy value with measured energy value from literature

5.3 Model Based on Proximate Analysis

5.3.1 Model Development

Simple linear regression (SLR) analysis was conducted, using the statistical modelling tool, R. The analysis steps followed to develop the SLR model energy potential are presented in Section 5.2.1 and illustrated in Figure 5.1.

5.3.2 Model Assumption

(i) Parameters

The preliminary goal for the model development was to generate a universal energy prediction model, considering the effects of volatile solids on the solid waste. Therefore, both fresh and mined waste compositions were used to develop the energy predicting model. Volatile solids were the only predictor considered for energy potential.

(ii) Data Collection

The mined solid waste was collected from Cell 0 and Cell 2 from 12 different boreholes, at different depths. The volatile solids were measured for the waste sample at each depth. The calorific value was measured for each possible combustible component. The overall energy potential was measured, considering the concerned waste composition. The fresh waste was collected from the City of Denton landfill during 2016-2018. Altogether, 46 data points were used to develop the model. Mined waste data from the City of Irving landfill was used to validate the developed model.

5.3.3 Simple Liner Regression analysis

5.3.3.1 Scatter plot of the response variable vs predictor variable

The response vs. predictor plot was used for studying whether a simple linear regression form would be suitable for fitting the data. The response vs. predictor plot is presented in Figure 5-10.

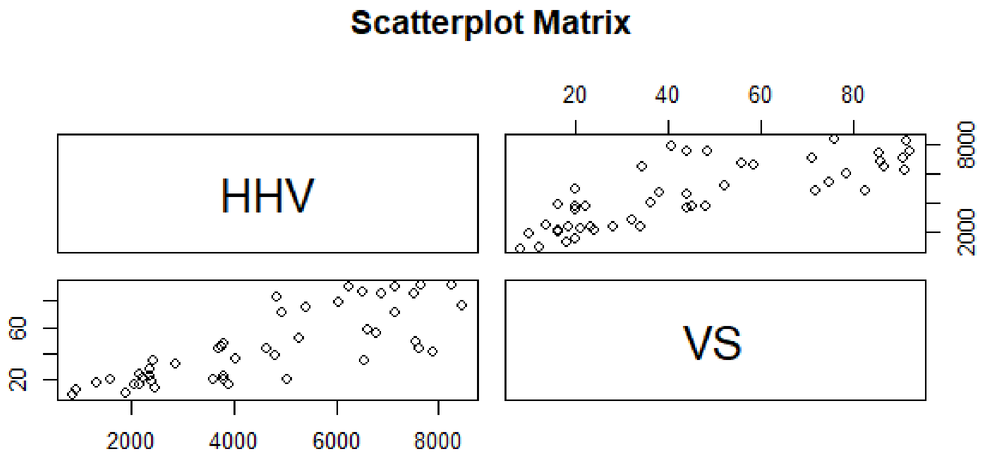


Figure 5-10 Scatter plot of Calorific Value vs Volatile Solid

5.3.3.2 Simple linear regression model

The calorific value data was modelled, using a first order basic regression model, where volatile solids were the predictor variable, and calorific value in Btu/lb. was the response variable. The basic regression model is

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$

where

Y_i is the value of the response variable for the ith trial. For the energy model it represents the expected number of calorific values in solid waste

β_0 is the y − intercept.

β_1 is the slope. For the model, it represents the impact of volatile solid for the calorific value in the solid waste.

x_i is the value of the predictor for the ith trial. This term represents the known quantities of volatile solid when calculating the number of calorific values in the model.

ε_i is the random error term for the ith trial

R was used to calculate the least squares and the parameter estimates using 46 data points.

Table 5-8 Parameter estimate for the preliminary SLR model

Parameter Estimates					
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	**1**	1669.48	388.01	4.302	<.0001
Volatile Solid	**1**	64.98	7.41	8.77	<.0001

Based on the preliminary analysis, the fitted SLR equation is presented

$$HHV = 1669.48 + 64.98x$$

Where

HHV= Higher Heating Value/Calorific Value of Solid Waste

X= volatile solid of the mixed waste.

The estimated total calorific value of solid waste is 1669.48 plus 64.98 of x (volatile solid of mixed waste). The coefficient of volatile solids, 64.98, means that the mean calorific value change 64.98 Btu/lb when the volatile solid increases by one.

Looking at the results of our t-test shown in table 5-8, $|t^*| > t(0.975; 46)$ and $p \ll \alpha$ so we reject H_o and confirm that our regression is significant.

Table 5-9 Analysis of variance of the SLR model

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	1	142889529.4	142889529.4	76.97313211	<.0001
Error	44	81679660.44	1856355.919		
Corrected Total	45	224569189.8			

R-Square	0.6363
Adj R-Sq	0.6280

The ANOVA results shown in Table 5-9 also confirm the results of our regression analysis. The R-Square value of 0.6363 shows that the calorific values varied by 63.63 % with the energy index. Also the F-value of 76.97 confirms the linear association of volatile solid and calorific value as F*> F (0.90; 1, 46).

5.3.3.3 Inference on the parameters

The calculation for a 95% confidence interval for the intercept is shown below.

$$b_0 = 1669.48$$

$$s\{b_0\} = 388.02$$

$$n = 46$$

$$\alpha = 0.05$$

$$\text{Confidence interval } (CI) = b_0 \pm t\left(1-\tfrac{\alpha}{2}; n-2\right) s\{b_0\}$$

$$CI = 1669.48 \pm t\left(1-\frac{0.05}{2}; 44\right) 388.02$$

$$where \ \ t(0.975; 44) = 2.02$$

$$CI = (885.68, 2453.28) \text{ with } 95\% \text{ confidence}$$

This range represents the calorific value solid waste without energy index with 95% confidence.

The calculation for a 95% confidence interval for the slope is shown below.

$$b_1 = 64.98$$

$$s\{b_1\} = 7.41$$

$$n = 46$$

$$\alpha = 0.05$$

$$\text{Confidence interval } (CI) = b_1 \pm t\left(1-\frac{\alpha}{2}; n-2\right) s\{b_1\}$$

$$CI = 64.98 \pm t\left(1-\frac{0.05}{2}; 44\right) 7.41$$

$$where\ \ t(0.975; 44) = 2.02 \text{ (using Excel T.INV)}$$

$$CI = (50.01\ , 79.95) \text{ with 95\% confidence}$$

5.3.3.4 Inferences on the True line and prediction

The excavated waste in the landfill mining project was degraded, and the volatile solids were around 20% in most of the cases. Therefore, it was crucial to assess the calorific value of volatile solids less than 20%. We considered a 95% confidence interval to estimate the mean number of calorific values:

$$b_0 = 1669.48$$

$$b_1 = 64.98$$

$$Calorific\ value\ \hat{Y}\ |_{x=20} = b_0 + b_1(20) = 1669.48 + 64.98 * 20 = 2969.08 \text{ Btu/lb}$$

$$Y_h = 2969.08$$

$$n = 46$$

$$\alpha = 0.05$$

$$\textstyle\sum_{n=1}^{i}(X_i - \bar{X})^2 = 33843.9$$

$$(X_H - \bar{X})^2 = (20 - 44.82)^2 = 616.03$$

$$s\{\hat{Y}_H\} = \sqrt{MSE\left[\frac{1}{n} + \frac{(X_H - \bar{X})^2}{\sum_{n=1}^{i}(X_i - \bar{X})^2}\right]} = \sqrt{1856355.919\left[\frac{1}{46} + \frac{616.03}{33843.9}\right]}$$

$$= 272.29$$

$$\text{Confidence interval } (CI) = Y_h \pm t\left(1-\frac{\alpha}{2}; n-2\right) s\{\hat{Y}_h\}$$

$$CI = 2969.08 \pm t\left(1 - \frac{0.05}{2}; 44\right) 272.29$$

$$where\ \ t(0.975; 44) = 2.02 \text{ (using Excel T.INV)}$$

$$CI = (2419.77, 3519.11) \text{ with 95\% confidence}$$

Using these values, 95% of volatile solid with 20% will have calorific value within the range of 2419.77 to 3519.11 Btu/lb.

Below we develop and interpret a 95% prediction interval for calorific value given 20%.

$$S\{pred\} = \sqrt{\left(S\{\hat{Y}_H\}\right)^2 + MSE} = \sqrt{(272.29)^2 + 1856355.919} = 1389.42$$

$$\text{Prediction interval } (PI) = Y_h \pm t\left(1 - \frac{\alpha}{2}; n - 2\right) s\{pred\}$$

$$PI = 2969.08 \pm t\left(1 - \frac{0.05}{2}; 61\right) 1389.42$$

$$where\ \ t(0.975; 44) = 2.02 \text{ (using Excel T.INV)}$$

$$PI = (162.45, 5775.71) \text{ with 95\% confidence}$$

We predict with 95% confidence that the volatile solid of 20% will have between 162.45 and 5775.71.This is a wider band than our confidence interval, but the reasonable values of calorific value given volatile solid support our model.

