



Faculty of Engineering

Characterisation and Analysis of Municipal Solid Waste in Kuching

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**Master of Engineering
2023**

Characterisation and Analysis of Municipal Solid Waste in Kuching

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A thesis submitted

In fulfillment of the requirements for the degree of Master of Engineering

Faculty of Engineering
UNIVERSITI MALAYSIA SARAWAK
2023

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ACKNOWLEDGEMENT

First I would like to take this opportunity to express my sincere gratitude to Associate Professor Ir Dr Lim Soh Fong, for the advice, guidance and encouragement during my period of Master's study at Universiti Malaysia Sarawak.

I would like to thank the management of Trienekens (Sarawak) Sdn Bhd for funding this study and my site supervisor, Mr Simon Chow for his support and help throughout this study. Special thanks to my colleagues who helps with the sample collection and sorting during my study.

Finally, I would like to thank the management of the Universiti Malaysia Sarawak for making it possible for me to complete my study. Thank you all.

ABSTRACT

The composition of waste disposed of is crucial for planning and decision-making of a sustainable waste management system. The municipal solid waste (MSW) from three principal council areas in Kuching, which are Kuching South City Council (KSCC), Kuching North City Hall (KNCH), and Padawan Municipal Council (PMC) are collected and characterised. This waste composition is evaluated for the sample collected directly from the source and lab analysis is conducted on the sample collected from the landfill. The municipal solid waste samples are collected directly from the pre-categorised source location according to the socio-economic level. The municipal solid waste generated in Kuching city has been analysed by using both qualitative and quantitative analysis, as well as characterising the municipal solid waste samples based on their physical, chemical, and thermal characteristics. This study discovered that there is no significant difference in the waste composition trend generated in different residential areas. Organic waste is found to be the highest waste component in all socio-economic groups. For the residential areas, the top three waste compositions are organic wastes (61.58% w/w), plastics (12.06% w/w), and nappies/sanitary napkins (11.67% w/w). The sample collected from the landfill is divided into two groups, the sample from the new landfill where the solid waste was disposed of in recent two years and the old landfill where the solid waste was disposed of more than 5 years. The moisture content, volatile matter, ash, and fixed carbon content were 54.71%, 26.42%, 18.67% and 0.21% respectively for the old landfill and 63.26%, 22.83%, 13.73% and 0.18% for the new landfill sample. The calorific value for the old landfill sample is found 2041.86 kcal/kg and the calorific value for the new landfill sample is found 2891.9 kcal/kg. Thus, the thorough evaluation in this study reveals that landfill waste is not suitable for waste to energy incineration process. The amount of solid waste

generated in Kuching city is increasing in trend as the population in Kuching city is increased. A sustainable waste management system with a zero-waste approach is proposed in Kuching city.

Keywords: Kuching, municipal solid waste, waste characterisation, proximate analysis, thermal analysis

Pencirian dan Analisis Sisa Pepejal Perbandaran di Kuching

ABSTRAK

Sisa pepejal perbandaran dari tiga kawasan majlis utama di Kuching, iaitu Majlis Bandaraya Kuching Selatan (KSCC), Dewan Bandaraya Kuching Utara (KNCH), dan Majlis Perbandaran Padawan (PMC) dikumpul dan dicirikan. Sampel sisa pepejal dikumpulkan terus dari lokasi sumber dan analisis lab dijalankan kepada sampel dari tapak pelupusan sampah. Sisa pepejal perbandaran dikumpulkan dari tempat persampelan yang dikategorikan mengikut tahap sosio-ekonomi. Sisa pepejal perbandaran yang dijana di bandaraya Kuching telah dianalisis dengan menggunakan analisis kualitatif dan kuantitatif, serta pencirian sisa pepejal perbandaran berdasarkan ciri fizikal, kimia dan habanya. Kajian ini mendapati tiada perbezaan yang ketara dalam trend komposisi sisa yang dicipta oleh penduduk di kawasan kediaman yang berbeza. Sisa organik didapati merupakan komponen sisa yang tertinggi dalam semua kumpulan sosio-ekonomi. Tiga komposisi sisa pepejal yang tertinggi ialah sisa organik (61.58 % b/b), plastik (12.06 % b/b), dan lampin (11.67 % b/b). Sampel yang dikumpulkan dari tapak pelupusan sampah dibahagikan kepada dua kumpulan, sampel dari tempat pelupusan baru iaitu sisa pepejal yang dilupuskan dalam lingkungan dua tahun lalu dan tempat pelupusan lama iaitu sisa pepejal yang dilupuskan lebih dari 5 tahun. Kandungan kelembapan, bahan meruap, abu dan kandungan tetap karbon adalah 54.71%, 26.42%, 18.67% and 0.21% untuk sampel dari tapak pelupusan lama and 63.26%, 22.83%, 13.73% and 0.18% untuk sampel dari tapak pelupusan baru. Nilai kalori untuk sampel dari tapak pelupusan lama adalah 2041.86 kcal/kg dan nilai kalori untuk sampel dari tapak pelupusan baru adalah 2891.9 kcal/kg. Kajian ini mendapati sampah di tapak pelupusan adalah tidak sesuai untuk loji pembakaran sisa pepejal kepada tenaga. Jumlah sisa pepejal di bandar raya Kuching

semakin meningkat apabila jumlah penduduk di bandar raya Kuching meningkat. Sistem pengurusan sisa dengan pendekatan sifar sisa telah dicadangkan di bandar raya Kuching.

Kata kunci: *Kuching, sisa pepejal perbandaran, pencirian sisa, analisis proksimat, analisis haba*

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LIST OF ABBREVIATIONS

% w/w	% weight/weight
ASTM	American Standard Test Method
CMCO	Conditional Movement Control Order
DOSM	Department of Statistics Malaysia
ED-XRF	Energy Dispersive X-ray Fluorescence
EPA USA	American Environmental Protection Agency
GDP	Gross Domestic Product
HDPE	High-Density Polyethylene
HHW	Household Hazardous Waste
HHV	Higher Heating Value
KIWMP	Kuching Integrated Waste Management Park
KNCH	Kuching North City Hall
KPKT	Housing and Local Government Ministry
KSCC	Kuching South City Council
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
LHV	Lower Heating Value
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
NREB	Natural Resources and Environment Board
PET	Polyethylene Terephthalate
PMC	Padawan Municipal Council
PP	Polypropylene

PPE	Personal Protective Equipment
PS	Polystyrene
PVC	Polyvinyl Chloride
RDF	Refuse-Derived Fuel
RMCO	Recovery Movement Control Order
RORO	Roll on, Roll off
SDG	Sustainable Development Goals
SWA	Solid Waste Analysis
SWCORP	Solid Waste Management and Public Cleansing Corporation
WEEE	Waste from Electrical and Electronic Equipment
WTE	Waste-to-Energy

CHAPTER 1

INTRODUCTION

1.1 Study Background

According to the World Bank Group (2022), 2.24 billion tonnes of solid waste is generated per day in the year 2020. In the year 2018, approximately 0.74 kg of solid waste per capita in a day is generated (Kaza et al., 2018) and it increased to 0.79kg of solid waste per capita in a day in the year 2020. The annual waste generation is expected to increase to 3.88 billion tonnes in the year 2050.

According to the Strategic Planning and International Division, Ministry of Housing and Local Government in their KPKT Statistic 2020 report, an estimated 14.4 million tonnes of solid waste is generated in Malaysia annually. The solid waste generation rate is calculated at 1.22kg/capita/day as the population in Malaysia is 32.4 million in the year 2020 (DOSM, 2022). The number is higher than the global waste generation estimated by the World Bank Group. As the population of Malaysia is increasing by 1.7% annually (DOSM, 2022), there will be more solid waste generated if there is no significant change in the behaviour of Malaysian toward solid waste management. In Kuching, a report by Tang (2020) revealed that 690,000 kg of municipal solid waste was generated in the city every day. This study evaluated and analysed the current waste trend and compare the differences between the selected waste streams which prioritise recovery, and recyclable opportunities and suggest new strategies for waste management forethought.

1.2 Problem Statement

Moving forward to achieve sustainable development in Malaysia, 6 states in Malaysia, which are Johor, Perlis, Kedah, Pahang, Melaka and Negeri Sembilan and the Federal Territories of Kuala Lumpur and Putrajaya have started implementing waste segregation at source in the year 2015 under Solid Waste and Public Cleansing Management Act 2007 (Act 672). According to the annual report 2020 by Solid Waste Management and Public Cleansing Corporation (SWCORP), the recycling rate in Malaysia is in an increasing trend since the year 2015, mainly due to the implementation of the waste segregation practice. Referring to Figure 1.1, the recycling rate of Malaysia attained 30.7% in the year 2020.

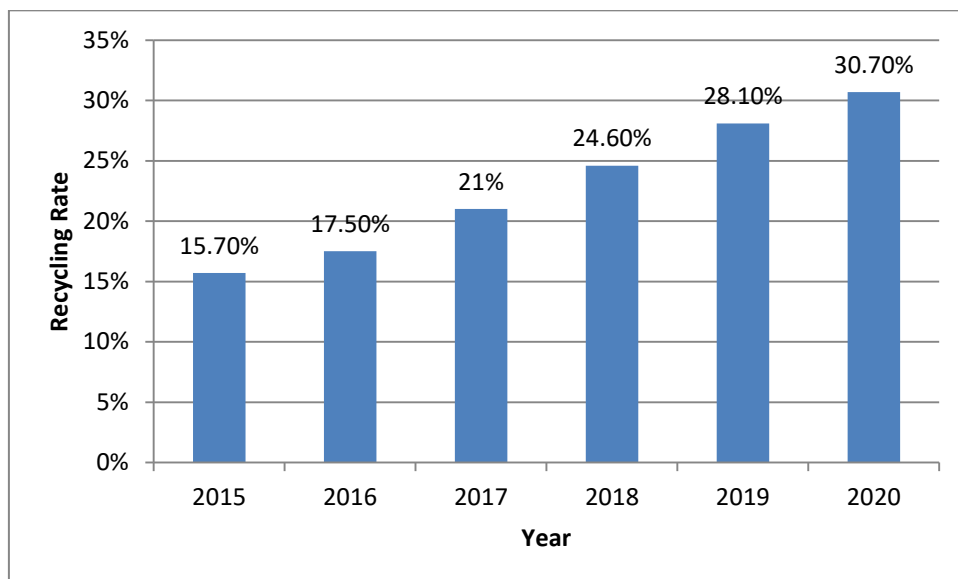


Figure 1.1: Recycling Rate Malaysia (SWCORP, 2022)

Although the recycling rate of Malaysia is increased, the recycling rate is still low when compared to Singapore, which has a recycling rate of 55% w/w in the year 2020. (National Environment Agency, 2022). The composition of plastic waste in municipal solid waste is remained high as well, recorded as 22.6% w/w (SWCORP, 2022).

Compared with Peninsular Malaysia, Sarawak is yet to change its regulation to enforce recycling activity. There is no recent municipal solid waste composition study at the Local Authority level as well (Tang, 2020). As there are differences in social and economic activities between Peninsular Malaysia and Sarawak, the waste composition in Peninsular Malaysia might be different from the waste composition in Sarawak or Kuching city.

Disposal of waste is the last option in the solid waste management hierarchy as it is not a sustainable solution for solid waste. Nowadays, even though the concept of waste-to-energy is prioritized over the recycling concept, the Housing and Local Government Ministry (KPKT) of Malaysia had planned to set up six waste-to-energy (WTE) plants by 2025 (The Malaysian Reserve, 2022). During the year the 1990s, four municipal solid waste incineration pilot plants are built at Langkawi, Tioman, Pangkor and Labuan. All of the pilot incineration plants were discontinued due to the high moisture content of the municipal solid waste, which lead to high fuel consumption in the incineration process. There is no expertise to operate the incineration plants as well (Shafie, 2019).

Although having similar weather conditions to Malaysia, Singapore has run their WTE incineration plant for solid waste disposal successfully. Compare with Malaysia, their solid waste is segregated before it is sent for disposal and the composition of food waste is only 21% (National Environment Agency, 2022) which indicates the lower moisture content of their solid waste. Hence, the key factor of a successful WTE plant is waste segregation to sort out the organic waste with high moisture content to increase the calorific value of the solid waste.

The landfill in Kuching which is located at Kuching Integrated Waste Management Park (KIWMP) has been operated since the year 2003. As it has been in operation for more than 20 years, the physical, chemical and thermal characteristics of the disposed solid waste might change over a long period via the bio-chemical degradation process.

1.3 Research Gap

The recent characteristic study of solid waste at source and solid waste disposed of in landfill is required for the implementation of sustainable and zero waste management in Sarawak. The facts about the composition of waste disposed of are crucial for planning and decision-making of a sustainable waste management system. Efficient methods are needed to assess the effect of legislative, logistic, and technical measures on the waste streams. The effect of such measures can be assessed by routine determination of solid waste composition and trends. (Brunner et al., 2004).

However, there is no recent details study on the solid waste composition in Kuching city. The most recent waste composition study specifically for Kuching city was conducted in the year 2003 by a consultant company, COWI. The current solid waste composition in Kuching city is unknown.

Yi (2019) reported that average 39.1% w/w of the solid waste in the studied landfills in Korea are combustible waste and the waste are recommended to be incinerated in waste to energy incineration plant for energy recovery. However, in Kuching, there is no study of the disposed waste at the landfill to determine the suitability of the disposed waste as a feedstock for waste to energy incinerator plants.

A study by Tufaner (2021) concluded that zero waste target is possible to achieve by combination of waste reduction, waste recycling, biogas harvesting from anaerobic digestion, and organic fertilizer production. However there is no similar study has been done for Kuching city. This research is conducted to study the solid waste composition in Kuching city and proposed zero waste management in Kuching by using the latest solid waste composition data from this study.

1.4 Hypothesis

This study is designed to access the hypothesis that:-

- i) The composition of solid waste in Kuching city is similar to the national solid waste composition, with organic waste as the highest fraction of the waste, followed by plastic and paper.
- ii) The amount of solid waste generated in Kuching city is increasing in trend as the population in Kuching city is increased.
- iii) The solid waste disposed at the landfill can be considered as a feedstock for waste to energy incinerator plants.
- iv) A sustainable waste management system with a zero-waste approach is feasible in Kuching city.

1.5 Research Objectives

The main focus of this project is to characterise and quantify the solid wastes generated in the city of Kuching in the state of Sarawak, Malaysia in establishing the trends of municipal solid waste generated and to propose a sustainable solid waste

management system with a zero waste proposition. The project, therefore, aims to accomplish four specific goals as stated below:

- i) Quantifying solid wastes generated for a better understanding of the types and amounts of generated wastes using both qualitative and quantitative analysis;
- ii) Analysing as well as characterising solid waste samples based on their physical, chemical, and thermal characteristics along with establishing the trends in the quantity of municipal solid wastes generated; and
- iii) Proposing a sustainable solid waste management system with zero waste.