Below the confidence bands are computed

$$\hat{Y}\,|_{x=20}\ \pm\ \sqrt{2F(0.95;2,44}(s\{\hat{Y}_h\})$$

$$where\ F(0.95;2,44)=\ 3.21$$

$$\text{Confidence band (CB)} =\ \pm\sqrt{2(3.21)}(272.29)$$

$$CB=\ (2279.19,3659)\text{ with 95\% confidence}$$

We are 95% confident that the true line for when volatile solid is equal to 20%, lies between 2279.19 and 3659 calorific values.

5.3.3.5 Checking Model Assumptions for SLR equation

We considered the following model assumptions:

1) The data can be represented with a linear model.

2) The residuals in the model are normally distributed and have a constant variance

3) Serial correlation is not significant and

4) No outliers significantly impact the model’s accuracy.

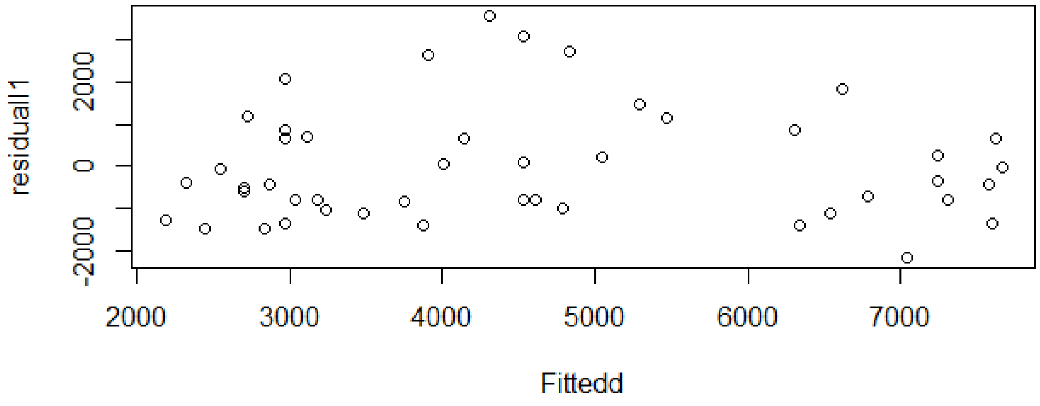


Figure 5-11 Residual vs. fitted plots for the preliminary model

Looking at the residual plot of residual vs fitted value in figure 5-11, the data appears to be random point cloud showing no curvature, no funnel shape (i.e non-constant variance).So linear model is reasonable.

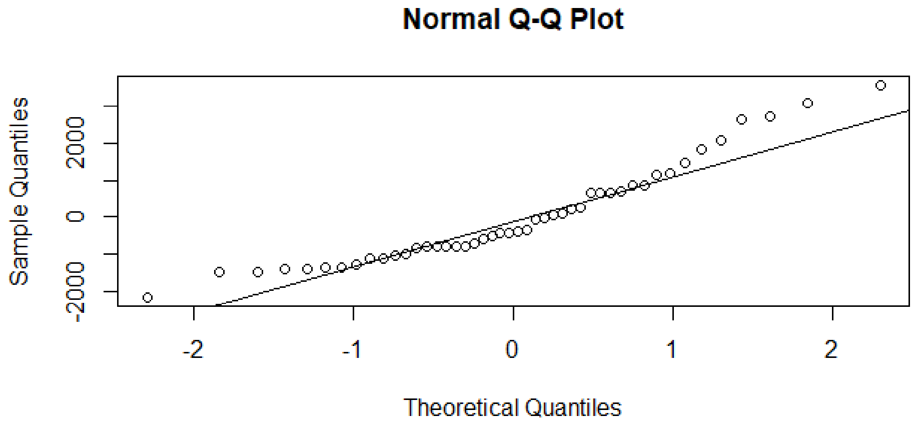


Figure 5-12 Normal probability plot of the residuals

Figure 5-12 shows the normality plot of residuals vs normal scores. On the left tail, there is longer tail on the normality plot and on the right tail, it has also longer tail. Overall, the normality line is not straight. We can conclude that normality is not ok for our model. Serial correlation is not significant here as we did not collect any time depended data.

Tests for Normality

$$H_0: \rho = 0; normal\ distribution$$

$$H_1: p \neq 0; not\ a\ normal\ distribution$$

$$if\ p \leq\ c(\propto; 63) then\ reject H_0$$

$$c(\propto = 0.05, n = 46) = 0.9945$$

$$0.7185 < 0.981\ Reject\ H_0, normality\ are\ NOT\ okay\ for\ correlation\ tests$$

Correlation Analysis

Correlation analysis helps in quantifying the liner association between two variables. Table 5-10 presents the Pearson’s correlation coefficients computed for response vs. predictor.

Pearson’s correlation coefficient “r” ranges from -1 to +1, while -1 indicates strong negative correlation and the +1 indicates a strong positive correlation between the parameters. When r=0, little or no correlation is indicated between the parameters.

Table 5-10 Correlation analysis for raw data

Pearson Correlation Coefficients, N=46		
	Calorific Value	Energy Index
Calorific Value	1.00	0.7977
Volatile Solid	0.7977	1.00

Breusch-Pagan test

Analytically, the Breusch-Pagan test is conducted below to determine whether or not the error variance is constant for all levels of x. The results support the conclusion of constant variance. Linear regression is performed, and the results are shown in Table 5-11 with analysis of variance.

Table 5-11 Parameter estimate and ANOVA between Volatile solid and residual squared

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	1915124	1096493	1.74	0.087686722
Volatile Solid	1	-30.44	223.3458	-.13629	0.892213049

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	1.32412E+11	1.32412E+11	0.018575192	0.892213049
Error	44	3.13652E+14	7.12845E+12		

Corrected Total	45	3.13784E+14			

$$H_0 : \gamma = 0; variance\ is\ constant$$

$$H_1 : \gamma \neq 0; variance\ is\ non - constant$$

$$Test\ statistic : {X_{BP}}^2 = \frac{SSR *}{2} / \left(\frac{SSE}{N}\right)^2$$

$$Reject\ H_0\ if\ {X_{BP}}^2 > \mathcal{X}^2\,(1{-}\propto;1) Fail\ to\ reject\ if\ {X_{BP}}^2 \leq \mathcal{X}^2\,(1{-}\propto;1)$$

SSR*= 1.32412E+11

SSE=81679660.44

$${X_{BP}}^2 = \frac{\frac{1.32412\mathrm{E}+11}{2}}{\left(\frac{81679660.44}{46}\right)^2} = .02$$

$$\mathcal{X}^2\,(0.95;1) = 3.84$$

$$.02 \leq 3.84\ Fail\ to\ reject\ H_0, Variance\ is\ constant$$

The Breusch-Pagan test also demonstrated that there was constant variance in our model. The conclusion was the same as with the residual plot. Hence we conclude, from the scatterplot and residual plot, that there are linear associations and constant variances respectively, and from the Q-Q plot that normality is *not* ok.

5.3.4 Final Model

Our goal for regression analysis is to develop a model which predicts the total calorific value in municipal solid waste. In this simple linear regression, volatile solid is the predictor for predicting total calorific value in solid waste. Using 46 data points our final SLR model is

$$HHV = 1669.48+ 64.98\ x$$

Where

HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb)

X= volatile solid of mixed waste

5.3.5 Model Validation

The energy predicting model had to be validated to observe the performance of the model. Mined data from the City of Irving landfill was used to predict the overall energy potential from the landfill cell. The predicted results were compared with the measured calorific value from the landfill to estimate the variation from the model.

The developed SLR equation for estimating the energy potential is

$$HHV = 1669.48 + 64.98x$$

Where

HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb)

X= Volatile Solid of mixed waste

A summary of comparisons between the predicted energy from the model and the landfill cell is presented in Table 5-12

Table 5-12 Summary of comparison between the predicted and measured energy potential

Sample No	Predicted Calorific Value (Btu/lb)	Measured Calorific Value (Btu/lb)	Variation (%)
1	5598.826154	4211.280514	24.7827956
2	3584.411238	2839.587182	20.7795369
3	3279.853913	3317.395946	-1.1446252
4	3646.008827	1679.534222	53.934993
5	3056.404901	2049.72957	32.9365828
6	4596.060153	3312.078378	27.9365746
6	3576.078802	2063.27205	42.3035072
8	2868.515714	1475.626316	48.5578444
9	4098.155944	2202.152444	46.2647963
10	5259.464158	4810.125643	8.54342765
11	3462.031724	1793.190965	48.2040863
12	4965.762744	3615.430143	27.1928538

The comparison between the predicted calorific value and the measured calorific value indicated that the maximum variation from the predicted energy from measured energy was 48.48%. However, the average variation from the estimated results was found to be 31.69 % Therefore, we can conclude that the model overpredicts the calorific value.