1.6 Scope of Study

The present study focused on the characterization of municipal solid waste generated in Kuching city. A sampling plan is established based on the social-economic level of the study area. The sampling period for the municipal solid waste from source is from October 2020 to November 2020. For the physical and chemical laboratory analysis, the sampling is done at a sanitary landfill in Kuching. The physical, chemical and thermal characteristic of the solid waste from landfill is analysed. A waste management plan is proposed based on the output from the solid waste characterization output and the physical, chemical and thermal characteristics of the municipal solid waste generated in Kuching city.

CHAPTER 2

LITERATURE REVIEW

2.1 Solid Waste

2.1.1 Definition and Criteria

Solid Waste and Public Cleansing Management Act 2007 [Act 672] is introduced by the Malaysia government in the year 2007. As defined in the act, solid waste includes:

- (i) Any scrap material or other unwanted surplus substance or rejected products arising from the application of any process.
- (ii) Any substance required to be disposed of as being broken, worn out, contaminated or otherwise spoiled.
- (iii) Any other material that according to this Act or any other written law is required by the authority to be disposed of, but does not include scheduled wastes as prescribed under the Environmental Quality Act 1974 [Act 127], sewage as defined in the Water Services Industry Act 2006 [Act 655] or radioactive waste as defined in the Atomic Energy Licensing Act 1984 [Act 304];

Typically solid waste can be divided into two main groups, which are municipal solid waste and hazardous solid waste. Municipal solid waste is the solid waste collected from municipalities including household waste, commercial waste and construction waste meanwhile hazardous solid waste is the solid waste that has potential threats to public health or the environment which includes industrial waste, biomedical waste and special waste. Solid wastes were classified as hazardous waste if they exhibited one or more of the following characteristics, ignitability, corrosivity, reactivity or toxicity.

2.1.2 Composition

The common composition of solid waste is organic waste, green waste, wood, plastic, paper, glass, metal, rubber, textile, leather and others. Typically the three highest compositions of municipal solid waste are organic waste, plastic and paper. Figure 2.1 shows the global waste composition (Kaza et al., 2018).

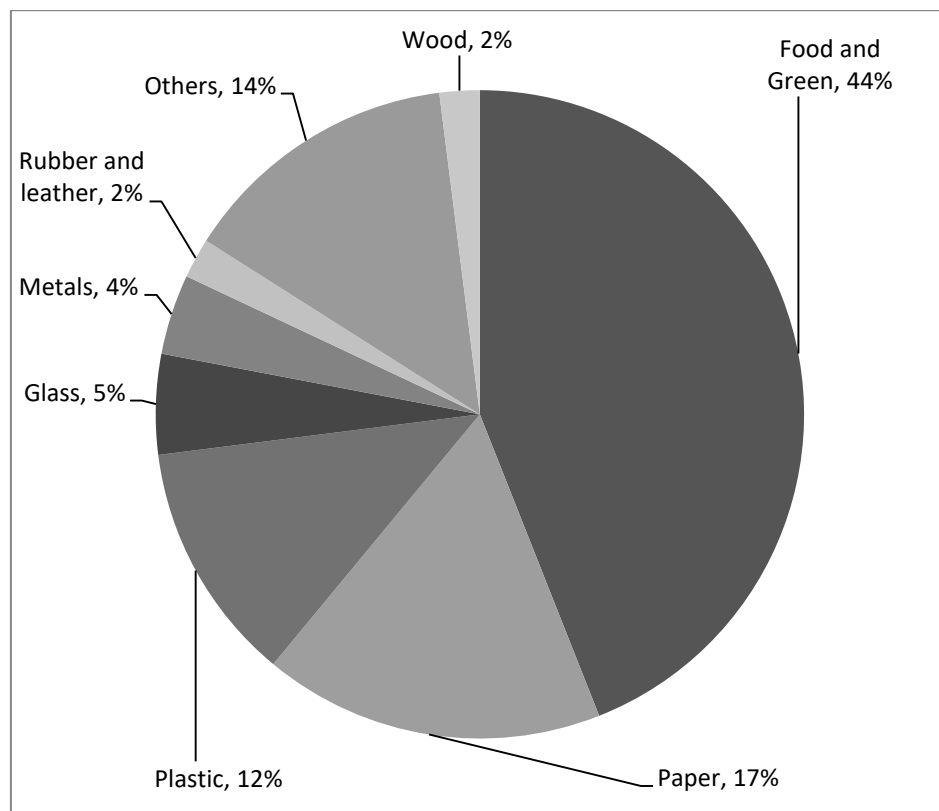


Figure 2.1: Global Waste Composition

National Solid Waste Management Department, Malaysia has reported on a waste composition study for Malaysia. Table 2.1 shows the waste composition study for Sarawak, Sabah and Peninsular Malaysia as reported by National Solid Waste Management Department, Malaysia (2013). This study classified solid waste into 7 main

categories which are organic waste, glass, metal, paper, plastic, Household Hazardous Waste (HHW), and others which included rubber, leather, textile, tetra pack, diapers. For all three regions in Malaysia, the top three highest waste composition is similar to the global waste composition. The highest waste composition is organic waste, followed by plastic waste and paper waste.

Table 2.1: Waste Composition in Malaysia (National Solid Waste Management Department, Malaysia, 2013)

Region	Waste Composition (% w/w)						
	Organic waste	Glass	Metal	Paper	Plastic	HHW	Others
Sarawak	42.3	5	5.5	10.8	16.4	1.8	18.2
Sabah	44.8	3.9	3.9	9.6	17.6	0.7	19.6
Peninsular Malaysia	51.6	3.2	2.6	9.4	12.6	1.3	19.3

The previous waste composition study specifically for Kuching city was conducted in the year 2003 by COWI. Table 2.2 shows the solid waste composition study in Kuching for the year 2013.

Table 2.2: Waste Composition in Kuching

Region	Waste Composition (% w/w)					
	Organic waste	Glass	Metal	Paper	Plastic	Others
Kuching	51.3	3.1	3.1	13.5	19.7	9.5

When we compare the waste composition study in the year 2003 in Kuching (Table 2.2) and the year 2013 in Sarawak (Table 2.1), it is observed that organic waste remained

the highest portion of the solid waste, which is about half a fraction of the solid waste. However, the waste composition for paper and plastic is reduced, most probably due to the increase in recycling activities. The diaper composition which did not been categorized previously, currently is about 10% w/w of the waste fraction.

A global waste composition study has been done by Kaza et al. (2018). Table 2.3 shows the waste composition in different regions. The waste composition is different according to the socio-economic group. The organic waste composition is decreased at the high-income level region and increased at the low-income level region.

Table 2.3: Waste Composition in Different Regions (Kaza et al., 2018)

Region	Waste Composition (% w/w)						
	Organic food	Glass	Metal	Paper	Plastic	Rubber	Wood
East Asia	53	2.6	3	15	12	<1	2
South Asia	57	4	3	10	8	2	1
Europe and Central Asia	36	8	3	18.6	11.5	<1	1.6
Latin America and the Caribbean	52	4	3	13	12	<1	<1
Middle East and North Africa	58	3	3	13	12	2	1
North American	28	4.5	9.3	28	12	9	5.6

2.1.3 Commercial and Institutional Solid Waste

Commercial activities are referring to the trading of products or providing services. Commercial activities can be divided into four groups, which are commercial entities,

markets, hotel and petrol station. Commercial entities are the individual premises used for retail, restaurant, food centre, government office and included shopping malls. The market consists of individual stalls for trading fresh produce and some consumable products. A hotel is defined as providing more than 30 rooms and is normally located in the city centre. The petrol station is the station for adding fuel for transportation with a small retail shop.

According to the report by National Solid Waste Management Department, Malaysia (2013), the average commercial waste composition is summarised as displayed in Figure 2.2.

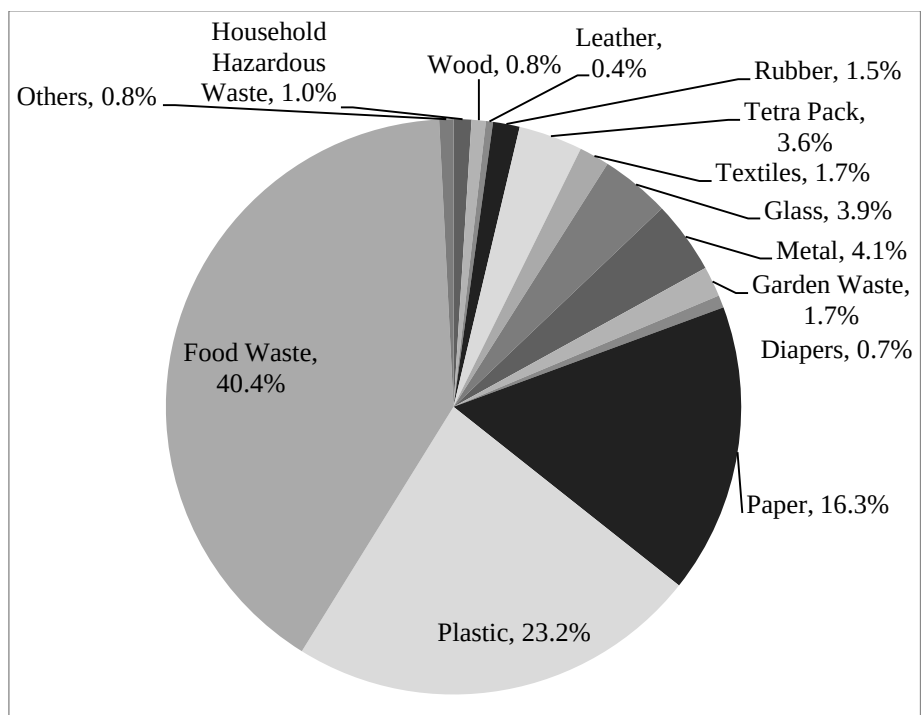


Figure 2.2: Commercial Waste Composition (National Solid Waste Management Department, Malaysia, 2013)

Meanwhile, for the institution area, it referred to facilities and services for public needs. It included the medical services sector and education sectors, such as hospitals,

clinics, schools and universities. The average institutional waste composition is summarised as displayed in Figure 2.3.

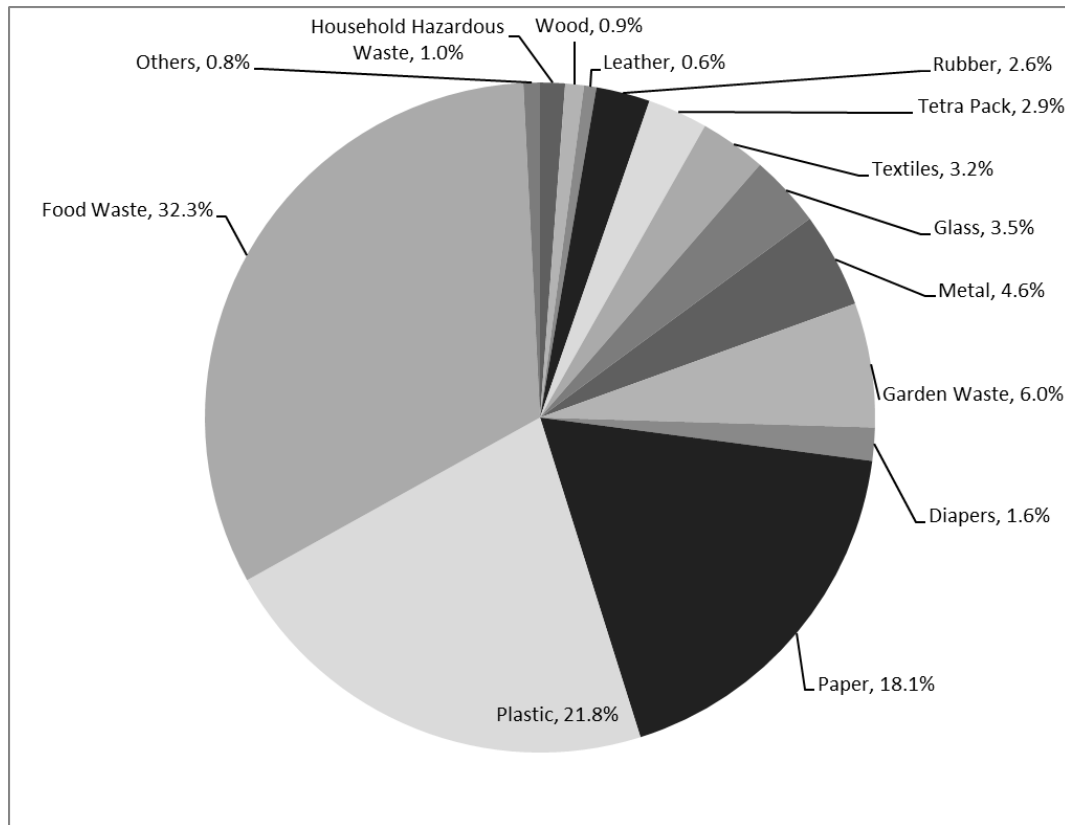


Figure 2.3: Institutional Waste Composition (National Solid Waste Management Department, Malaysia, 2013)

2.2 Solid Waste Management

2.2.1 Global Perspective

Solid waste management system involves six functional elements as follows:

- (i) Waste generation - Activities in which materials are identified as no longer being of value and are being thrown away.

- (ii) Waste handling, sorting, storage, and processing at the source - Activities associated with the handling, sorting, storage and processing of solid waste at or near the point of generation.
- (iii) Collection - Activities associated with the gathering of solid waste and transfer of these materials after collection to the location for emptying the collection vehicle.
- (iv) Transportation - Activities associated with the transport of waste to the disposal site.
- (v) Material recovery – Activities to recover usable materials or energy from solid waste away from the source of waste generation, normally occurs at materials recovery facility.
- (vi) Disposal - Those activities associated with the ultimate disposal of solid wastes, normally is landfilling or uncontrolled dumping.

As the global total solid waste generated is increased every year, solid waste has become one of the greatest threats to our environment if it is not being managed properly. Therefore it is very important to develop sustainable solid waste management. In the waste hierarchy, waste minimization is the most preferable option and disposal of the waste is the least option, as illustrated in Figure 2.4.

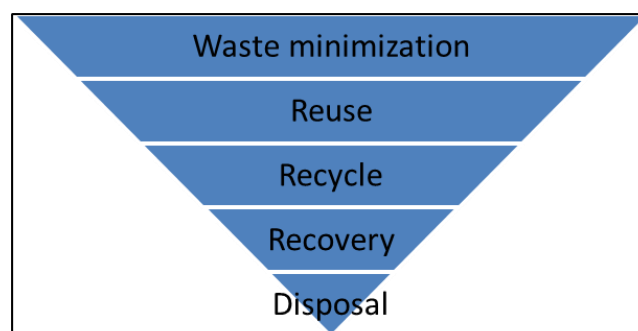


Figure 2.4: Waste Hierarchy

The zero-waste concept was first introduced by Zero Waste International Alliance in the year 2002. Zero waste is defined as the conservation of all resources through responsible production, consumption, reuse and recovery of all products, packaging and materials, without burning them and without discharges to land, water or air that threaten the environment or human health (Zero Waste International Alliance, 2018). The zero-waste 7Rs concept, which is 'Reduce', 'Reuse', 'Recycle', 'Rethink', 'Recovery', 'Residuals management', and 'Regulations' is promoting the conservation of natural resources.

The regulations and policies of a nation are playing essential roles in solid waste management. In September 2015, 17 Sustainable Development Goals (SDGs) were introduced by United Nations to promote sustainable practice. United Nations Environment Programme, the environmental authority of the United Nations system is taking the lead on 25 SDG indicators that are linked with 6 SDGs out of the 17 SDGs. The indicators included topics related to resource management, circular economy, efficient use of natural resources and environmentally sound management of chemicals and waste.

In a European country, the waste framework directive was first introduced in the year 1975 and used as the guideline for their waste management system. In the year 2005, Germany implemented a landfill ban to prevent untreated municipal waste disposed of at landfill. The current framework directive used by European countries is Waste Framework Directive (2008/98/EC) which promotes sustainable products by extending the producer responsibility.

China's industries used to import solid waste such as plastic, paper and metal waste from developed countries. In the year 2015, more than 70 percent of the plastic waste was exported to China, which created environmental pollution in the country. The government,

therefore, come with an import ban on foreign waste in July 2017 and launched Blue Sky 2018 to create a better environment in the country. Blue Sky Policy was aiming to prevent the illegal smuggling of the banned recovered material into China.

2.2.2 National Perspective - Malaysia

In Malaysia, the 3R concept which is recycling, reducing and reusing solid waste is first mentioned in the 8th Malaysian Plan (2001-2005). Following that, the Solid Waste and Public Cleansing Management Act is introduced in the year 2007. National Solid Waste Management Department is established under the Ministry of Housing and Local Government to plan and implement the solid waste management policy. In the latest 12th Malaysian Plan (2021-2025), the transformation from a linear economy to a circular economy is emphasized. The circular economy will follow the reduce, reuse and recycle (3R) approach, whereby resource use is minimised, reuse of products maximised and materials are recycled into the manufacturing loop. The single-use products, including plastics and packaging materials in eateries and at public events are discouraged.

In Peninsular Malaysia, the recycling rate is found increased significantly after enforcement of Act 672 by SWCORP. However, plastic waste is found to remain a high percentage of municipal solid waste although several campaigns have been taken such as the launching of the no plastic bag campaign day since the year 2011. Majority of the Malaysian are willing to pay for extra RM0.20 for plastic bags. The same condition is found in Kuching city, "No Styrofoam" and "No Plastic Bag Day" Campaign has been launched in the year 2018 by Padawan Municipal Council, but plastic waste remains a great threat. In October 2018, Roadmap Towards Zero Single-Use Plastics 2018 – 2030 is officially launched by the Ministry Of Energy, Science, Technology, Environment &

Climate Change, Malaysia. Through this roadmap, pollution charges will be incurred by consumers and manufacturers of single-use plastics.

Late in the 1990s, four municipal solid waste incineration pilot plants are built at Langkawi, Tioman, Pangkor and Labuan. The incinerator plants were built to reduce the municipal waste volume due to limited space for landfill disposal at the selected island. All of the pilot plants were discontinued due to high operation costs and a lack of expertise. Following the establishment of the National Solid Wastes Management Department, four new incinerator plants are built from the year 2008 to 2012, located at Langkawi, Tioman, Pangkor and Cameron Highland. However, the incinerator plants are not able to run autogenously as designed by the appointed contractor due to the high moisture content of municipal solid waste. Consequently, the incinerator plant planned to be built at Labuan is cancelled (Kementerian Kesejahteraan Bandar, Perumahan & Kerajaan Tempatan, 2014). New contractors were appointed to revamp and operate the incinerator plants after the termination of the contract in the year 2014 to the year 2015. The incinerator at Tioman started to operate in the year 2018, the incinerator at Pangkor and Cameron Highland started to operate in the year 2020 and the incinerator at Langkawi started to operate in the year 2021. Additional fuel is required for the incinerator to maintain the temperature in the incinerator.

The Housing and Local Government Ministry had planned to set up six waste-to-energy (WTE) plants towards 2025. The first WTE plant is built at Tanah Merah, Negeri Sembilan which is planned to be in operation by the year 2022. The other five WTE plants are planned to be set up at Sungai Udang, Melacca, Rawang, Selangor, Bukit Payong, Johor, Seelong, Johor, Semeling, Kedah and Gebeng, Pahang.

According to the report KPKT Statistics 2020 (Strategic Planning and International Division, Ministry of Housing and Local Government), there is 138 landfills in operation and 173 landfill were closed. As there are so many saturated landfills in Malaysia, the landfill mining concept can be considered to reclaim the land. The concept of landfill mining has been introduced since the year 1953, initiated in Israel to obtain fertilizers for orchards. Landfill mining is defined as a process of extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground. However, the material extracted might have different characteristics after the biochemical process in the landfill. For instance, the plastic recovered from landfill mining have different characteristics from the recycled plastic collected from the source (Zhou et al., 2014). By using innovative transformation technologies, landfill mining is evolved and enhanced landfill mining which the landfilled waste stream is transformed into new material or energy. Landfill mining not only can recover the material, but it also reclaims the landfilled land. As summarized by Márquez et al. (2019), landfill mining is mainly done in European countries and America. In South East Asia, only Thailand has carried out landfill mining activity. Currently, there is no landfill mining activity in Malaysia.

2.2.3 Local Perspective - Kuching

In Sarawak, the Natural Resources and Environment Board (NREB), Sarawak was established on 1st February 1994 according to Section 3(1) of the Natural Resources and Environment Ordinance, 1993 under Chapter 84, Law of Sarawak 1958. One of the roles of NREB is to monitor the disposal of solid waste in Sarawak. The solid waste in Sarawak is mainly disposed of at dumpsites and landfill, as it is the simplest and cheapest way to dispose of the solid waste.

In Kuching, the solid waste management system is under the local authority's responsibility. Local authorities assigned service contractors to collect and dispose of the solid waste. The solid waste in Kuching is disposed of at Matang dumpsite before a level 4 landfill located at KIWMP is built in the year 2003. The leachate generated from the landfill is treated in a leachate wastewater treatment plant before it is discharged into the river. Approximately 80 per cent of the solid waste in Kuching City is disposed of in the landfill, while the remaining waste is disposed of through open dumping or collected for recycling.

As the landfill has been operated for more than 20 years, landfill mining can be considered for the landfill. Generally, landfill mining was not commonly applied due to the limitation of technology and cost efficiency. The success of landfill mining is very much depending on the characteristic of the extracted waste from the landfill. A study by Putra (2018) on the Piyungan landfill, in Yogyakarta, Indonesia revealed that the solid waste in the landfill is dominated by soil and plastic waste. The soil is mainly from the composting of organic matter and soil cover in landfill operations. However different type of landfill operation method is implemented at the landfill in Kuching. There is no soil used for waste covering in the landfill. Therefore the physical, chemical and thermal characteristic of the solid waste in a landfill is important to determine the suitable treatment method for the solid waste in the landfill.

2.3 Quantification of Solid Wastes

2.3.1 Sampling Method

For municipal solid waste composition analysis, it is not practical to analyse the whole solid waste generated in Kuching city. Therefore sampling technique is applied to calculate the total solid waste composition.

Basically, there are four sampling procedures:

(i) Truckload method

The whole content of the waste collection truck is sorted for waste composition study.

(ii) Cone and quartering method

The whole content of the waste collection truck is unloaded in a clean and flat area. The waste is quartering until the desired amount for waste sorting.

(iii) Spot sampling method

The solid waste sample is collected from a few waste collection trucks to form a composite sample for the sorting process.

(iv) Laboratory sampling method

The whole content of the waste collection truck is quartering until the desired amount for laboratory sorting.

Currently, the methodology for solid waste composition study is not standardized. The sampling method for the solid waste composition study methodology varies from nation to nation.

2.3.2 Global Perspective

In European countries, a standard methodology for Solid Waste Analysis is developed under European Commission Fifth Framework, which named as ‘Solid Waste Analysis Tool’ (SWA-Tool) project. In this tool, the solid waste collected is including residual household waste and residual co-collected commercial waste but excluded the separately collected waste such as recycled waste and hazardous waste. The waste sample is collected from the source for waste composition analysis.

Meanwhile under the American Society for Testing and Materials (ASTM) International, there is a standard test method for the determination of the composition of unprocessed municipal solid waste. The municipal solid waste is a sampling from the vehicle load. The size of the sampling is then reduced by using coning and quartering methods.

2.3.3 National Perspective

In Malaysia, guidelines for a sampling of household solid waste - composition and characterisation analysis is introduced in the year 2012. This method is applied by the Malaysian government in National Solid Waste Department.

2.4 Waste Disposal Methods

Solid waste can be treated and disposed of by several methods. It can be treated for energy recoveries such as pyrolysis, refuse-derived fuel (RDF), waste-to-energy incineration or disposed of by incineration, landfilling or open dumping.

As reported by Kaza et al. (2018), the main disposal method for solid waste is landfilling, which is about 36.7 percent. Another 33 percent of solid waste is disposed of through open dumps. Only 19 percent of solid waste is undergo material recovery

processes such as composting and recycling. Another 11 percent of solid waste is treated through incineration. Figure 2.5 shows the global waste disposal method.

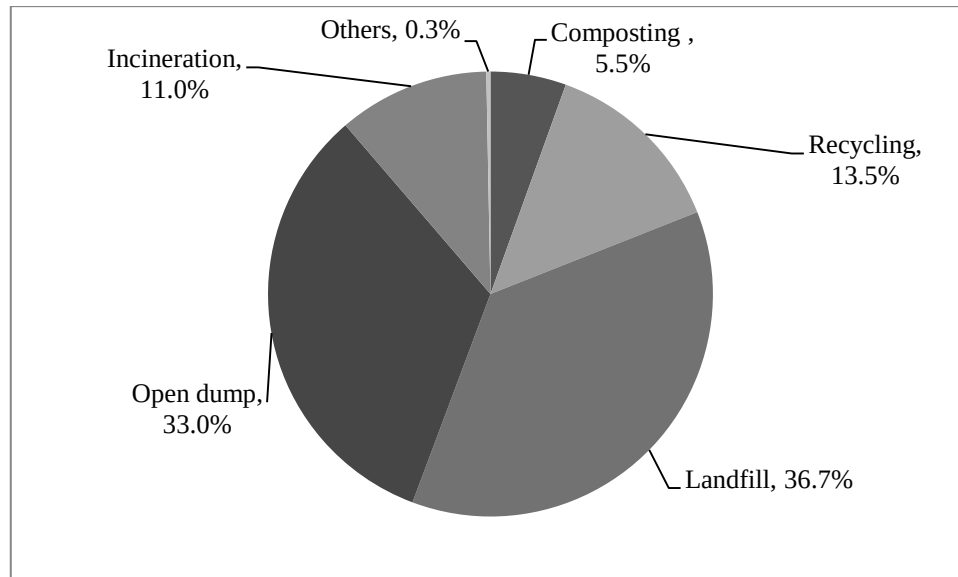


Figure 2.5: Global Waste Disposal Method

The solid waste disposal method is vary depending on the income level of a country. Open dumping is the main disposal method in low-income countries as it requires very low operation costs. Meanwhile, environmental awareness is higher in high-income countries. The solid waste will undergo material recovery and incineration before it is finally disposed of at a landfill.

2.4.1 Landfill

The landfill which commonly referring to sanitary landfill is defined as a waste disposal site for the deposit of solid waste onto or into the land. A sanitary landfill is an engineering facility which is different from an open dump site which leads to environmental pollution. It can be classified according to the landfill degradation process or operational method as shown in Tables 2.4 and 2.5.

Table 2.4: Classification of Landfill Based on Landfill Degradation Process

Type	Waste decomposting process in landfill
1	Anaerobic landfill
2	Anaerobic sanitary landfill with daily cover
3	Improved anaerobic sanitary landfill with buried leachate collection pipes
4	Semi-aerobic landfill with natural ventilation and leachate collection facilities
5	Aerobic landfill with forced aeration

Table 2.5: Classification of Landfill Based on Operational Method

Landfill level	Description
Level I	Controlled tipping
Level II	Sanitary landfill with bund and daily cover
Level III	Sanitary landfill with leachate recirculation system
Level IV	Sanitary landfill with leachate treatment facilities and more

Decomposition of organic components in municipal solid waste in landfill under anaerobic conditions roughly produces 55 percent to 65 percent of methane gas, 35 percent to 45 percent of carbon dioxide, and 0 percent to 10 percent of other gas including nitrogen, oxygen, hydrogen sulphide and ammonia gas. In Malaysia, landfills are the major source of methane gas emissions. Figure 2.6 illustrated the generation of methane gas from landfills in Malaysia.

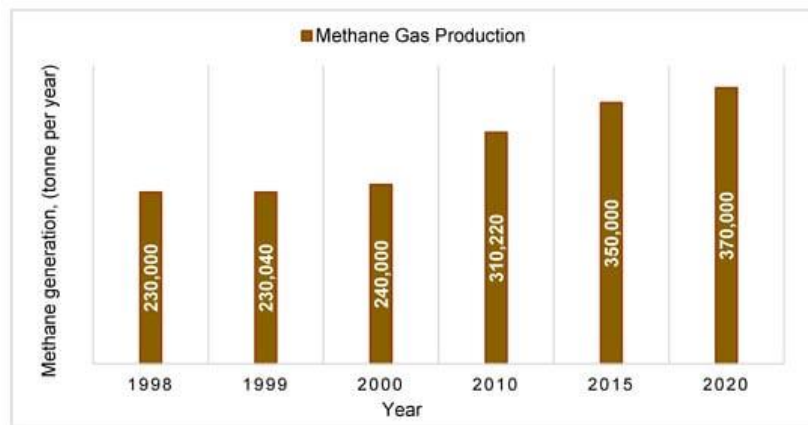


Figure 2.6: Methane Gas Production from Landfills in Malaysia (Yong et al., 2019)

Methane gas is one of the most powerful greenhouses gas, compare with carbon dioxide. However, supplying methane gas to gas engines, it is the potential to act as renewable energy as well.

2.4.2 Composting

Organic waste will be degraded by the microorganisms either in an aerobic condition which is commonly known as composting or in an anaerobic condition which is known as anaerobic digestion. When organic matter decomposes in a landfill, it will undergo anaerobic decomposition. Biogas which is a greenhouse gas will be released from the anaerobic decomposition.