Figure 5-13 presents the predicted or estimated energy potential from the SLR model with the actual measurement in the lab.

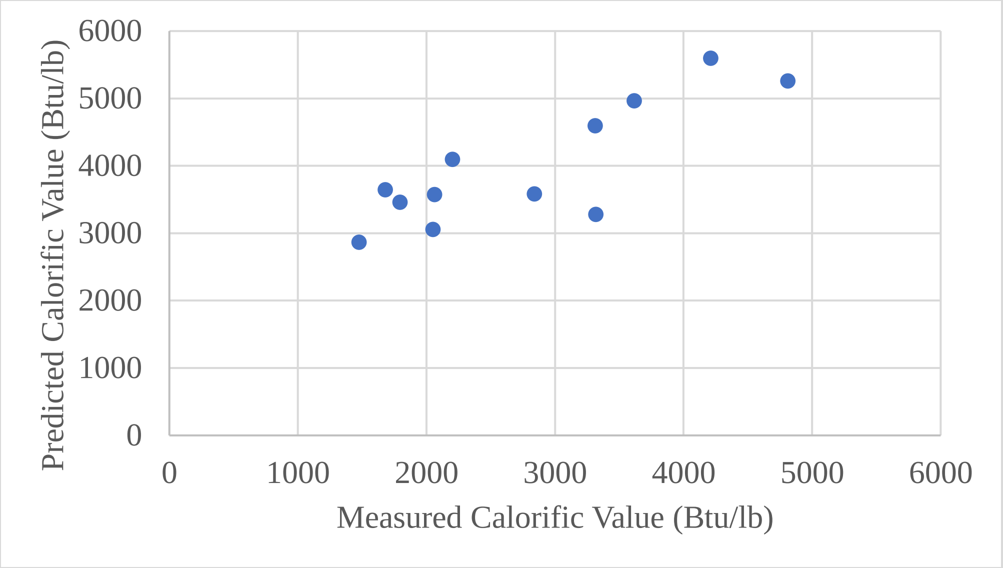


Figure 5-13 Validation of model developed using Proximate analysis

5.4 Model Based on Elemental Analysis

5.4.1 Model Development

Simple linear regression (SLR) analysis was conducted, using a statistical modelling tool, R.The analysis steps followed to develop the SLR model's energy potential are presented in Section 5.2.1, and are illustrated in Figure 5.1.

5.4.2 Model Assumption

(i) Parameters

The preliminary concern for the model development was to generate a universal energy prediction model considering the effect of elemental composition of the solid waste. Therefore, carbon (C %) was used to develop energy predicting model.

(ii) Data Collection

The mined solid waste was collected from Cell 0 and Cell 2, from different depths of 12 different boreholes. The elemental composition of 35 randomly selected samples and the calorific value of respective waste components were measured. The overall energy potential of the waste composition was also measured. The fresh waste was collected from the City of Denton landfill during 2016-2018. Altogether, 35 data points were used to develop the model. Elemental results from the literature used to validate the developed model.

5.4.3 Simple Linear Regression analysis

This section included a detail regression analysis. Based laboratory results, a single linear regression analysis was performed. However, it was intended to develop an MLR equation to predict energy potential using three predictors (Carbon, Hydrogen, Nitrogen).

5.4.3.1 Scatter plot Matrix

The response vs. predictor plot is used for studying whether a simple linear regression form would be suitable for fitting the data. The response vs. predictor plot is presented in Figure 5-14.

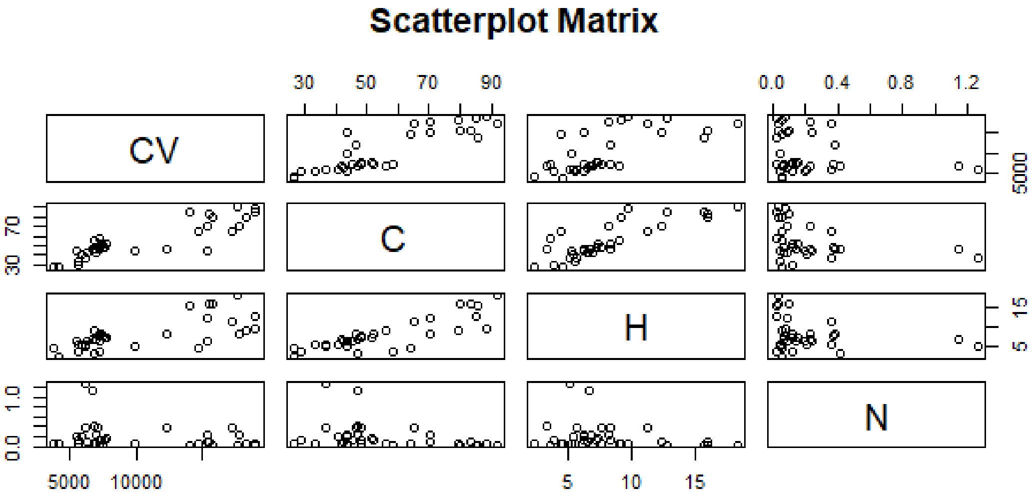


Figure 5-14 Scatter plot of Calorific value vs Predictors

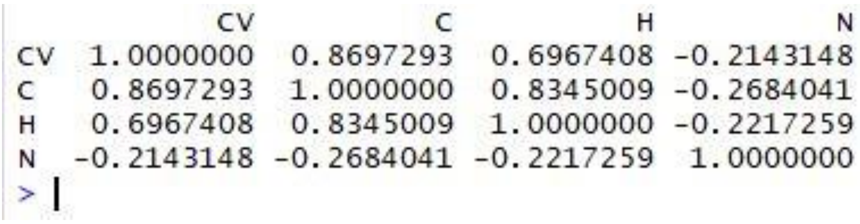
It was observed in Figure 5-13 that the calorific value (CV) vs percent of carbon (C%), and calorific value (CV) vs percent of hydrogen (H%) graph showed an increasing trend. Thus, an increase in carbon and hydrogen increased the calorific value of the solid waste. The calorific value (CV) vs nitrogen (N) did not show any trend/linearity. Based on the scatterplot, nitrogen might be a poor predictor for the model.

The predictor vs predictor plots aid in determining whether the predictors are linearly correlated. Any significant trend (upwards or downwards) in the plots indicates that the predictors are correlated. Multicollinearity in the MLR model complicates and weakens the model. Based on the plot, there is a strong linearity between the percent of carbon and the percent of hydrogen. Hence, multicollinearity is a big issue for this model. The presence of multicollinearity explains the variations in the response variable by two or more predictors; either of the predictors can be used in the model.

5.4.3.2 Correlation Analysis

Correlation analysis indicates the quantification of linear association between two predictors. Table 5-13 presents Pearson's correlation coefficients output for all predictors and response variable. Pearson's correlation coefficient "r" ranges from -1 to +1, while -1 indicates strong negative correlation and the +1 indicates a strong positive correlation between the parameters. When r=0, little or no correlation is indicated between the parameters.

Table 5-13 Pearson correlation coefficient from R



```
           CV          C          H          N
CV  1.0000000  0.8697293  0.6967408 -0.2143148
C   0.8697293  1.0000000  0.8345009 -0.2684041
H   0.6967408  0.8345009  1.0000000 -0.2217259
N  -0.2143148 -0.2684041 -0.2217259  1.0000000
> |
```

A shown in Table 5-13, the correlation between the percent of carbon and the percent of hydrogen was very high (.83). Other values were within good range. If r<0.7, multicollinearity would not cause that issue in the model; however, the multicollinearity was considerably present in this data set. Therefore, it can be concluded that one of the predictors of carbon or hydrogen should be present in the model.

5.4.3.3 Preliminary Multiple Linear Regression Equation

Initially an attempt was made to develop an MLR model as follows

$$CV = \beta_0 + \beta_1 C + \beta_2 H + \beta_3 N + \varepsilon_i$$

Where,

CV= Calorific Value of the solid waste (Btu/lb)

C=Carbon (%)
H=Hydrogen (%)
N= Nitrogen (%)
$\beta_0, \beta_1, \beta_2, \beta_3$ = correlation parameters to be determined from multiple linear regression. The preliminary model was developed using R and the estimators for the model parameters are presented in table 5-14.