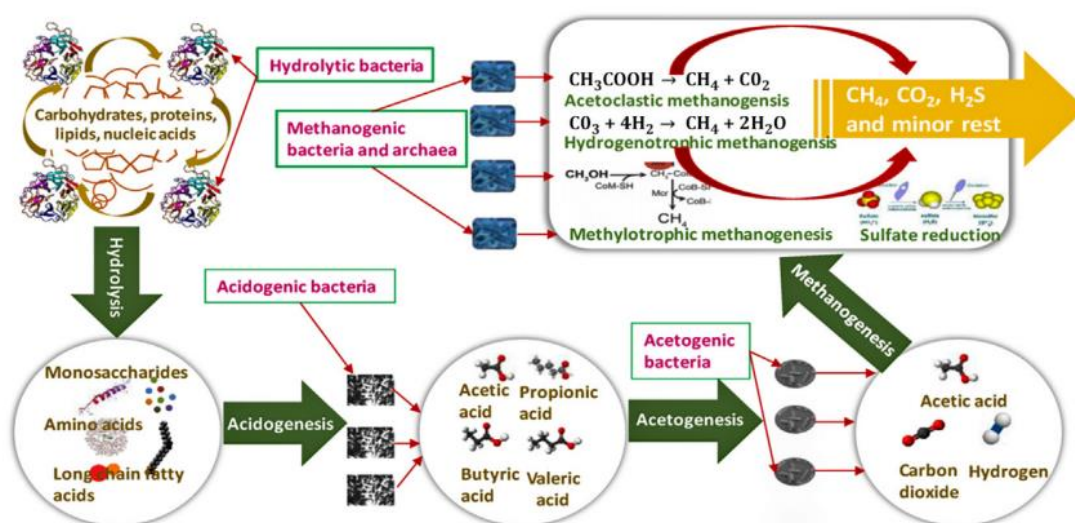


Figure 2.7: Anaerobic Digestion (Sarker et al., 2020)

As illustrated in Figure 2.7, composting in anaerobic condition or anaerobic digestion is consist of four main steps, which are hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis is the first step to breaking down the complex organic matter into soluble organic molecules, such as long-chain fatty acids and amino acids. The second step is acidogenesis or fermentation which further degrades the soluble organic into volatile fatty acids such as butyric acid, propionic acid and acetic acid. The third step is acetogenesis which organic acids are converted into hydrogen, carbon dioxide and acetic acid. The final step is methanogenesis which acetic acid, carbon dioxide, and hydrogen are converted to biogas by methanogens.

Therefore to fight climate change, it is encouraging to do composting under aerobic condition which does not release biogas which is one of the main greenhouse gas. The compost formed is rich in nitrogen, phosphorus and potassium which are the three main nutrients for the growth of plants. Therefore compost is always used as fertilizer.

The composting process can be improved by the addition of co-compost material or correct microorganisms. The time of composting is significantly reduced with the addition of effective microorganisms. In the year 2007, Kuching North City Hall introduced the Effective Microorganisms Bokashi home composting system in Kampung Salak, Kuching. The fermented food waste from the system can be used for fertilisers and about 3kg of food waste is successfully avoided from disposal from each home.

Although the compost is useful as fertilizer, it is also associated with some offensive smells, especially from the hydrogen sulphide gas which is released under the anaerobic process. Pathogenic microbes detected in compost are another main concern in composting.

2.4.3 Recycling

Recycling is the most often practice we heard when we talk about sustainable waste management. It is a process to recover raw materials from waste and convert it into new products. Recycling can help to reduce the waste disposed of in landfill and conserve natural resources. It also reduces greenhouse gas emissions. Typical materials that can be recycled are plastic, paper, metal and glass. Plastic waste is the most common recycled item. Table 2.6 describes the application of the different types of plastic and their recycling status.

Table 2.6: Type of Plastic

Code Number / Recyclable	Type of Plastic	Description
1 / Yes	Polyethylene Terephthalate (PET)	Intended for single use. Typically used as water bottles and packaging and it is widely recycled.
2 / Yes	High-Density Polyethylene (HDPE)	Stiff plastic, weather resistant and durable. Typically used as detergent bottles and chemical containers. It is commonly recycled.
3/ No	Polyvinyl Chloride (PVC)	Soft and flexible, contains numerous toxins. Typically used to manufacture pipes and plumbing. It is non-recyclable due to the high percentage of toxic chemicals.
4 / Yes	Low-Density Polyethylene (LDPE)	Soft and flexible plastic. Typically found as plastic packaging and film. It is recyclable but not commonly recycled.
5 / Yes	Polypropylene (PP)	Tough and lightweight, with excellent heat-resistance qualities. It is normally found in food containers, pails and rope. It is recyclable but not commonly recycled
6 / No	Polystyrene (PS)	Lightweight and structurally weak and contains numerous toxins. Typically is used as material for disposable styrofoam drinking cups and plastic utensils. It is non-recyclable due to the high percentage of toxic chemicals.
7 / No	Others (Bisphenol-A, Polycarbonate)	A mixture of other plastics. It is commonly used to manufacture baby bottles, water cooler bottles and car parts. It is non-recyclable as it mixed of different types of material

The main challenges of recycling are waste sorting and separation. Many people are confused between recyclable and non-recyclable items. For instance, contaminated polystyrene food container is always can be seen in the recycle bin although it is non-recyclable.

2.4.3.1 Mechanical Recycling

Mechanical recycling does not change the molecular structure of the product. It mechanically crushes the recycled material and remelts it into granulate. The granulate can be used as raw material for a new product.

2.4.3.2 Chemical Recycling - Pyrolysis

Chemical recycling is changing the polymer chains of the recycling materials and transforming them into other products. Pyrolysis is one of the chemical treatment processes which is the process of breakdown larger molecules into smaller molecules at high temperatures.

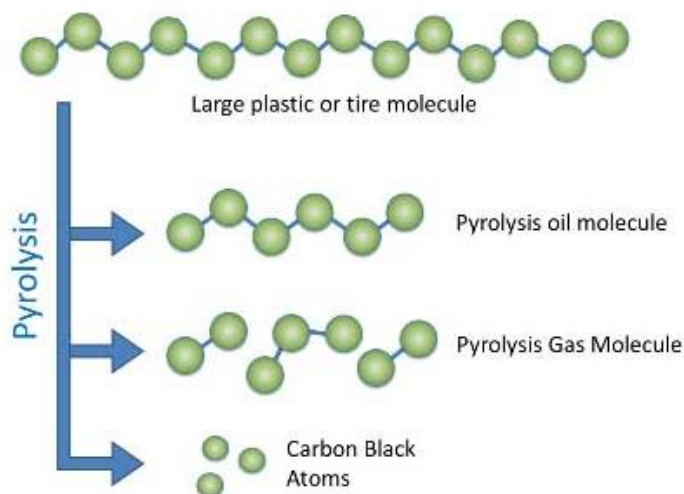


Figure 2.8: Pyrolysis

As illustrated in Figure 2.8, plastic waste can be transformed into pyrolysis oil under the pyrolysis process. The carbon-containing waste, mainly contributed by the

plastic waste is thermally decomposed at a temperature of 400–600°C in the absence of oxygen into pyrolysis oil. The pyrolysis oil can be further treated into diesel in an oil distillation plant.

2.4.4 Waste to Energy – Incineration Process

Municipal solid waste incineration is a thermal treatment process by burning waste for disease control and to reduce the waste volume. Waste-to-energy incineration is different from MSW incineration. It is an incineration process at temperatures of 850°C and above, in the presence of oxygen, equipped with mechanisms which recovered the energy.

The main advantage of WTE incineration is it uses waste as a resource to produce energy beside reduce to the volume of waste and disease control. However, the high moisture content of the municipal solid waste, the high capital investment cost and operating cost, lack of skilled operators are the main challenges to operating the WTE incinerator.

2.5 Qualitative and Quantitative Analysis

The quantification of solid waste or waste characterization provides details on the composition of the solid waste. However, there is some limitation to quantitative analysis. Some important data such as information on the waste stream and existing waste management practice are not captured if the solid waste analysis is done solely based on quantitative analysis (Newenhouse et al., 2000). Field observation is done for additional information on the finding from quantitative analysis. By integrating qualitative methods such as interviews and field observation with quantitative methods, the full picture of solid waste can be obtained.

2.6 Social-Economy Factors

As reported by Adeleke et al. (2021), the major factor that affected the waste composition is the socio-economic level of the study area. A waste composition study has been done by Kaza et al. (2018) also observed that waste composition is different according to the socio-economic group. The organic waste composition is higher in the low-income level region.

However, in the waste composition reported by National Solid Waste Management Department, Malaysia (2013), there is no significant difference in waste composition for the solid waste collected from different income level groups. Figure 2.9 shows the waste composition of the solid waste collected from different income level groups in Malaysia.

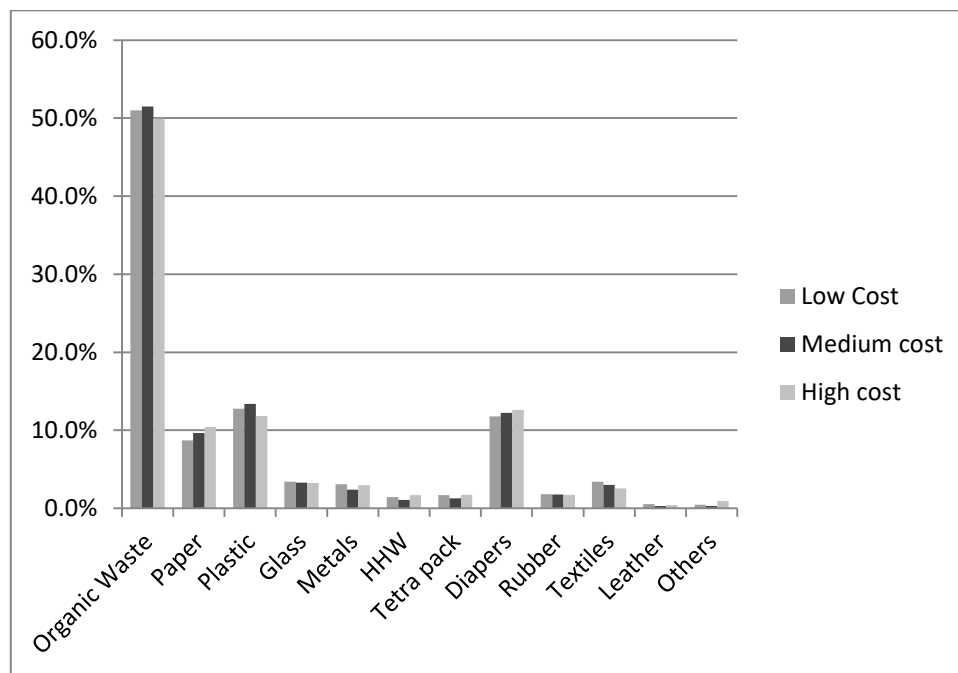


Figure 2.9: Solid Waste Composition from Different Income Level Groups in Malaysia

2.7 Projection of Municipal Solid Waste Generation

As reported by Araiza-Aguilar et al. (2020), the most important parameters in forecasting solid waste generation are population, migration and population density, where the population of the municipality is the most influential variable. A study by Zulkipli et al. (2021) also reported that the volume of municipal solid waste generated in Malaysia is related to the population and gross domestic product (GDP). Typically the waste generation rates are increased when the economic activities are increased. The growth of the economy in a country can be reflected in its GDP. As the population of a country is increased, the amount of total solid waste generated is increased as well.

2.8 Physical, Chemical, and Thermal Characteristics

According to the World Bank Group (Kaza et al., 2018), globally there is about 40 percent of municipal solid waste is disposed of in a landfill. In Kuching, the percentage is even higher as about 80 percent of the municipal solid waste is landfilled. Although landfill is one of the easier solutions for waste management, it also brings several problems to our environment. Landfill typically required very huge areas for disposing of waste. Greenhouse gas, methane is very often released from landfill. Leachate from the landfill might contaminate underground water if it not being treated properly.

Incineration, which can reduce the amount of waste disposed of in the landfill, is come into consideration for solid waste treatment. It not only reduces the space consumed and greenhouse gas but also able to generate energy. As reported by Abd Kadir et al. (2013), the incineration of municipal waste in Malaysia has failed due to high operating costs. In order to reduce the operating cost, the quality of solid waste fed to the incinerator needs to be controlled. As reported by Patil et al. (2014), the quantity of waste, the heat produced from the combustion of waste and operation and maintenance costs is the main

factor for the effectiveness of incineration. Therefore the physical, chemical and thermal characteristic of solid waste is very important for a waste management system, especially for a waste-to-energy system.

2.8.1 Physical Characteristics

Common physical characteristics of waste are moisture content and specific weight. Proximate analysis is one of the analyses to determine the physical characteristic of the waste. The proximate analysis determines the moisture content, volatile matter, ash and fixed carbon of the waste. The proximate analysis provides basic information on the potential waste to convert as an alternative fuel. The total moisture of the waste includes air-dry loss moisture and inherent moisture. Air dry loss moisture is the moisture loss at room temperature while inherent moisture is the moisture loss when it is heated between 103 °C to 105 °C. Volatile matter and fixed carbon both represent the combustion part of the waste. Volatile matter consists of short and long-chain aliphatic carbon atoms or aromatic hydrocarbons meanwhile fixed carbon is the residue carbon after the volatile matter is driven off. Ash is the incombustible material remaining after a combustion process.

2.8.2 Chemical Characteristics

The chemical properties of the waste, provide details data for the element in the solid waste. The chemical properties of solid waste are very important in determining the level of treatment required and evaluating alternative treatment and recovery processes. The chemical properties of the leachate generated from the municipal solid waste is important to determine the necessity of the leachate treatment facilities and the impact of the leachate wastewater to the environment.

2.8.3 Thermal Characteristics

The thermal properties of the waste are the most crucial factor to determine the feasibility of a waste-to-energy incineration plant. The thermal properties of the waste are typically expressed in calorific value, which shows the number of energy released upon the combustion process. There are two types of calorific values, which are higher heating value (HHV) and lower heating value (LHV). The HHV includes the heat of condensation of water vapour in the combustion process meanwhile the LHV considers the energy loss used to vaporize water. Therefore LHV is more realistic for waste-to-energy plant design calculations.

2.9 Life Cycle Assessment (LCA)

LCA is an environmental management tool which studies the environmental aspect and potential negative impact on the environment throughout the product's life. It is widely used in manufacturing companies in developed countries in practising “cradle to grave”, from raw material, production to disposal of the product. However, the application of LCA is not only limited to the manufacturing industry but also able to use to access the potential environmental impact of municipal solid waste management.

LCA is proven as an effective tool in municipal solid waste management. It helps to compare scenarios and identify the potential environmental impact of alternative disposal methods of municipal solid waste. For instance, Yay (2015) studied the MSW treatment by LCA and found out a combination of Material Recovery Facility (MRF), composting and incineration is the most environmentally friendly treatment option for MSW management at Sakarya, Turkey.

Although different software might have different results according to their database as commented by Kulczycka et al. (2015), however, it is still worth for LCA approach as the direction in choosing the best route for municipal solid waste treatment. In view of environmental impact, the implementation of recycling, composting, incineration with energy recovery and sanitary landfill is always bringing the least negative impact to the environment (Ferronato et al., 2020). Currently, there is no LCA study done on municipal waste in Kuching.

2.10 Chapter Summary

Municipal solid waste is an unwanted substance that required being disposed of. It included residential waste, commercial waste, and institutional waste but not including hazardous waste. The municipal solid waste composition is the most important element in solid waste management. It might be different according to the socio-economic group, but typically the three highest compositions of municipal solid waste are organic waste, plastic and paper. Solid waste management system involving waste generation, waste handling, sorting, storage, and processing at the source, waste collection, waste transportation, material recovery from waste and waste disposal. The common municipal solid waste treatment methods are recycling, waste-to-energy incineration, MSW incineration, landfilling, open dumping and composting. Nowadays circular economy is emphasized over linear economy, in which solid waste management in a sustainable way is more favoured. In Kuching, over 80 percent of the solid waste is landfilled. Determination of the physical, chemical and thermal characteristics of solid waste is very important for deciding the waste disposal method.

CHAPTER 3

MATERIALS AND METHODS

3.1 Study Area

As shown in Figure 3.1, there are two types of sampling for this study; (i) sampling from a source and (ii) sampling from a landfill. This study was only focused on the capital city of Sarawak, Kuching City. The results from both samplings were analysed and used for the zero-waste approach.

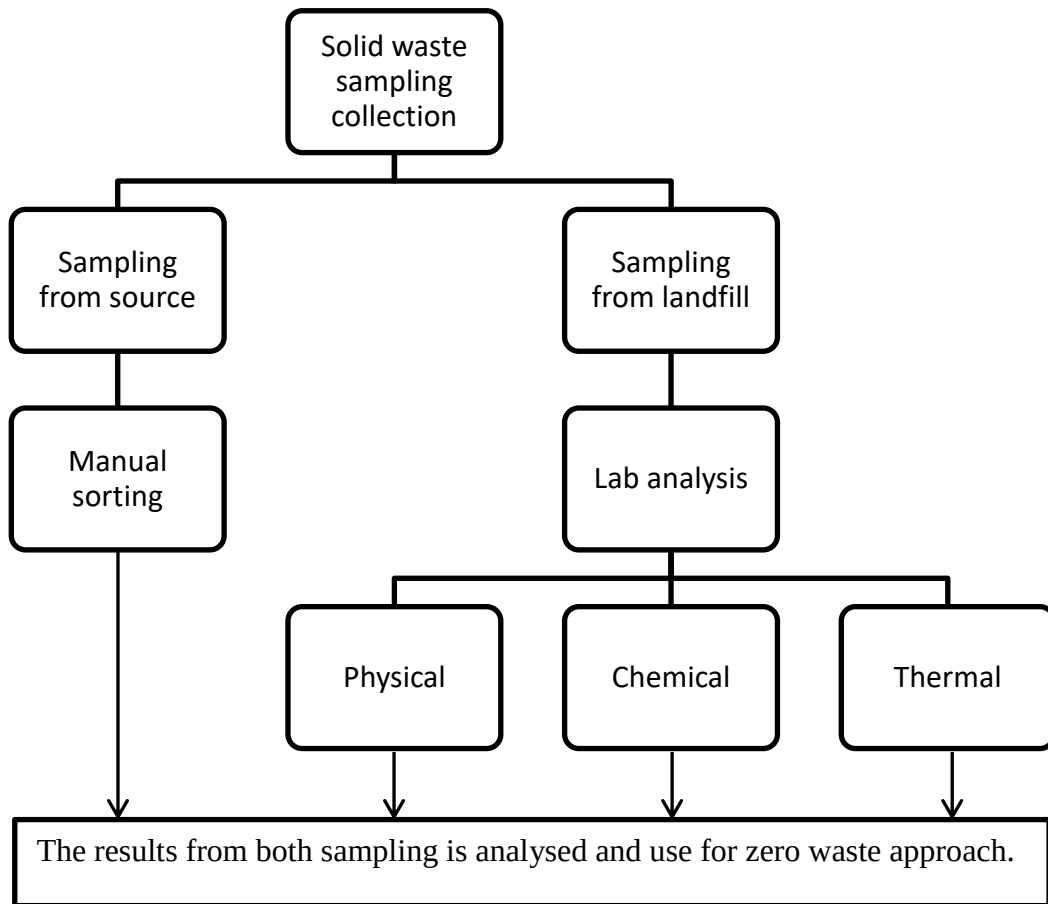


Figure 3.1: Flow Chart of the Methodology Used in This Study

According to the Department of Statistics Malaysia (DOSM) (2022), the population of Kuching is 609,205 comprised of citizens 599,228 (98.4%) and non-citizens 9,977 (1.6%) in the year 2020. The composition by ethnicity for Kuching citizens is Bumiputera 376,481 (62.8%), Chinese 218,716 (36.5%), Indians 2,562 (0.4%) and others 1,469 (0.3%). Kuching recorded a sex ratio of 102 males for every 100 females. There are three principal council areas of Kuching, which are Kuching South City Council with a population of 174,625, Kuching North City Hall with a population of 174,522, and Padawan Municipal Council with a population of 260,058.

3.2 Sampling from Source

The samplings from the source were done from October 2020 to November 2020, which is during the Recovery Movement Control Order (RMCO) period. During the study period, the municipal solid waste in Kuching was collected by the local waste management company, Trienekens Sarawak, twice per week. The collected waste was transferred to the landfill located in Mambong by compactor truck. As no collection truck collects waste from the same socio-economic group, therefore the sampling for this study was conducted on-site instead of sampling from the collection truck.

There was a total of nineteen sampling points was selected according to their socio-economic level and commercial activities. The selected routes of the sampling locations are shown in Table 3.1.

Table 3.1: Details of the Sampling Locations

Route Numbers	Category
i.	Low-Income Residential Area
ii.	Medium-Income Residential Area
iii.	High-Income Residential Area
iv.	Condominium
v.	Low-Cost Apartment and Flat
vi.	Dayak Village
vii.	Malay Village
viii.	Chinese Commercial Area
ix.	Malay Commercial Area
x.	Shopping Mall
xi.	Malay Market
xii.	Chinese Market
xiii.	Government Office
xiv.	Petrol Station
xv.	Public Hospital
xvi.	Private Hospital
xvii.	School
xviii.	Private University
xix.	Hotel

The socio-economic level was presumed according to the house type and market value of the house, and the main ethnic group in the selected area. House type in Kuching

can be divided into landed property and multi-storey property. Landed property included terraced houses, semi-detached houses, detached houses and the traditional kampong house. Semi-detached houses in the city centre are predominantly (>80%) by a high-income group while the single-storey low-cost house is predominantly by a low-income group. The terrace house near the city centre was presumed predominant by the medium-income group. Meanwhile, the multi-storey property included flats, apartments, and condominiums. A condominium is more expensive as it is equipped with a variety of luxury facilities such as a swimming pool, modern security system, lift, and covered car park compared with a flat without those facilities. Therefore, the condominium is normally predominantly a high-income group and the flat resident group is normally referred to as the low-income group. The commercial activities were presumed based on the nature of the business in the selected area during this study.

The solid waste samples were collected from the 1000 L communal bin at each of the selected areas and transferred to another empty 1000 L communal bin prepared earlier. The prepared communal bin was labelled according to the waste sampling area. The assumption was made that the waste sample in the communal bin was generated by the same group of residents in the selected area. The communal bin was transferred to a flat area at KIWMP for a manual sorting process. All the waste samples collected were manually sorted into separate plastic bags according to the pre-selected waste categories. Each category of waste will weigh by using a calibrated platform scale (Ishida, MTX-150). The sampling process has been repeated four times for the same location. The weight from each category was recorded in the datasheet. The same method was used for all the predefined areas. Personal protective equipment (PPE) such as safety shoes, dust masks, and vinyl hand gloves were provided to the person doing the waste sorting.

Figure 3.2 shows the sampling at the source from the communal bin.



Figure 3.2: Sampling at Source

3.2.1 Category of Solid Waste

The solid wastes were sorted out manually according to the 11 categories; organic waste and biodegradable such as food and fruits waste, garden waste, and wood, paper waste which will further sorting to cardboard, newspaper, office paper, magazine and mixed paper, tetra pack, glass, plastic waste which will further sorting to polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and other plastic, metal, construction waste, hazardous waste and e-waste, nappies and sanitary napkins, leather, textile, rubber, and materials that do not fit in any of the above categories.

3.3 Sampling from Landfill - Laboratory Analysis

For laboratory analysis, the solid waste samples were collected from the municipal landfill which has been operated since the year 2003. Two types of samples were collected

according to the age of landfill, which is “old solid waste” which is the solid waste disposed of 5 – 10 years ago and “new solid waste” which is the solid waste disposed of within 2 years. The landfill engineer identified the area inside the landfill which contained the “old solid waste” and “new solid waste”. The samples were collected by using an excavator, about 1 meter from the surface and transferred to a Roll on, Roll off (RORO) container. About 1 kg of sample was prepared from the sample collected in the container by using the laboratory sampling method, followed by a shredding process to prepare the homogenous solid waste sample. For the same category, 3 samples have been collected. The same samples undergo three types of analysis, which are physical analysis, lab analysis and thermal analysis.

3.3.1 Physical Analysis

For physical analysis, proximate analysis was carried out to determine the moisture content, volatile matter, ash content, and fixed carbon. The proximate analysis was carried out according to American Standard Test Method (ASTM) standards.

3.3.1.1 Moisture Content

About 5 grams of the homogenous solid waste sample was weighed by analytical balance (Sartorius CP224S) and dried in an oven (Mettler ULE-500) at a temperature of 105 °C for 1 hour according to ASTM standards E790. The percentage of moisture contents was calculated using Equation 3.1. The moisture content is the weight loss percentage during the drying process.

$$\text{Moisture in the analysis sample, \%} = \frac{(A-B)}{A} \times 100\% \quad \text{Equation 3.1}$$

Where, A is the grams of sample used and B is the grams of the sample after heating.

3.3.1.2 Volatile Matter

The same sample from moisture content analysis was placed in a furnace (Carbolite ELF/11/6B/301) and ignited at 950°C for 7 minutes according to ASTM E897. The sample was cooled and weighed. The volatile matter will be calculated using Equation 3.2

$$\text{Volatile matter in the analysis sample, \%} = \frac{(B-C)}{A} \times 100\% \quad \text{Equation 3.2}$$

Where, A is the grams of sample used, B is the grams of the sample after moisture analysis, and C is the grams of the sample after heating at 950°C.

3.3.1.3 Ash Content

The sample from the volatile matter analysis is next placed in a furnace (Carbolite ELF/11/6B/301) and heated at a temperature of about 750 °C for 1 hour in accordance with ASTM E830. The sample was then cooled and weighed. The ash contents were calculated according to Equation 3.3 which is the percentage of the remaining weight.

$$\text{Ash Content in the analysed sample, \%} = \frac{(C-D)}{A} \times 100\% \quad \text{Equation 3.3}$$

Where, A is the grams of sample used, C is the grams of the sample after volatile matter analysis, and D is the grams of the sample after heating at 750°C.

3.3.1.4 Fixed Carbon Content

Fixed carbon was calculated by subtracting out the moisture content, volatile matter and ash content from the total weight of the sample (Equation 3.4)

$$\text{Fixed carbon content, \%} = 100\% - \text{moisture content\%} - \text{volatile matter\%} - \text{ash content\%} \quad \text{Equation 3.4}$$

3.3.2 Chemical Analysis

The Toxicity Characteristic Leaching Procedure test was done on the homogenous solid waste sample collected. The leachate from the test was analysed by flame atomic absorption spectroscopy (Varian SpectraAA 220FS) to determine the heavy metal content of the leachate. The solid samples were also tested through Elemental Compound Screening using Energy Dispersive X-ray Fluorescence (ED-XRF) Spectrometer to identify the elements contained in the samples.

3.3.3 Thermal Analysis

The homogenous solid waste sample was put into a bomb calorimeter (IKA C5000) to determine the calorific value by the ASTM D5865-10a method.

3.4 Field Observation

Field observation is a method to gain information through direct observation at a representative location. The field observation was done at the sampling area, which is the selected study area and at the solid waste disposal area in Kuching. The existence of recycling activities at the collection area, the appearance of the disposed solid waste, the method of solid waste disposal and the condition of the landfill were observed.

3.5 Projection on Amount of Solid Waste Generated

In this study, the amount of solid waste generated in Kuching was estimated by using a methodology adapted from the waste generation projection methodology suggested by Kaza et al. (2018). A regression model was developed to relate the GDP growth and the waste generation rates. In this model, the proxy waste generation rates per year can be

modelled per Equation 3.5 and the projected waste generation rate can be calculated following Equation 3.6.

$$\text{Proxy waste generation per capita} = 1647.41 - 419.73 \ln (\text{GDP per capita}) + 29.43 \ln (\text{GDP per capita})^2 \quad \text{Equation 3.5}$$

$$\text{Projected Waste Generation Rate Target Year} = \frac{\text{Proxy Waste Generation Rate Target Year}}{\text{Proxy Waste Generation Rate Base Year}} \times \text{Actual Waste Generation Rate Base Year} \quad \text{Equation 3.6}$$

The amount of solid waste generated can be estimated by multiplying the population in Kuching with the projected waste generation rate of the target year as per Equation 3.7.

$$\text{Amount of solid waste} = \text{Population} \times \text{Projected Waste Generation Rate} \quad \text{Equation 3.7}$$

3.6 Estimation of Methane Gas Generation in Landfill

The amount of methane gas and biogas generated from the controlled landfill in Kuching was estimated by using the LandGEM model (version 3.02) developed by the American Environmental Protection Agency (EPA USA). In this study, the input to the model is using the operation data from the existing landfill in Kuching, with the assumption that it will be filled until the year 2030. The solid waste disposal rate is calculated by using the formula in section 3.5.

3.7 Life Cycle Assessment

The LCA of municipal solid waste was conducted according to ISO 14040 standards, which divided the study into four phases, which is goal and scope definition, inventory analysis, impact assessment and interpretation. Phase I introduces the goal and scope of the LCA study. The goal is to compare two MSW treatment methods, landfilling with biogas recovery, and MSW incineration. The transportation of municipal solid waste is not considered in this LCA study. Phase II presents the life cycle inventory. The waste composition result obtained in this study was used as the input to the OpenLCA software. ELCB database in OpenLCA software was used for the LCA analysis. Phase III describes the life cycle impact assessment. Four impact elements were analyzed, which were acidification, eutrophication, global warming and human toxicity. Phase IV is the interpretation of the results. This included the evaluation of the results.

3.8 Proposed Zero Waste Management by Multilevel System Analysis

Zero waste management is the approach to managing waste by conservation of all resources in the waste. Multilevel system analysis is one of the system thinking tools which solve a problem at a different level, with both quantity and quality approaches. In a waste management system, it can be used to identify the greatest resource recovery potential stream. Ng et al. (2016) have proved the potential of zinc recovery from municipal waste by using multilevel system analysis.

There were a few important key points of prospects and challenges in MSW management, such as the available waste treatment technology, the budget allocated for MSW treatment, the attitude of the community toward solid waste management, and the legal requirement and the policies of the local government (Andriani et al., 2019). The

multilevel system analysis was applied to the results obtained from the quantitative and qualitative analysis of the solid waste in this study. Different type of solid waste is treated by using different type of treatment method, in order to maximize the material and energy recovery and minimize the amount of solid waste disposed of. The flow of the waste stream was drawn by using the software, STAN version 2.6.801. The most feasible and best available technology was proposed for zero waste management in Kuching.