Table 5-14 Parameter estimate for the preliminary MLR model

Parameter Estimates					
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	**1**	-2849.29	1555.77	-1.83	.0767
C	**1**	256.84	43.49	5.90	1.61+E-06
H	**1**	-123.39	205.77	-0.6	.5531
N	**1**	377.65	1656.41	.228	.8211

Significance of the preliminary model parameters should be analyzed by performing a T test for each predictor. Table 5-14 expresses the t values and corresponding p values for 3 parameters:

$H0$: $\beta k = 0$

$H1$: $\beta k \neq 0$

Assuming $\alpha = 0.1$ significant level, only one p value is less than α value and in conclusion, it can be said that carbon is the only significant predictor. The other two predictors (Hydrogen, Nitrogen) are found insignificant which supports the previous assumption from scatterplot and correlation matrix. Eventually, it has become a simple linear regression model.

5.4.3.3 Simple linear regression model

The calorific value data will be modelled using a first order basic regression model where carbon will be the predictor variable and calorific value in btu/lb will be the response variable. The basic regression model is

$$Y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$$

where

Y_i is the value of the response variable for the ith trial. For the energy model it represents the expected number of calorific values in solid waste.

β_0 is the y − intercept.

β_1 is the slope. For the model, it represents the impact of volatile solid for the calorific value in the solid waste.

x_i is the value of the predictor for the ith trial. This term represents the known quantities of volatile solid when calculating the number of calorific values in the model.

ε_i is the random error term for the ith trial

R was used to calculate the least squares and the parameter estimates using 35 data points showed in Table 5-15.

Table 5-15 Parameter estimate for the preliminary SLR model

Parameter Estimates					
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	**1**	-2503.5	1325.5	-1.889	0.0678
Carbon	**1**	233.8	23.1	10.23	< 0.05

Based on the preliminary analysis, the fitted SLR equation is presented

$$HHV = 233.8\,X-2503.5$$

Where

HHV= Higher Heating Value/Calorific Value of Solid Waste

X= Carbon %

The estimated total calorific value of solid waste is 233.8 of x (Volatile Solid of mixed waste) minus 2503.5. The coefficient of carbon 233.8 means the mean calorific value change 233.8 when the carbon % increases by one.

Looking at the results of our t-test shown in Table 5-15, $|t^*| > t\ (0.975;35)$ and $p << \alpha$ so we reject H_o and confirm that our regression is significant

Table 5-16 Analysis of variance of the SLR model

Analysis of Variance					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	1	647465018	647465018	102.48	<.0001
Error	33	208484325	1856355.919		
Corrected Total	34	855949343			

R-Square	.7549
Adj R-Sq	.749

The ANOVA results shown in Table 5-15 also confirm the results of our regression analysis. The R-Square value of 0.7549 shows that the calorific values varies by

75.49 % with the energy index. Also the F-value of 102.48 confirms the linear association of volatile solid and calorific value as F*> F (0.90; 1, 34).

5.4.3.4 Inference on the parameters

The calculation for a 95% confidence interval for the intercept is shown below.

$$b_0 = -2505.5$$

$$s\{b_0\} = 1325.5$$

$$n = 35$$

$$\alpha = 0.05$$

Confidence interval (*CI*) = $b_0 \pm t\left(1-\frac{\alpha}{2}; n-2\right) s\{b_0\}$

$$CI = -2505.5 \pm t\left(1-\frac{0.05}{2}; 35\right) 1325.5$$

$$where\ \ t(0.975; 44) = 2.03$$

$CI = (-5266.84, 217.57)$ with 95% confidence

This range represents the calorific value solid waste without energy index with 95% confidence.

The calculation for a 95% confidence interval for the slope is shown below.

$$b_1 = 233.8$$

$$s\{b_1\} = 23.1$$

$$n = 35$$

$$\alpha = 0.05$$

Confidence interval (*CI*) = $b_1 \pm t\left(1-\frac{\alpha}{2}; n-2\right) s\{b_1\}$

$$CI = 233.8 \pm t\left(1-\frac{0.05}{2}; 35\right) 23.1$$

$$where \ \ t(0.975; 35) = \ 2.03 \text{ (using Excel T.INV)}$$

$$CI = \ (187.11\ , 282.68) \text{ with 95\% confidence}$$

5.4.3.5 Checking Model Assumptions for SLR equation

We consider the following model assumptions:

1) The data can be represented with a linear model.

2) The residuals in the model are normally distributed and with a constant variance

3) Serial correlation is not significant

4) No outliers significantly impact the model's accuracy.

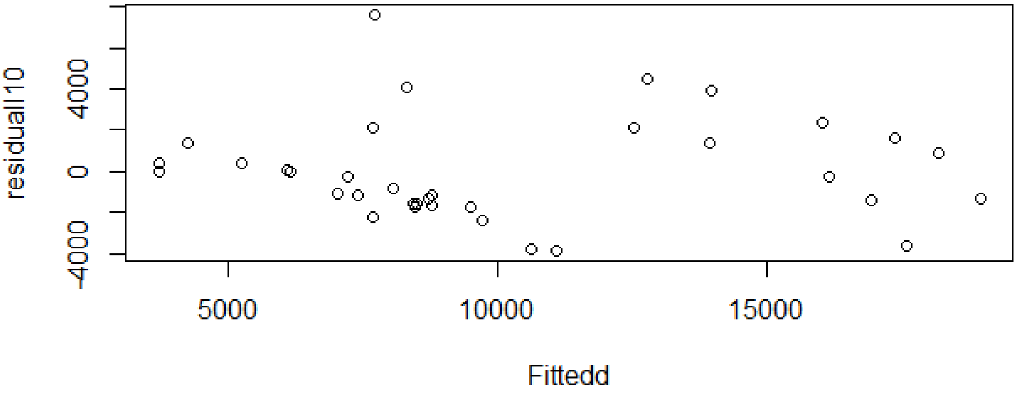


Figure 5-15 Residual vs. fitted plots for the preliminary model

Looking at the residual plot of residual vs fitted value in figure 5-15, the data appears to be random point cloud showing no curvature, no funnel shape (i.e non-constant variance).So linear model is reasonable.

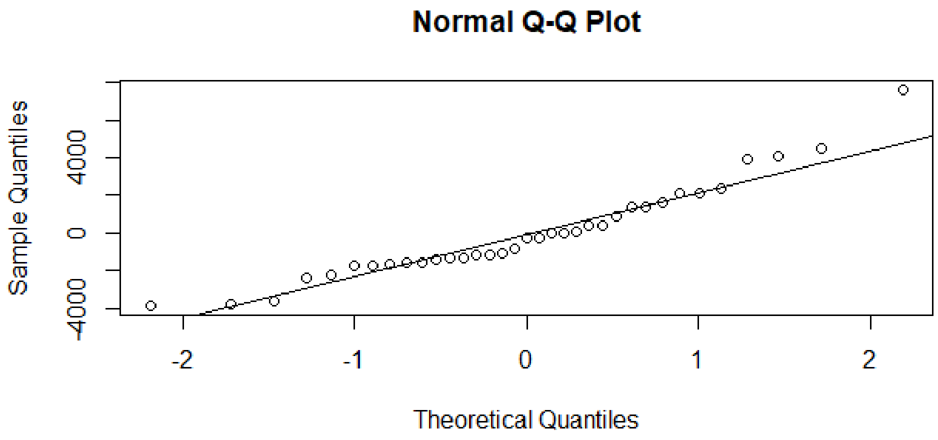


Figure 5-16 Normal probability plot of the residuals

Figure 5-16 shows the normality plot of residuals vs normal scores. On the left tail, there is longer tail on the normality plot and on the right tail, it has also longer tail. Overall, the normality line is not straight. We can conclude that normality is not ok for our model. Serial correlation is not significant here as we did not take any time depended data.

<u>Tests for Normality</u>

$$H_0: \rho = 0; normal\ distribution$$

$$H_1: p \neq 0; not\ a\ normal\ distribution$$

$$if\ p \leq\ c(\propto; 63) then\ reject H_0$$

$$c(\propto = 0.05, n = 46) = 0.9945$$

$$0.7185 < 0.981\ Reject\ H_0, normality\ are\ NOT\ okay\ for\ correlation\ tests$$

Correlation Analysis

Correlation analysis helps in quantifying the liner association between two variables. Table 5-17 presents the Pearson's correlation coefficients computed for response vs. predictor.

Pearson's correlation coefficient "r" ranges from -1 to +1, while -1 indicates strong negative correlation and the +1 indicates a strong positive correlation between the parameters. When r=0, little or no correlation is indicated between the parameters.

Table 5-17 Correlation Analysis for raw data

Pearson Correlation Coefficients, N=46		
	Calorific Value	Energy Index
Calorific Value	1	0.87
Carbon (%)	.87	1

Breusch-Pagan test

Analytically, the Breusch-Pagan test is conducted below to determine whether or not the error variance is constant for all levels of x. The results support the conclusion of constant variance. Linear regression is performed, and the results are shown in Table 5-18 with analysis of variance.

Table 5-18 Parameter estimate and ANOVA between Carbon (%) and residual squared

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept		4510127	5622617	0.80214	0.428211
Carbon (%)		26642.68	97977.46	0.271927	0.787373

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	8.41E+12	8.41E+12	0.073944	0.787373
Error	33	3.75E+15	1.14E+14		
Corrected Total	34	3.76E+15			

$$H_0\colon \gamma = 0; variance\ is\ constant$$

$$H_1\colon \gamma \neq 0; variance\ is\ non - constant$$

$$Test\ statistic\colon {X_{BP}}^2 = \frac{SSR*}{2} / \left(\frac{SSE}{N}\right)^2$$

$$Reject\ H_0\ if\ {X_{BP}}^2 > \mathcal{X}^2\,(1{-}\propto;1) Fail\ to\ reject\ if\ {X_{BP}}^2 \leq \mathcal{X}^2\,(1{-}\propto;1)$$

SSR*= 8.41E+12

SSE=208484325

$${X_{BP}}^2 = \frac{\frac{8.41\text{E} + 12}{2}}{\left(\frac{208484325}{35}\right)^2} = .119$$

$$\mathcal{X}^2\,(0.95;1) = 3.84$$

$$.119 \leq\ 3.84\ Fail\ to\ reject\ H_0, Variance\ is\ constant$$

The Breusch-Pagan test also demonstrated that we have constant variance in our model. The conclusion is same with residual plot. Since we conclude that there are linear association and constant variance from residuals versus Volatile solid plot and normality is not ok from Q-Q plot.

5.4.4 Final Model

Our goal for regression analysis is to develop a model which predicts the total calorific value in municipal solid waste. In this simple linear regression, volatile solid is the predictor for predicting total calorific value in solid waste. Using 46 data points our final SLR model is

$$\text{HHV} = 233.8\ \text{X}-2503.5$$

Where

HHV= Higher Heating Value/Calorific Value of Solid Waste

X= Carbon %

5.4.5 Model Validation

It is required that the developed energy predicting model be validated to observe the performance of the model. Elemental results from literature shown in Table 5-19 was used to validate the model.

The developed SLR equation for estimating the energy potential is

$$HHV = 233.8\ X-2503.5$$

Where

HHV= Higher Heating Value/Calorific Value of Solid Waste

X= Carbon %

A summary of comparisons between the predicted and measured calorific value of solid waste is presented in Table 5-19

Table 5-19 Predicted and measured calorific value of solid waste

Sample	Experimental Value Literature (Btu/lb)	Predicted Value Using Equation (Btu/lb)	% Error	Reference for Experimental Value
1	5246	4639.81	11.55528021	Wu et al.,1997
2	8299	9591.502	15.57418966	Sorum et al.,2001
3	7267	7933.108	9.166203385	Sorum et al.,2001
4	4472	5187.127	15.99121199	Sorum et al.,2001
5	7611	7209.616	5.273735383	Siang and Zakaria.,2006
6	7851.8	8492.17	8.155709519	Parikh et. al.,2005
7	8557	8774.05	2.536519808	Parikh et. al.,2005
8	8901	9370.696	5.276890237	Parikh et. al.,2005
9	8600	9713.65	12.9494186	Parikh et. al.,2005
10	8643	9666.67	11.84391994	Parikh et. al.,2005
11	8501.1	8785.795	3.348919552	Parikh et. al.,2005
12	7955	9072.373	14.04617222	Parikh et. al.,2005
13	8514	8889.151	4.406283768	Becidan et al.,2007
14	16985	16243.87	4.363438328	Becidan et al.,2007
15	8256	6401.56	22.46172481	Courtemanche and Levendis et al.,1998

16	17200	17676.76	2.771860465	Courtemanche and Levendis et al.,1998
17	19135	19086.16	0.255239091	Courtemanche and Levendis et al.,1998
18	9546	12250.57	28.33197151	Siang and Zakaria.,2006
19	14319	16337.83	14.09895942	Islam and Beg 2004
20	15303.7	17258.638	12.77428334	Kim et. al.,1994
21	12470	11621.038	6.808035285	Courtemanche and Levendis et al.,1998
22	10767.2	9871.033	8.323120217	Siang and Zakaria.,2006
23	8458.1	7343.509	13.17779407	Meraz et.al.,2003

The comparison between the predicted calorific value and the measured calorific value indicated that the maximum variation was found 22.46 %. However, the average variation from the estimated results was found to be 3.87 % Therefore, we can conclude that the model predicts the overall energy potential within an average variation of 5%.

Figure 5-17 presents the predicted or estimated energy potential from the SLR model with the actual measurement in the lab from literature.

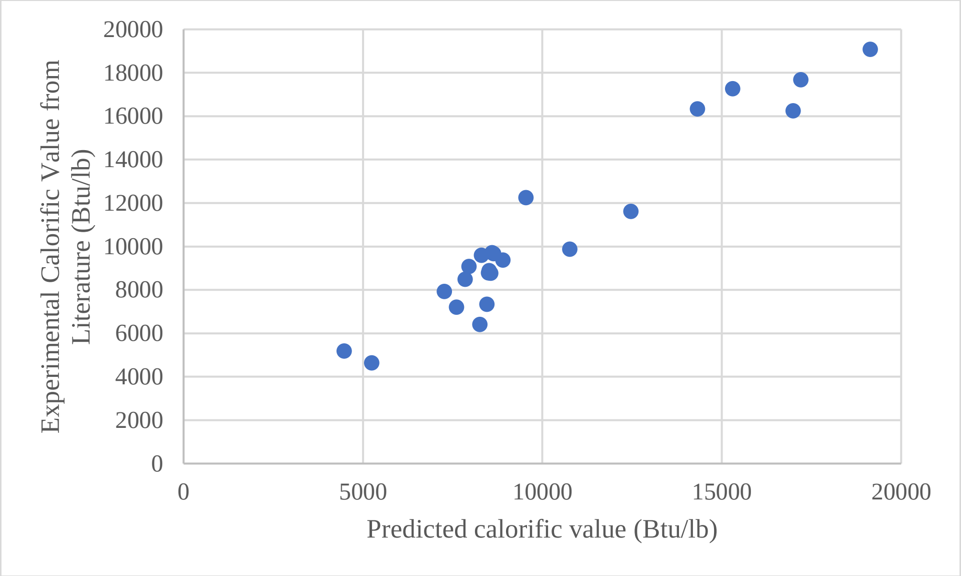


Figure 5-17 Predicted vs Experimental calorific c alue

5.5 Summary of the models

Summary of the empirical models based on the current study are listed in table 5-20

Table 5-20 Summary of the empirical models

Empirical Model	**Method**	**R^2**
HHV = 1344.67lnx + 3854.4 Where HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb) X= Energy index based on the waste composition	Physical Composition	**0.77**

HHV = 1669.48+ 64.98 x Where HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb) X= volatile solid of mixed waste	Proximate Analysis	**0.63**
HHV= 234.9*C-2524.64 Where HHV= Higher heating value/calorific value of Municipal Waste (Btu/lb) C= Carbon % in the Waste	Elemental Analysis	**0.75**

6 Chapter: Conclusion and recommendation

Landfill mining is considered one of the sustainable solutions for waste management. Energy recovery from excavated waste is an important benefit of landfill mining. A thorough study of the waste composition of excavated waste is critical for assessing the potential for energy. The experimental determination of energy from solid waste enables the accurate measurement of the energy potential of solid waste. There are also some alternative methods (proximate analysis and elemental composition) that can be used to measure the energy potential of waste without any experimental determination. Numerous mathematical models have been developed to predict the energy potential of waste around the world; however, none of them can be applied universally. The main motive of this research was to develop a universal mathematical model, using experimental fresh and mined waste data. The effects of different factors on the energy potential of solid waste was also explained.

6.1 Summary and conclusion

The results and conclusions, based on the laboratory investigations, are summarized below:

1. Mined samples were collected from Cell 0 (closed section of the conventional landfill) and Cell 2 (intermediate cover on ELR-operated landfill) of the City of Denton landfill. Fresh waste was collected from the

City of Denton landfill during 2016-2018. Altogether, 65 samples were collected from 12 different boreholes at 10 ft. depth intervals. The weight of each sample bag was approximately 15 to 20 lb.

2. Mined waste from the City of Irving landfill was collected from a closed cell of a conventional landfill, from which 22 samples were collected from three different boreholes at intervals of 10 ft. depth.
3. Based on the manual waste sorting, the average mined waste composition from the City of Denton landfill consisted of 23.47 % paper, 9.07% plastic, 7.89% yard/wood, 1.55 textiles, 1.34% Styrofoam and sponge, 3.67% metal, 1.29% glass, and 47.86% fine. The percentage of paper (23.47%) was higher than that reported in previous research papers. The fine/degraded fraction (47.86%) was similar to the range reported in literature. Due to the unavailability of the proper amount of moisture inside the landfill, a high percent of degradable material (paper, textile, wood) were found partially degraded.
4. In the City of Irving Landfill, the average mined waste composition was 11.25% paper, 9.34% plastic, 7.69% yard/wood, 5.58% textiles, .34% Styrofoam and sponge, 1.72% metal, 0.25% glass, and 60.82% fine. The data from the City of Irving landfill was used to validate the empirical model.