3.9 Chapter Summary

This study was only focused on the capital city of Sarawak, Kuching City. There are two types of sampling for this study; sampling from a source and sampling from a landfill. For sampling from source, there was a total of nineteen sampling points was selected according to their socio-economic level and commercial activities. The solid wastes were sorted out manually according to the 11 categories. Meanwhile, for sampling from a landfill, the sample is collected from Kuching Waste Management Park (KIWMP) landfill, which operated since the year 2003. Two types of samples were collected according to the age of landfill, which is “old solid waste” which is the solid waste disposed of 5 – 10 years ago and “new solid waste” which is the solid waste disposed of within 2 years. The waste samples at landfill will be sent for laboratory analyses include physical, chemical and thermal characteristics. The field observation is done at the sampling area, which is the selected study area and at the solid waste disposal area in Kuching. The appearance of the disposed solid waste, the method of solid waste disposal and the condition of the landfill was observed. A regression model was developed to relate the GDP growth and the waste generation rates. From the quantitative and qualitative analysis of the solid waste in this study, the most feasible and best available technology was proposed for zero waste management in Kuching.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Physical Characterization

Physical waste characterization is used to estimate the quantities of certain materials in solid waste streams. This information is designed specifically for solid waste planning. The physical characterization of the solid waste samples is performed according to three main groups, which are residential area, commercial area and institutional area.

4.1.1 Residential Area

For the residential area category, the result is analysed from the first seven groups of sampling which are Route 1 to Route 7. Route 1 to Route 7 is different in social-economic levels as described in Chapter 3. The average composition from these seven groups sampling is shown in Figure 4.1. Similar to most of the waste composition studies, organic waste is the highest waste composition, which is 61.58% w/w. All seven groups of sampling area recorded more than 50% w/w of organic waste. Plastic waste is the second-highest waste composition, recorded at 12.06% w/w. The third-highest waste composition is the nappies and sanitary napkins category, which is 11.67 % w/w. The nappies and sanitary napkins composition is similar to the composition reported by SWCORP in the year 2020, which is 12.8%.

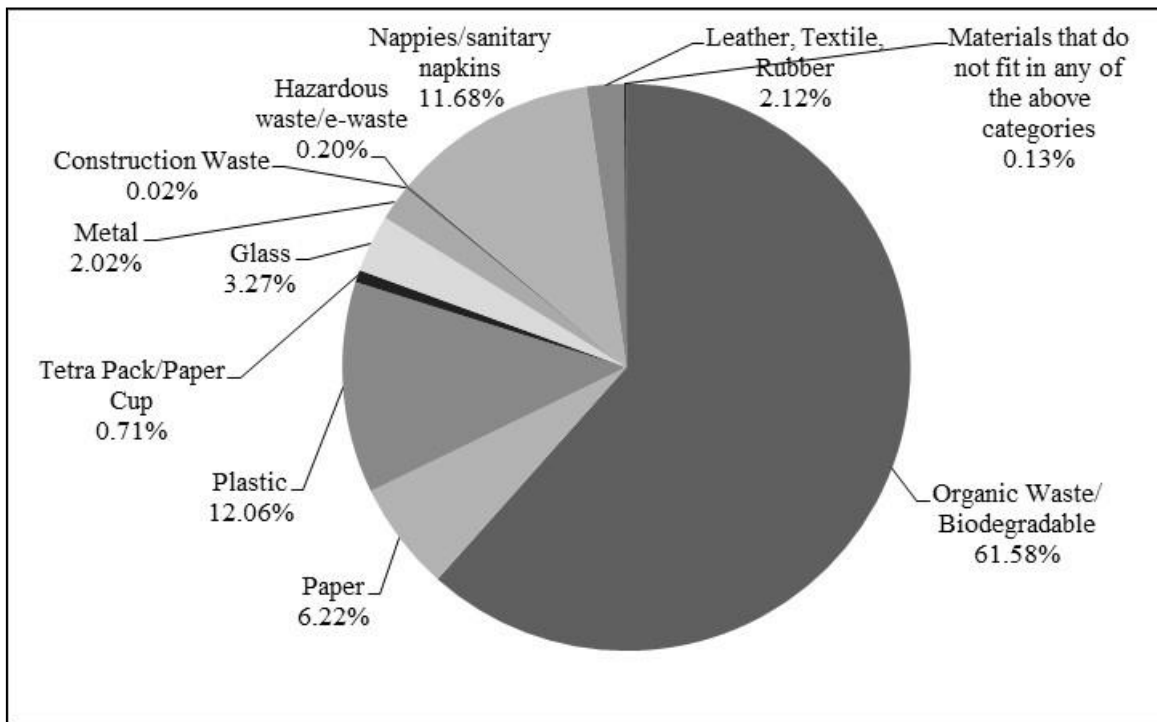


Figure 4.1: Overall Waste Composition of Municipal Solid Waste from the Residential Areas in Kuching

4.1.1.1 Social-Economic Parameter

Few assumptions are made in categorising the social-economic level of the resident. The first assumption is the higher income group will stay at the house with a higher market value while the lower income group will stay at the house with a lower market value. The resident who stays at a semi-detached house and condominium is assumed from the higher income group. The resident who stays in a low-cost single-storey house and low-cost apartment and flat is assumed from the lower income group while the resident who stays in a double-storey detached house is assumed from the medium income group. The second assumption is the majority of the residents are Dayak and Malay ethnic in the selected areas (Route 6 and Route 7).

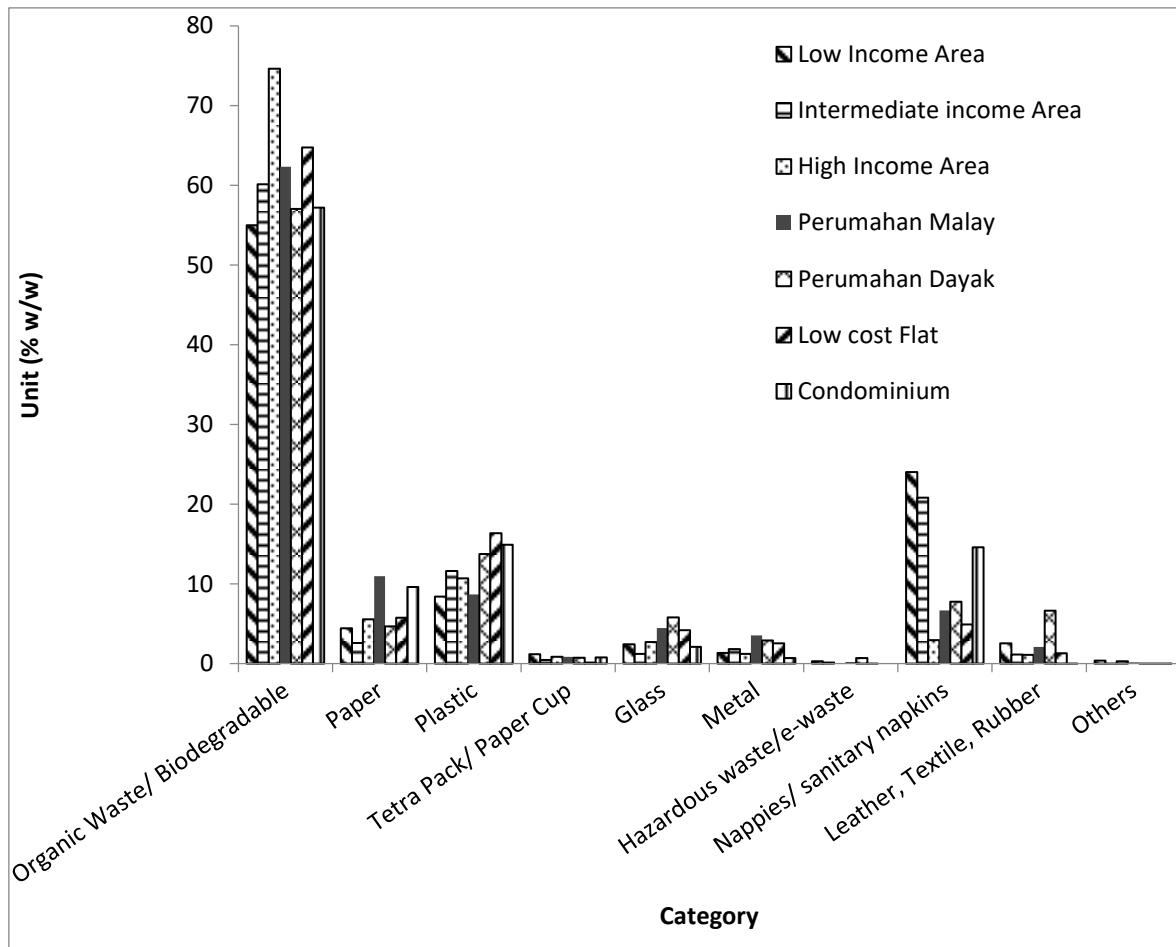


Figure 4.2: Solid Waste Composition at Residential Areas According to Social-Economic Level

From Figure 4.2, it is found that there is no significant difference when we compare the waste composition from the seven residential sampling groups. A lot of studies and reports revealed that the waste composition is different according to income level, however, it is not significantly applied in this study. The sampling period is done during the recovery movement control order (RMCO) and conditional movement control order (CMCO) period. During the enforcement of the movement control order, the lifestyle of the residents changed dramatically. The resident from the high-income group, which majority is business owner, might preferable to stay at home or be restricted from work. They are also affordable to pay for food delivery service. Therefore hard polypropylene, which is usually used for food packing and organic matter is found higher composition in

high-income areas. The second highest waste component found is plastic for the municipal solid waste samples collected from high-income residential areas, low-cost flats, condominiums and Dayak village, which are 10.7 % w/w, 16.36 % w/w, 14.92 % w/w and 13.76 % w/w, respectively. The type of plastic found is mainly food packaging and soft plastic bags (LDPE/PP). According to Brouwer et al. (2020), this type of plastic is low in recycling values. Although it is commonly reused as trash bags, however eventually those plastic bags are still ended up disposed of in landfill. Soft plastic and food packaging are not collected by the recycling company as well (Alyssa & Wong, 2019). The second-highest waste component found in the low-income residential area and medium-income residential area is nappies and sanitary napkins, which are 24.03 % w/w and 20.83 % w/w, respectively. According to the Department of Statistics, Malaysia (2022), there is 49.5% of female residents. For the Malay village area, paper is the second-highest component is paper, which recorded 10.97 % w/w.

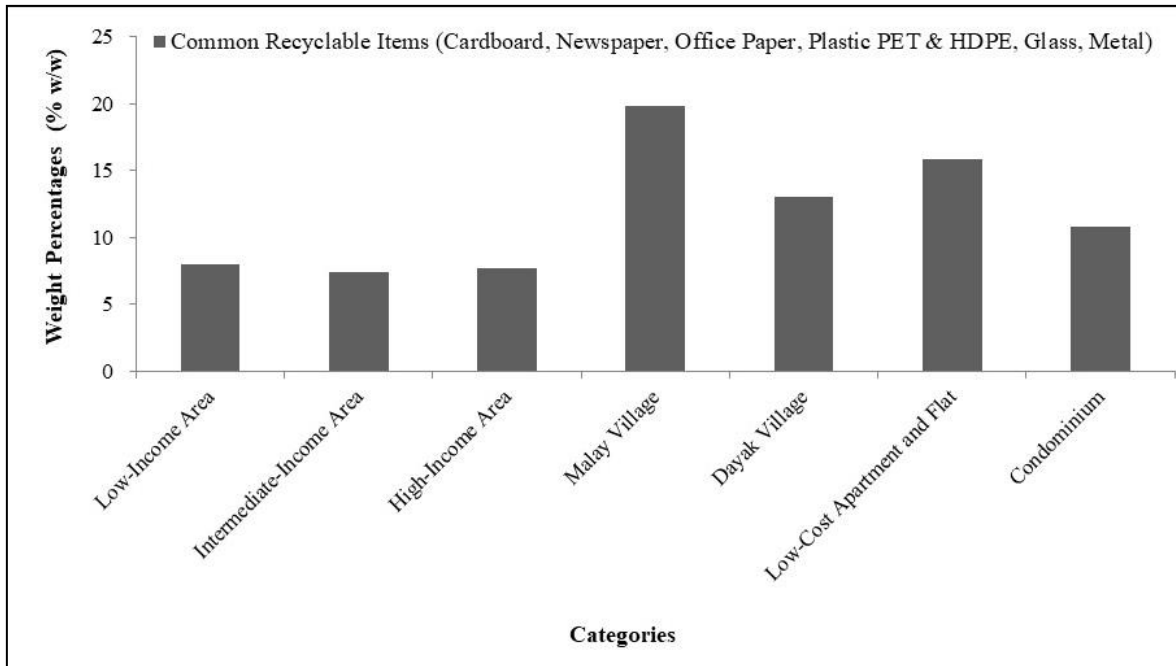


Figure 4.3: Common Recycling Items at the Different Residential Areas

As reported by National Solid Waste Management Department, Malaysia (2013), the common recycling items in high value, such as HDPE & PET, Glass, metal, cardboard, newspaper and office paper is recorded at 15.82% w/w for the waste generated from Malaysian households. As shown in Figure 4.3, the common recycling items is found lower than the average percentage of common recycling items except for the low-cost apartment and flat area (15.83 % w/w) and Malay village (19.81 % w/w). These findings reveal that the recycling awareness for Kuching residents is at an acceptable level.

4.1.2 Commercial Area

A commercial area is real estate which is intended for use in the business of selling and buying goods as well as services. In this study, the selected commercial area is divided into four groups, which are commercial entities, markets, hotels, and petrol stations.