5. The average composition of mined waste from the City of Denton landfill was compared to the average composition of fresh waste from the active phase (2016-2018). As was expected, the paper fraction in the mined waste was considerably less than in the fresh waste, due to the gradual degradation. The plastic fraction was notably less in the mined waste since the use of plastics didn’t become popular until the 1990s. Therefore, the original composition of plastic might have been even less. The timelines of the actual disposal of the waste were different. The fresh waste composition from 2016-2018 was different from the actual fresh waste composition of 1985. Therefore, the idea that the change in waste composition in mined waste was due to degradation might not be accurate.
6. In the City of Denton landfill, the average moisture content of the excavated waste from 12 different boreholes was 20.33% (wet basis), with a range from 10.64% to 41.18%. In the City of Irving landfill, the average moisture content was found as 25.32%, based on 3 boreholes. The mean moisture content of the mined waste indicates the adverse environment for further waste degradation, since 40-70% moisture content is required for optimum biological activity (Barlaz et al., 1990).
7. The volatile solid was determined with the biodegradable portion. The average volatile solid was 66.25% in fresh waste, whereas it was 32.36% in mined waste. It can be summarized that the mined waste experienced almost

50% more degradation compared to the fresh waste disposed of in the City of Denton landfill (2016-18).

8. The average calorific value of mined paper waste was determined as 6211.301 Btu/lb., whereas the average calorific value of fresh paper waste was 6682.94 Btu/lb. The average calorific value of mined plastic waste was 14223.63 Btu/lb., which is similar to the average calorific value of fresh plastic waste (13655.19 Btu/lb.) because plastic is non-degradable. The average calorific value of mined wood waste was 6577.13 Btu/lb. in Cell 0, which was almost equal to the average energy of wood from fresh waste (6813.332 Btu/lb.). Therefore, the energy potential of recovered excavated waste components was almost equal to that of the fresh waste component. The quality of the recovered waste was very good in terms of energy.
9. Overall, the average mixed calorific value from fresh waste was 6838.9 Btu/lb., whereas the mined energy value was 3665.88 Btu/lb. (Figure 4-26). Therefore, 52% of the energy value remained in the mined waste from Cell 0 in the City of Denton landfill, based on the experimental results,
10. No significant trend of calorific value was found with increased depth. The fine fraction was found to be a good predictor of the calorific value of mined waste. The ELR conventional landfill operation did not have any effect on the energy potential; however, this was based on a small number of samples.
11. Excavated fractions contained a significant amount (42.13%) of

combustible waste, such as paper, plastic, wood, etc.

12. Overall, the calorific value of waste increased with the increase of volatile solids. However, the calorific value of waste did not exhibit any significant trend with the change of moisture content.
13. The energy index was introduced, using the waste composition. Considering all of the fresh and mined data, the energy value gradually decreased with the decrease of the energy index, showing a nonlinear trend.
14. Simple linear regression was used to predict the calorific value of solid waste, using the energy index. The model was found to have an adjusted R^2 of 0.7741 and is given by

$$\text{HHV} = 3854.46 + 1344.67 \ln x$$

Where HHV= Higher Heating Value/Calorific Value of Solid Waste, X= Energy Index of the solid waste

Mined waste from the City of Irving landfill was used to validate the model.

15. Simple linear regression was used to predict the calorific value of solid waste, using the volatile solid of mixed waste. The model was found to have an adjusted R^2 0.6280, and is given by $\text{HHV} = 3854.46 + 1344.67 \ln x$.

Where HHV= Higher Heating Value/Calorific Value of Solid Waste, X= Volatile solid of mixed waste.

Mined waste from the City of Irving landfill was used to validate the model.

16. Simple linear regression was used to predict the calorific value of the solid waste, using the elemental composition of waste. The model was found to have an adjusted R^2 of 0.7443, and is given by $HHV = 234.89X-2524.64$.

Where HHV= Higher Heating Value/Calorific Value of Solid Waste, X=carbon %.

Mined waste from the City of Irving landfill was used to validate the model.

6.2 Future Recommendation

Based on the current study, the following topics are recommended for future research.

- Further research is needed to address the exact experimental determination of waste degradation/decomposition of excavated waste, which is directly correlated with the energy value.
- Waste was sorted into major waste components, like paper, plastic, etc. Further composition of the individual waste components, like different types of paper and plastic, are required to determine the weighted energy value of individual components.
- The effects of temperature on energy values can be investigated in the future. Temperatures inside the landfills were found to be higher than the

surrounding temperatures. Until now, there has not been a prediction model for the inside temperature.

- Further comprehensive study is required to investigate the detailed properties of fine/degraded materials that make up approximately 50-60% of the excavated waste.
- Contamination is a big issue in landfill mining, and is an issue that should be incorporated into future studies. Contamination in mined waste might have some effect on energy value. Leachate quality and elemental concentration by XRF analysis can be added to measure the contamination of mined waste.
- Fixed carbon can be included to improve the accuracy of the model-based proximate analysis.
- The elemental analysis was determined by a CHN analyzer. An advanced elemental analyzer can be used for further research to measure sulphur (S) and oxygen (O) as well.

References

.

Abu-Qudais, M. D., & Abu-Qdais, H. A. (2000). Energy content of municipal solid waste in Jordan and its potential utilization. *Energy conversion and Management*, *41*(9), 983-991.

Agentschap, N. L. (2010). Warmte in Nederland. NL Energie en Klimaat. Utrecht, Agentschap NL.

Alam, M. Z., Hossain, M. S., & Samir, S. (2017). Performance Evaluation of a Bioreactor Landfill Operation. In *Geotechnical Frontiers 2017* (pp. 267-273).

Alter, H., Ingle, G., Kaiser, E., 1974. Chemical analyses of the organic portions of household refuse; the effect of effect of certain elements on incineration and resource recovery. Solid Waste Management 64, 387–391.

Amber, I., Kulla, D. M., & Gukop, N. (2012). Generation, characteristics and energy potential of solid municipal waste in Nigeria. Journal of Energy in Southern Africa, 23(3), 47-51.

American Public Health Association (APHA), 1992. Standard MethodsFor The Examination of Water and Wastewater, 18th ed. AmericanPublic Health Association, Washington, DC

Attal, A., Akunna, J., Camacho, P., Salmon, P., and Paris, I. (1992) "Anaerobic degradation of municipal wastes in landfill." Water Sci. Technol., 25(7), 243–253.

Barlaz, M. A., Ham, R. K., and Schaefer, D. M. (1990). “Methane production from municipal refuse.” Crit Rev. Environ. Control, 19(6),557–584.

Bosmans, A., De Dobbelaere, C., & Helsen, L. (2014). Pyrolysis characteristics of excavated waste material processed into refuse derived fuel. Fuel, 122, 198-205.

Brammer, F. (1995). Landfill mining: a possibility to reduce landfill volume and environmental pollution. In *Proceedings, Sardinia'95, 5th International Landfill Symposium, Caglari* (pp. 795-806).

Carboo, D., and Fobil, J. N. (2009). "Physico-chemical analysis of municipal solid waste (MSW) in the Accra metropolis." *West African Journal of Applied Ecology,* 7(1),

Chang, N. B., & Davila, E. (2008). Municipal solid waste characterizations and management strategies for the Lower Rio Grande Valley, Texas. *Waste Management*, *28*(5), 776-794.

Chang, Y. M., Liu, C. C., Hung, C. Y., Hu, A., & Chen, S. S. (2008). Change in MSW characteristics under recent management strategies in Taiwan. Waste Management, 28(12), 2443-2455.

Chen, Y. M., Zhan, T. L. T., Wei, H. Y., & Ke, H. (2009). “Aging and Compressibility of Municipal Solid Wastes.” Waste Management, 29(1), 86-95.

Chiemchaisri, C., Chiemchaisri, W., Kumar, S., and Hettiaratchi, J. P. A. (2007). "Solid waste characteristics and their relationship to gas production in tropical landfill." Environ.Monit.Assess., 135(1), 41-48.

Chiemchaisri, C., Charnnok, B., Visvanathan, C., 2010. Recovery of plastic wastes from dumpsite as refuseederived fuel and its utilization in small gasification system. Bioresour. Technol. 101 (5), 1522e1527.

Chin, N. O. R. M. A. N., & Franconeri, P. E. T. E. R. (1980, May). Composition and heating value of municipal solid waste in the Spring Creek area of New York City. In *Proceedings of the 1980 National Waste Processing Conference New York. The American Society of Mechanical En gineers*.

Chunming, W., Qilun, Z., Yunghua, J., & Yongbin, W. (2013). Physical composition and Calorific value calculation of MSW in Zengcheng, Guangzhou, China. Sci J Environ Pollut Prot, 2, 18.

Cossu, R., Hogland, W., Salerni, E., (1996). Landfill mining in Europe and the USA. ISWA Year Book 1996, 107–114.

Danthurebandara, M., Van Passel, S., Vanderreydt, I., & Van Acker, K. (2015). Assessment of environmental and economic feasibility of Enhanced Landfill Mining. *Waste management*, *45*, 434-447.

Dickinson, W. (1995). Landfill mining comes of age. *Solid Waste Technologies*, *9*(2), 5

Directive, E. C. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union L, 312(3).

El-Fadel, M. A. (1991). *Modeling gas and heat generation and transport in sanitary landfills*. Stanford Univ., CA (United States).

Forster, G. A. (1995). Assessment of landfill reclamation and the effects of age on the combustion of recovered municipal solid waste (No. NREL/TP--430-7449). National Renewable Energy Lab., Golden, CO (United States)

Flyhammar, P., 1997. Heavy metals in municipal solid waste deposits. Lund University of Technology, Water Resources Engineering AFR-report 231. Lund Sweden.

Gabr, M. A., and Valero, S. N. (1995) "Geotechnical properties of municipal solid waste." Geotech. Test. J., 18(2), 241–251.

Gaitanarou, Z., Tentes, G., & Katselis, Y. (2014). Landfill mining: An empirical review on past and state-of-the-art applications.

Gomes, C., Lopes, M.L., Lopes M.G., (2005), "A study of MSW properties of a Portuguese landfill.", International Workshop << Hydro-Physico-Mechanics of Landfills, LIRIGM, Grenoble 1 University, France.21-22 March.

Geysen, D., Jones, P., Van Acker, K., Van Passel, S., Crabs, M., Eyckmans, J., ... & Ballard, M. (2009). Enhanced landfill mining-a future perspective of landfilling.

Giugliano, M., Grosso, M., & Rigamonti, L. (2008). Energy recovery from municipal waste: A case study for a middle-sized Italian district. Waste management, 28(1), 39-50.

Halada, K., Ijima, K., Shimada, M., & Katagiri, N. (2009). A possibility of urban mining in Japan. *Journal of the Japan Institute of Metals*, *73*(3), 151-160.

Ham, R. K., Norman, M. R., and Fritschel, P. R. ~1993!. "Chemical characterization of Fresh Kills landfill refuse and extracts." J. Environ. Eng., 119~6!, 1176–1195.

Hogland, W. (2002). Remediation of an old landsfill site. Environmental Science and Pollution Research, 9(1), 49-54.

Hogland, W., Marques, M., & Nimmermark, S. (2004). Landfill mining and waste characterization: a strategy for remediation of contaminated areas. *Journal of material Cycles and Waste management*, *6*(2), 119-124.

Horttanainen, M., Teirasvuo, N., Kapustina, V., Hupponen, M., & Luoranen, M. (2013). The composition, heating value and renewable share of the energy content of mixed municipal solid waste in Finland. *Waste management*, *33*(12), 2680-2686

Hossain, M. S., Haque, M. A., & Hoyos, L. R. (2010). Dynamic properties of municipal solid waste in bioreactor landfills with degradation. *Geotechnical and Geological Engineering*, *28*(4), 391-403.

Hull, R. M., Krogmann, U., & Strom, P. F. (2005). Composition and characteristics of excavated materials from a New Jersey landfill. *Journal of environmental engineering*, *131*(3), 478-490.

Jones, P. T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., ... & Hoekstra, N. (2013). Enhanced Landfill Mining in view of multiple resource recovery: a critical review. *Journal of Cleaner Production*, *55*, 45-55.

Joseph, K., Nagendran, R., Palanivelu, K., Thanasekaran, K., & Visvanathan, C. (2004). Dumpsite rehabilitation and landfill mining. CES, Anna University, Chennai, India under ARRPET available online: http://www. swlf. ait. ac. th.

Kaartinen, T., Sormunen, K., & Rintala, J. (2013). Case study on sampling, processing and characterization of landfilled municipal solid waste in the view of landfill mining. *Journal of Cleaner Production, 55*, 56-66

Kalanatarifard, A., & Yang, G. S. (2012). Identification of the municipal solid waste characteristics and potential of plastic recovery at Bakri Landfill, Muar, Malaysia. *Journal of Sustainable Development*, *5*(7), 11.

Kapur, A., 2006. The future of the red metal: discards, energy, water, residues and depletion. Progress of Industrial Ecology – An International Journal 3, 209–236.

Kathiravale, S., Yunus, M. N. M., Sopian, K., Samsuddin, A. H., & Rahman, R. A. (2003). Modeling the heating value of Municipal Solid Waste☆. *Fuel*, *82*(9), 1119-1125.

Kathirvale, S., Yunus, M. N. M., Sopian, K., & Samsuddin, A. H. (2004). Energy potential from municipal solid waste in Malaysia. Renewable energy, 29(4), 559-567.

Kavazanjian Jr., E., (1999). “Seismic design of solid waste containment facilities.” In: Proceedings of the Eighth Canadian Conference on Earthquake Engineering, Vancouver, BC, June 1999, pp. 51–89.

Kelly, R. J., Shearer, B. D., Kim, J., Goldsmith, C. D., Hater, G. R., and Novak, J. T. (2006). "Relationships between analytical methods utilized as tools in the evaluation of landfill waste stability." Waste Manage., 26(12), 1349-1356.

Koganti, K. (2015). Characterization and comparison of fresh and landfilled solid waste (Master’s thesis)

Komilis, D. P., & Tziouvaras, I. S. (2009). A statistical analysis to assess the maturity and stability of six composts. Waste Management, 29(5), 1504-1513.

Komilis, D., Kissas, K., & Symeonidis, A. (2014). Effect of organic matter and moisture on the calorific value of solid wastes: An update of the Tanner diagram. *Waste management*, *34*(2), 249-255.

Komilis, D., Evangelou, A., Giannakis, G., & Lymperis, C. (2012). Revisiting the elemental composition and the calorific value of the organic fraction of municipal solid wastes. *Waste management*, *32*(3), 372-381

Korai, M. S., Mahar, R. B., Uqaili, M. A., & Brohi, K. M. (2015, September). Assessment of municipal solid waste management practices and Energy recovery potential in Pakistan. In Proceedings of the 14th international conference on environmental science and technology rhodes (pp. 3-5).

Krogmann, U., Qu, M., 1997. Landfill mining in the United States. Proceedings Sardinia ’97, Sixth International Landfill Symposium, Cagliari, 543–552.

Krook, J., Svensson, N., & Eklund, M. (2012). Landfill mining: a critical review of two decades of research. *Waste management*, *32*(3), 513-520.

Krüse, T. (2015). Landfill mining-how to explore an old landfill's resource potential. *Institute for Water Quality, Resource & Waste Management. TU Wien, Vienna*.

Kurian, J., Esakku, S., Palanivelu, K., & Selvam, A. (2003, October). Studies on landfill mining at solid waste dumpsites in India. In *Proceedings Sardinia* (Vol. 3, pp. 248-255).

Landva, A. O., & Clark, J. I. (1990). Geotechnics of waste fill. In *Geotechnics of waste fills—Theory and practice*. ASTM International.

Lariviere, M. (2007). Methodology for allocating municipal solid waste to biogenic and non-biogenic energy. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels. May. http://www. eia. doe. gov/cneaf/solar. renewables/page/mswaste/msw. pdf.

Lin, C. J., Chyan, J. M., Chen, I. M., & Wang, Y. T. (2013). Swift model for a lower heating value prediction based on wet-based physical components of municipal solid waste. *Waste management, 33*(2), 268-276.

Liu, J. I., Paode, R. D., & Holsen, T. M. (1996). Modeling the energy content of municipal solid waste using multiple regression analysis. *Journal of the Air & Waste Management Association*, *46*(7), 650-656.

Manassero, M., Van Impe, W.F., Bouazza, A., (1997). "Waste disposal and containment." Environmental Geotechnics, Kamon, M., A.A. Balkema, Rotterdam, 1425–1474.

Mboowa, D., Quereshi, S., Bhattacharjee, C., Tonny, K., & Dutta, S. (2017). Qualitative determination of energy potential and methane generation from municipal solid waste (MSW) in Dhanbad (India). Energy, 123, 386-391.

Majumder, A. K., Jain, R., Banerjee, P., & Barnwal, J. P. (2008). Development of a new proximate analysis based correlation to predict calorific value of coal. *Fuel*, *87*(13-14), 3077-3081.