4.1.2.1 Commercial Entities

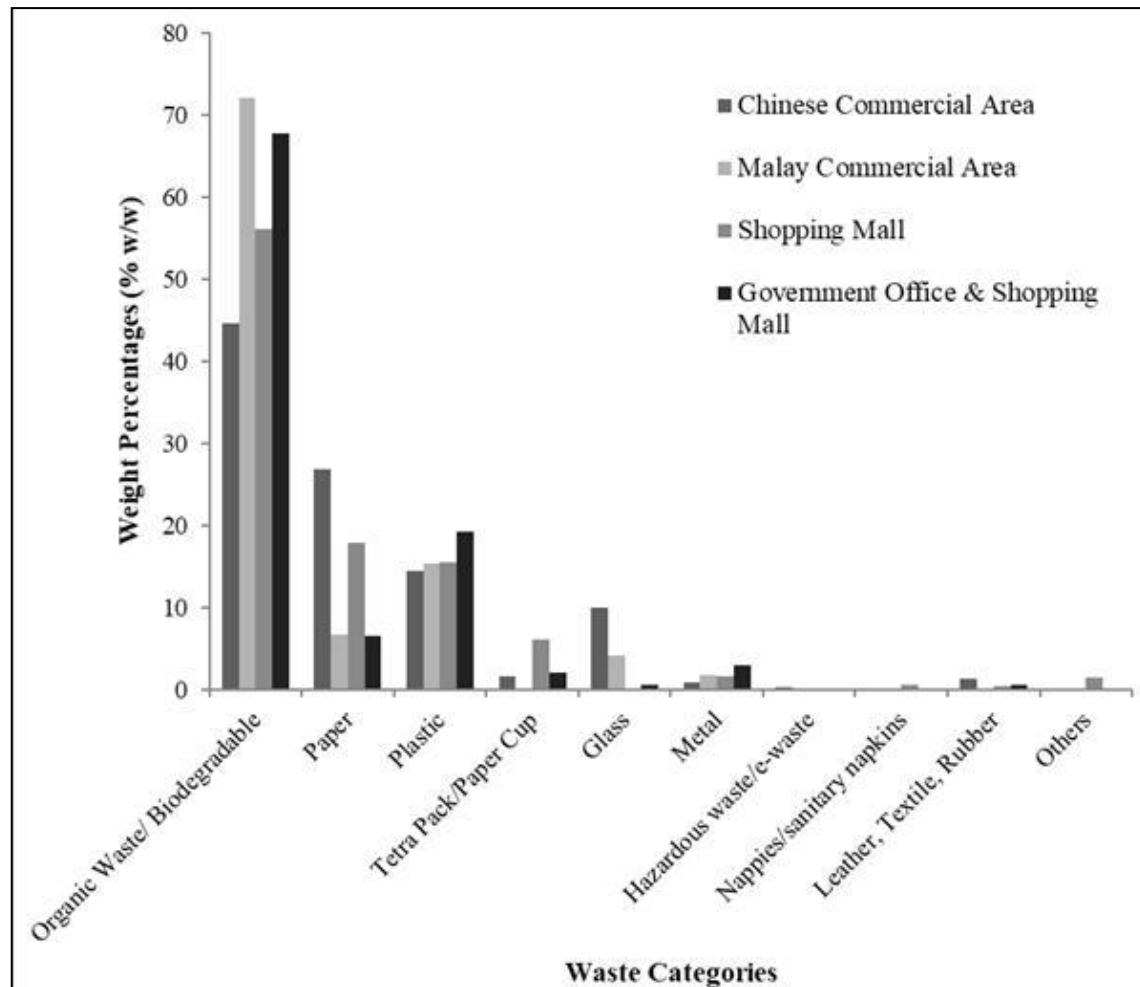


Figure 4.4: Waste Composition at the Commercial Entities

The solid waste generated from traditional shophouses, shopping complexes and government offices was collected for commercial entities samples. As shown in Figure 4.4, the solid waste composition varies according to the nature of the business. Similar to the samples from the residential area, the organic waste remains the highest waste component, with the results ranging from 44.57 % w/w to 72.08 % w/w. According to department of statistic, Malaysia (2017), there were 167,490 establishments operated in food and beverage services in year 2016 compared to 130,570 establishments in 2010 with annual growth rate of 5.1 per cent. These high amounts of organic waste may be due to the food

waste from blooming food-related businesses which commonly exist in all the commercial areas.

In this study, we also compare the waste composition between the solid wastes generated from Chinese commercial areas and Malay commercial areas. The second-highest waste component found in Chinese commercial areas is paper which is 26.82 % w/w while the second-highest waste component found in Malay commercial areas is plastic, recorded at 15.29 % w/w. Most of the paper found in Chinese commercial areas is cardboard, which is used as goods packaging. A few interviews with the commercial shop owners are carried out for their recycling activities. It was found that the cardboard is only being recycled by the shop which consistently generates high numbers of cardboard. The wet or contaminated cardboard is disposed of as solid waste due to the condition is not able to reuse purpose and it is also not accepted by the recycler. The composition of paper found at the shopping mall is 17.92 % w/w, but mainly mixed paper instead of cardboard. Mixed paper is hard to be recycled compared with cardboard. During the sample collection, it was seen that paper recycling is practised by department stores at shopping malls, especially cardboard. The finding from the National Solid Waste Management Department, Malaysia (2013) shows that 86.2% w/w of supermarkets practising recycling whereas only 40.6% of retail stores practising recycling. This explained the percentage of cardboard found at traditional shop lots is higher compared with the percentage of cardboard found in the shopping mall. For the Malay commercial area, the main type of plastic waste extracted is soft plastic bags, PET, and PP, which mostly are commonly used as food packaging and single-use drinking bottles. The composition of tetra packs and paper cups found in the commercial area is higher than in the residential area. Varying from the normal type of paper, tetra pack and paper cups consist of multilayers of paper

with aluminium and plastic layer. Therefore, it is not being collected by local recyclers as it required higher operating costs and advanced technology for recycling (Zawadiak et al., 2017).

At the government office, the second-highest component discovered is plastic waste which has values of 19.23 % w/w. This might be due to PP food packaging, plastic cups and plastic cutleries getting popular to be used in catering services and food courts for the convenience of food providers.

The glass composition is found relatively high at 9.92% w/w and 4.15% w/w, respectively in both Chinese and Malay commercial areas due to glass not commonly being recycled. Although in this study we found that the overall recycling rate is increased, however, it is toward the opposite way for the glass recycling practice. The main reason for this is the income gained from glass recycling is much lower compared with other recycled items.

4.1.2.2 Market

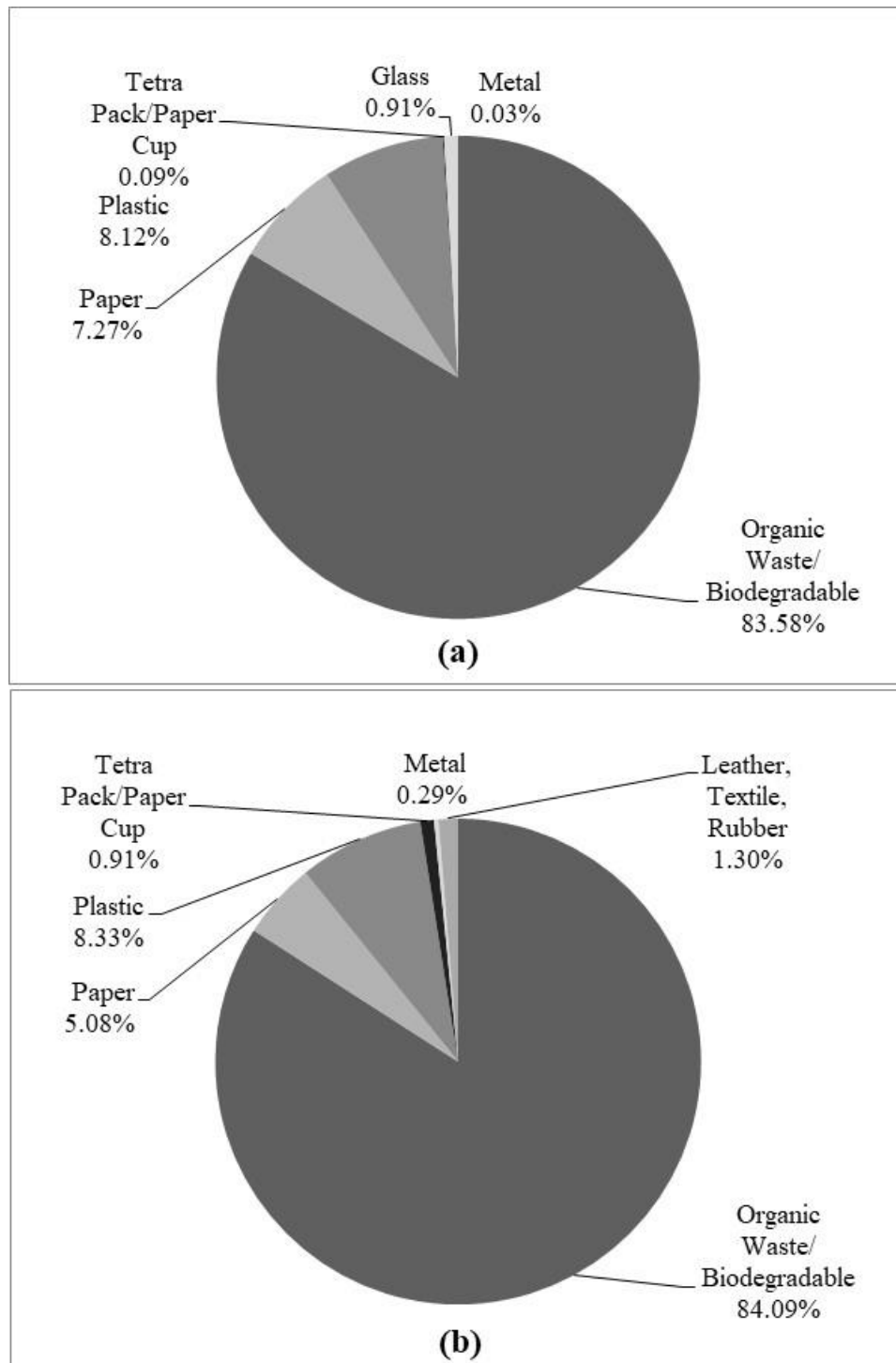


Figure 4.5: Waste Composition at (a) Chinese Market and (b) Malay Market

In this study, we compare the wet market in which the majority of the hawkers are from a different ethnic group that is Malay and Chinese. The selected wet markets are

similar in business activities. Referring to Figure 4.5, both waste samples from the Malay market and the Chinese market discovered organic waste is the highest waste composition, which is 84.08% w/w and 83.57% w/w, respectively. Both market samples are also having the same second and third-highest compositions which are plastic wastes and paper wastes. This is in line with the nature of business in the areas in which the main selling goods are vegetables and other fresh produce. Although the report by National Solid Waste Management Department, Malaysia (2013) revealed that approximately 74.6 % w/w of the wet market is exercising recycling as a sustainable practice, this study found that there is no proper management of organic waste in local wet markets.

4.1.2.3 Hotel

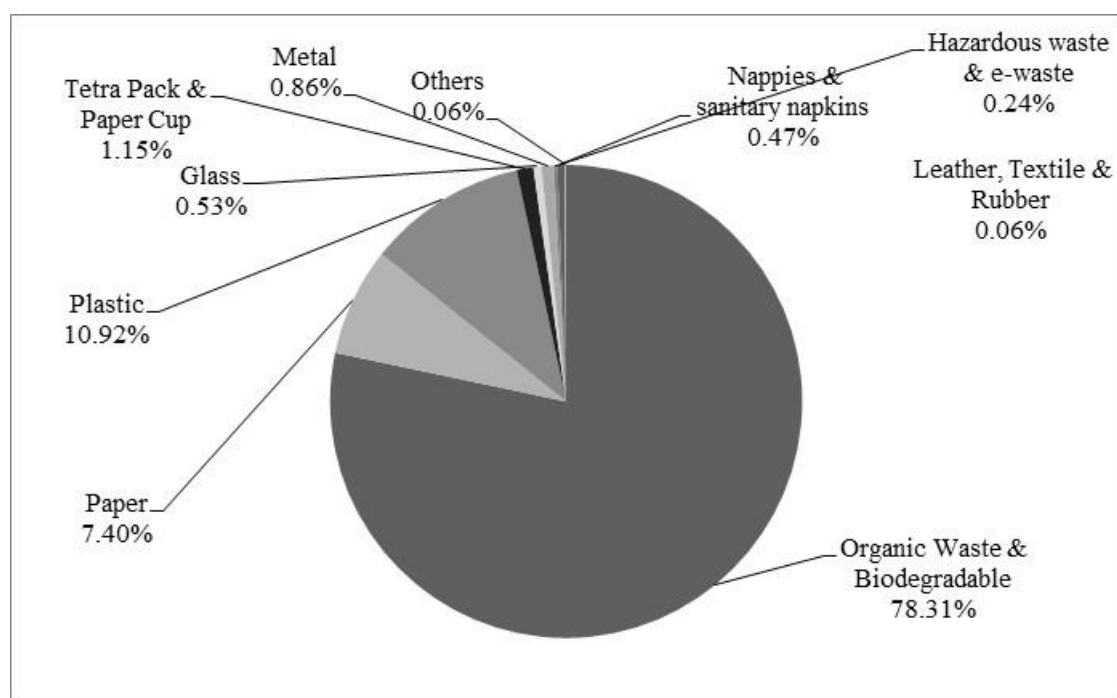


Figure 4.6: Waste Composition at the Hotel

The selected hotel in Kuching for sampling has served as one of the quarantine accommodation locations by the local government. Therefore a large amount of organic food and food packaging was observed during the sample sorting. Referring to Figure 4.6,

the organic waste was recorded at 78.31% w/w and hard PP waste is recorded at 2.13% w/w. The recycling activities have been seen during the waste sample collection. The result is in line with the plastic and paper waste composition, which are only 10.92 % w/w and 7.4 % w/w, respectively.

Table 4.1: Waste Composition at the Hotel

Type of Waste	Percentage (% w/w)
1. Organic Waste/ Biodegradable	78.31%
2. Paper	7.40%
a) Cardboard	0.18%
b) Newspaper	0.27%
c) Office Paper	0.00%
d) Mixed Paper	6.95%
3. Plastic	10.92%
a) PET	1.04%
b) HDPE	0.15%
c) LDPE/soft plastic(PP/others)	6.63%
d) PP (hard)	2.13%
e) PS	0.74%
f) PVC	0.24%
g) other plastic	0.00%
4. Tetra Pack/Paper Cup	1.15%
5. Glass	0.53%
6. Metal	0.86%
7. Construction Waste	0.00%
8. Hazardous waste/e-waste	0.24%
9. Nappies/sanitary napkins	0.47%
10. Leather, Textile, Rubber	0.06%
11. Materials that do not fit in any of the above categories	0.06%

Referring to Table 4.1, plastic waste and paper waste mainly are soft plastic and mixed paper which is difficult to be recycled. High recycling value items such as cardboard and office paper are hardly found in the waste sample. As the selected hotel is one of the green concept hotels which address the SDG in their sustainable business strategy. This result confirms that the hotel has adopted the recycling practice in its daily business operation.

4.1.2.4 Petrol Station

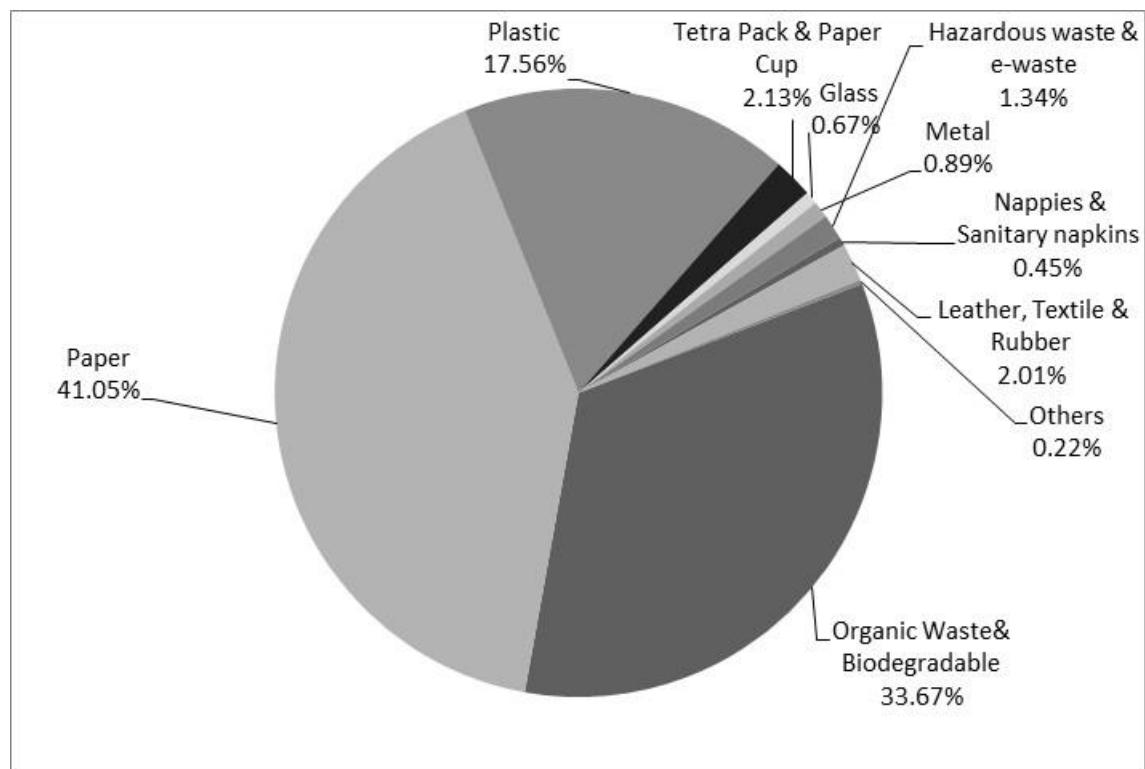


Figure 4.7: Waste Composition at the Petrol Station

The waste generated at petrol stations mainly is generated by the employees at the petrol station itself. Refer to figure 4.7, 10.74 % w/w of office paper waste and 5.25 % w/w of recyclable plastic waste (mainly PET and HDPE) is found indicating recycling activity is unlikely carried out at petrol stations. Towards sustainable practices, it is recommended to have a recycling bin at the petrol station to encourage recycling activity.