Mboowa, D., Quereshi, S., Bhattacharjee, C., Tonny, K., & Dutta, S. (2017). Qualitative determination of energy potential and methane generation from municipal solid waste (MSW) in Dhanbad (India). *Energy*, *123*, 386-391.

Menikpura, S. N. M., & Basnayake, B. F. A. (2009). New applications of 'Hess Law'and comparisons with models for determining calorific values of municipal solid wastes in the Sri Lankan context. *Renewable energy*, *34*(6), 1587-1594.

Miller, L. V., Mackey, R. E., and Flynt, J. ~1991!. "Excavation & recycling feasibility study of a municipal solid waste landfill utilizing leachate recycling." Proc., Solid Waste Association of North America 29th Annual Int. Solid Waste Exposition, Cincinnati.

Miranda, R., & Blanco, A. (2010). Environmental awareness and paper recycling. *Cellulose Chemistry & Technology*, *44*(10), 431.

Mönkäre, T. J., Palmroth, M. R., & Rintala, J. A. (2016). Characterization of fine fraction mined from two Finnish landfills. *Waste Management*, *47*, 34-39.

Montejo, C., Costa, C., Ramos, P., & del Carmen Márquez, M. (2011). Analysis and comparison of municipal solid waste and reject fraction as fuels for incineration plants. Applied Thermal Engineering, 31(13), 2135-2140.

Mor, S., Ravindra, K., De Visscher, A., Dahiya, R.P., Chandra, A., 2006. Municipal solid waste characterization and its assessment for potential methane generation: a case study. Science of the Total Environment 371, 1–10.

Obermeier, T. (1995). Landfill reconstruction: biological treatment of landfill waste. In Proceedings, Sardinia'95, 5th International Landfill Symposium, Caglari (pp. 819-826).

Omari, A., Said, M., Njau, K., John, G., & Mtui, P. (2014). Energy recovery routes from Municipal Solid Waste, A case study of Arusha-Tanzania. Journal of Energy Technologies and Policy, 4(5), 1-7.

Özyuğuran, A., & Yaman, S. (2017). Prediction of Calorific Value of Biomass from Proximate Analysis. *Energy Procedia*, *107*, 130-136.

Parr Instrument Company. (2013). Calorimeter: Introduction to Colorimetry. Molin, IL

Peces, M., Astals, S., & Mata-Alvarez, J. (2014). Assessing total and volatile solids in municipal solid waste samples. *Environmental technology*, *35*(24), 3041-3046.

PerkinElmer Instrument. (2002). Elemental Analyzer: 2400 Series II CHNS/O Analyzer. Shelton,CT

Prechthai, T., Padmasri, M., Visvanathan, C., 2008. Quality assessment of mined MSW from an open dumpsite for recycling potential. Resource, Conservation and Recycling 53, 70e78.

Quaghebeur, M., Laenen, B., Geysen, D., Nielsen, P., Pontikes, Y., Van Gerven, T., & Spooren, J. (2013). Characterization of landfilled materials: screening of the enhanced landfill mining potential. *Journal of Cleaner Production*, *55*, 72-83.

Reeves, T. S., & Murray, G. C. (1997). Landfill mining–a tool for rural landfill management and closure. In *Proceedings of the Air and Waste Management. Association's 90th Annual Meeting and Exhibition. Toronto, Canada*.

Reis, V. J. (1995). "Summary of landfill reclamation feasibility studies." Draft Rep. for the New York State Energy Research and Development Authority, Albany, N.Y.

Richard, D., Ambrosie, R., Zavoral, P., & Zimmerman, R. (1996). Fargo takes a second look at the old landfill site. In *INTERNATIONAL MADISON WASTE CONFERENCE MUNICIPAL AND INDUSTRIAL WASTE* (pp. 197-205). DEPARTMENT OF ENGINEERING PROFESSIONAL DEVELOPMENT.

Rosendal, R. M. (2009). Landfill Mining-Process, Feasibility, Economy, Benefits and Limitations.

Rettenberger, G. (1995). Results from a landfill mining demonstration project. In *Proc. of Fifth International Landfill Symposium, I* (pp. 827-840).

Sapkota, A., 2017. "Effect of Manure and Enzyme on the Degradation of Organic Fraction of Municipal Solid Waste in Biocell." MS Thesis, University of Texas at Arlington, Spring, 2017.

Savage, G. M. (1993). Landfill mining: past and present. *Biocycle, 1993*.

Salerni, E. (1997). "Town of Hague landfill reclamation study: Researching ways to increase waste heating value and reduce waste volume.” 97–1, New York State Energy Research and Development Authority, Albany, N.Y.

Samir, S. (2011). Characterization And Evaluation Of Gas Generation Potential Of Municipal Solid Waste From A Closed Section Of A Landfill.

Schillinger, F. J., & McCulloch, B. P. (1994). Summary of landfill reclamation feasibility studies.

Shi, H., Mahinpey, N., Aqsha, A., & Silbermann, R. (2016). Characterization, thermochemical conversion studies, and heating value modeling of municipal solid waste. *Waste management*, *48*, 34-47.

Sormunen, K., Ettala, M., & Rintala, J. (2008). Detailed internal characterisation of two Finnish landfills by waste sampling. *Waste Management*, *28*(1), 151-163.

Spencer, R. (1990). Landfill space reuse. *Biocycle*, *31*(2), 30-33.

Tchobanoglous, G. (1993). Integrated solid waste management engineering principles and management issues (No. 628 T3).

Townsend, T. G., Miller, W. L., Lee, H. J., and Earle, J. F. K. (1996). "Acceleration of landfill stabilization using leachate recycle." J.Environ.Eng., 122(4).

Van Passel, S., Dubois, M., Eyckmans, J., De Gheldere, S., Ang, F., Jones, P. T., & Van Acker, K. (2013). The economics of enhanced landfill mining: private and societal performance drivers. Journal of cleaner production, 55, 92-102.

Vargas-Moreno, J. M., Callejón-Ferre, A. J., Pérez-Alonso, J., & Velázquez-Martí, B. (2012). A review of the mathematical models for predicting the heating value of biomass materials. Renewable and sustainable energy reviews, 16(5), 3065-3083.

Von Stein, E. L., Savage, G. M., and Solid Waste Association of North America ~1993. "Evaluation of the Collier County, Florida landfill mining demonstration." EPA/600/R-93

Xiang-rong, Z., Jian-min, J., Peng-fei, F. (2003). "Geotechnical behavior of the MSW in Tianziling Landfill." Journal of Zhejiang University SCIENCE., 4(3), 324-330.

Yi, L., Feng, J., Qin, Y. H., & Li, W. Y. (2017). Prediction of elemental composition of coal using proximate analysis. *Fuel*, *193*, 315-321.

Zanetti, M. C., Marchese, F., and Genon, G. ~1997!. "Investigation on quality of landfilled MSW." Proc., 6th Int. Landfill Symp., S. Margherita di Pula, Italy, Environmental Sanitary Engineering Centre, Cagliari, Italy, 155–162

Zhao, Y., Song, L., Huang, R., Song, L., Li, X., 2007.Recycling of aged refuse from a closed landfill. Waste Management Research 25, 130–138

Zhou, C., Fang, W., Xu, W., Cao, A., & Wang, R. (2014). Characteristics and the recovery potential of plastic wastes obtained from landfill mining. *Journal of cleaner production*, *80*, 80-86.

Zhu, X. R., Jin, J. M., & Fang, P. F. (2003). Geotechnical behavior of the MSW in Tianziling landfill. *Journal of Zhejiang University-SCIENCE A*, *4*(3), 324-330.

Zornberg, J., Jernigan, B. L., Sanglerat, T. R., and Cooley, B. H. ~1999!. “Retention of free liquids in landfills undergoing vertical expansion.” J. Geotech. Geoenviron. Eng. 125~7!, 583–594.

Biographical Information

Rakib was born in Dhaka, Bangladesh on November 19, 1988. He earned her Bachelor's degree in Civil Engineering from Bangladesh University of Engineering and Technology in February, 2011. After completing his bachelor, he worked as Assistant Engineer (Civil) in Roads and Highways Department of Government Republic of Bangladesh. In 2015 he joined The University of Texas at Arlington (UTA) as doctoral student in Civil Engineering under the supervision of Dr. Sahadat Hossain. He was the Team leader of ''SWIS'' team from UTA which placed 2nd in the SWANA International Solid Waste Design Competition held in WASTECON 2017.He was also the member in ''SWIS'' team which became 1st in SWANA National Solid Waste Design Competition 2016.He was awarded ''Outstanding Graduate Student'' at The University of Texas at Arlington(UTA) in 2016-17 .The author's research interests include municipal solid waste, landfill mining and reclamation, energy and resource extraction, bioreactor landfills or enhanced leachate recirculation landfills.