4.1.3 Institutional Area

The institution area is defined as facilities and services for public needs such as the medical service sector and education sector. These include government and private sectors such as hospitals, clinics, schools and universities.

4.1.3.1 Medical Service sector

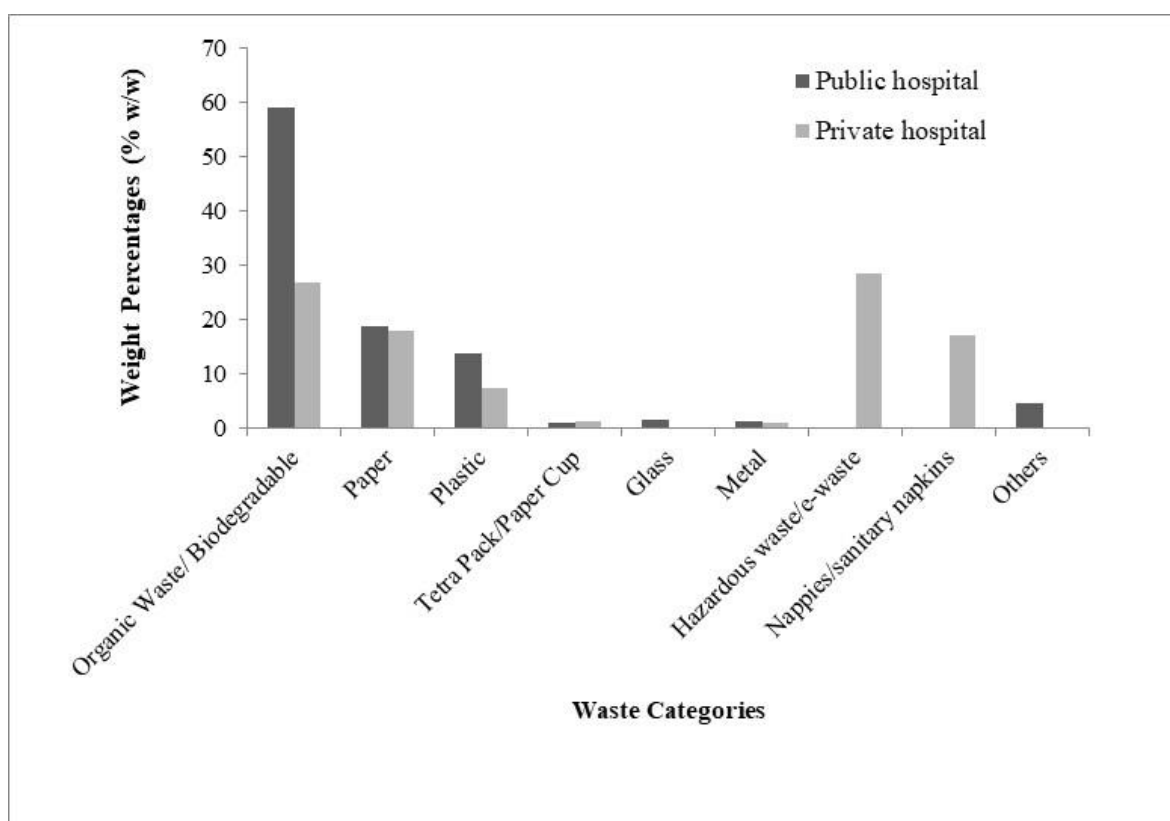


Figure 4.8: Waste Composition in the Medical Service Sector

As shown in Figure 4.8, there is a significant difference between the waste compositions of public hospitals and private hospitals. There is 59.08 % w/w of organic waste composition in the public hospital waste samples while only 26.86 % w/w of organic waste is identified in the private hospital waste samples. It was discovered that the food packing (PP/PET composition) waste at the government hospital is higher than the private hospital. At the public hospital, a food court and canteen are available for the public and patients while the private hospital is only providing food services to their patients. About

18% w/w of mixed paper is discovered at both hospitals probably due to the frequent usage of disposable tissue papers at hospitals. There is almost no hazardous waste found at a public hospital but it was discovered 28.59 % w/w of hazardous waste was found at the private hospital. The hazardous waste mainly is clinical waste which is stored in a yellow plastic bag. The person in charge of the private hospital was contacted for clarification as the hazardous waste shall never be disposed of in the general waste bin.

4.1.3.2 Education Sector

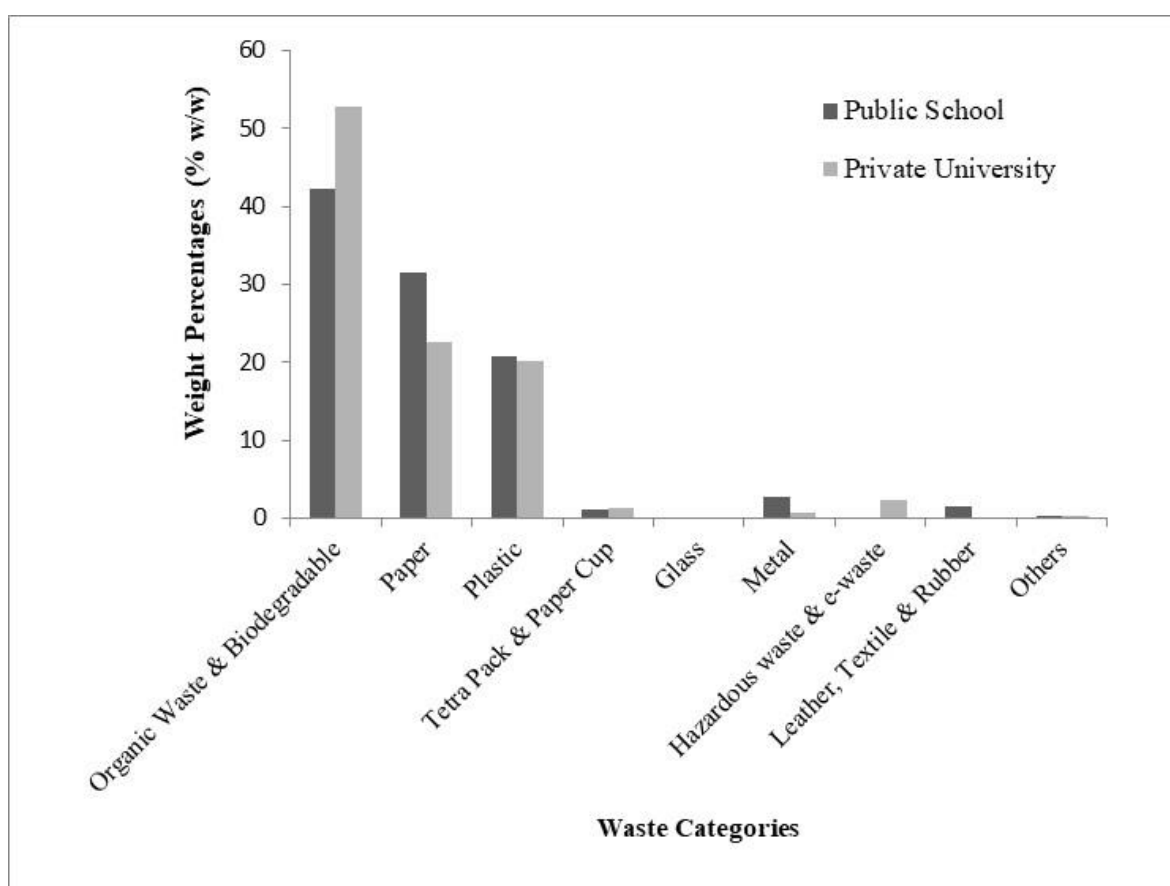


Figure 4.9: Waste Composition at Institutional Area - The Education Sector

Organic waste is found at the highest waste component as well in the academic institution area, which is 42.34 % w/w at school and 52.71 % w/w at private universities as shown in Figure 4.9. At school, the office paper percentage is recorded as 10.94 % w/w indicating that the paper recycling practice at school is not successful. For the private

universities, although it was discovered high paper waste percentage, however, it mainly is a mixed paper which hardly being recycled. The plastic waste which mainly is soft plastic was found to be above 20% w/w for both locations.

4.2 Lab Analysis

4.2.1 Physical Analysis - Proximity Analysis

The moisture, volatile matter, ash, and fixed carbon content is the good indication of the combustibility of municipal solid waste. Tables 4.2 and 4.3 show the result of proximate analysis for municipal solid waste in Kuching. The moisture content, volatile matter, ash, and fixed carbon content were 54.71%, 26.42%, 18.67% and 0.21% respectively for the old landfill and 63.26%, 22.83%, 13.73% and 0.18% for the new landfill.

Table 4.2: Proximate Analysis for Old Landfill Sample

Sample	Proximate analysis (%)			
	Moisture content	Volatile matter	Ash content	Fixed carbon
Old Landfill 1	62.43%	23.46%	13.95%	0.16%
Old Landfill 2	39.82%	33.43%	26.49%	0.26%
Old Landfill 3	61.87%	22.36%	15.56%	0.21%
Average	54.71%	26.42%	18.67%	0.21%

Table 4.3: Proximate Analysis for New Landfill Sample

Sample	Proximate Analysis (%)			
	Moisture content	Volatile matter	Ash content	Fixed carbon
New Landfill 1	58.31%	27.09%	14.59%	0.01%
New Landfill 2	64.23%	21.67%	13.85%	0.25%
New Landfill 3	67.23%	19.72%	12.77%	0.28%
Average	63.26%	22.83%	13.73%	0.18%

The moisture content is high in both samples. It might be due to the samples being collected from an uncovered landfill and there is relatively high rainfall in Kuching. As estimated by The World Bank (2017), Malaysia recorded 2875mm of rainfall in the year 2017, ranked No. 8 among 182 countries. According to the Department of Statistics Malaysia (2021), Kuching recorded 3307.5mm of rainfall in the year 2019, even higher than the highest average rainfall country in the world, Colombia which recorded 3240mm of rainfall (The World Bank, 2017). The municipal waste in Kuching is also containing a high composition of organic waste which will generate water in the biodegradation process. The organic waste will be broken down by microorganisms in the landfill under aerobic conditions at the surface of the landfill and release water and carbon dioxide. Therefore, new landfill samples collected mostly from the surface of the landfill contain higher moisture content. The bottom part of the landfill, which mainly is an old landfill sample, will undergo decomposition under anaerobic conditions. Methane gas and very little amount of water vapour are released under an anaerobic process. An old landfill sample which is covered and not exposed to rainwater is not obtainable in this study.

The volatile matter and fixed carbon are representing the combustible material in the solid waste. Volatile matter is the matter tended to vaporize in the combustion process. High volatile matter fuel can be ignited at low temperatures in the combustion process. Fixed carbon is a substance that can be burned apart by volatile matter.

According to Ibikunle et al (2019), The heating value can be calculated by Equation 4.1.

$$\text{Heating Value} = -7.19477 + 0.116768 * \text{Fixed Carbon} - 0.347288 * \text{Moisture Content} + 0.151701 * \text{Volatile Matter} \quad \text{Equation 4.1}$$

The higher fixed carbon and the volatile matter will increase the heating value of the solid waste, but the moisture content will decrease the heating value. The volatile matter and fixed carbon from both samples are lower than the moisture content, making the solid waste not suitable for combustion. The ash content represents the non-combustible fraction. Both samples show an ash content between 13% to 20%, similar to the value reported by the Confederation of European Waste-to-Energy Plants (2017), which is approximately 20% of the weight fed in. The obtained results are analysed on a dry sample basis as shown in Tables 4.4 and 4.5.

On the dry basis analysis of the waste sample, the fuel ratio (Fixed Carbon/Volatile Matter) for all samples is below 0.01, which represents the fuel can be ignited at low temperatures. However, there will leave about 40% of ash after the combustion is completed.

Table 4.4: Proximate Analysis for New Landfill Sample (Dry Basis)

Sample	Proximate Analysis (%)		
	Volatile Matter	Ash Content	Fixed Carbon
Old Landfill 1	62.44%	37.14%	0.16%
Old Landfill 2	55.55%	44.01%	0.43%
Old Landfill 3	58.64%	40.81%	0.54%
Average	58.88%	40.65%	0.38%

Table 4.5: Proximate Analysis for New Landfill Sample (Dry Basis)

Sample	Proximate analysis (%)		
	Volatile Matter	Ash Content	Fixed Carbon
New Landfill 1	64.99%	35.00%	0.01%
New Landfill 2	60.58%	38.71%	0.71%
New Landfill 3	60.19%	38.96%	0.85%
Average	61.92%	37.56%	0.53%

4.2.2 Chemical Analysis – Heavy Metal

Table 4.6 shows the chemical analysis of heavy metal in the leachate of the old landfill sample and the new landfill sample.

Table 4.6: Chemical Analysis of Heavy Metal in Leachate of Landfill Sample

Parameter	Reading (mg/L)		
	Old Landfill	New Landfill	Standard
Cadmium (as Cd), mg/L	0.02	0.02	0.01
Chromium total (as Cr), mg/L	<0.02	<0.02	NA
Copper (as Cu), mg/L	0.04	0.04	0.02
Iron (as Fe), mg/L	0.28	1.83	1
Lead (as Pb), mg/L	0.49	0.38	0.05
Manganese (as Mn), mg/L	0.87	0.67	0.1
Nickel (as Ni), mg/L	0.13	0.12	0.05
Zinc (as Zn), mg/L	1.24	1.32	5

The concentration of heavy metals found in the leachate of municipal solid waste is high for Lead, manganese and Nickel compare with Standards based on National Water Quality Standards for Malaysia (NWQSM): Class IIB. The significant concentration of Lead and Nickel indicates that the residual paints, glass, lead-acid batteries and other Waste from Electrical and Electronic Equipment (WEEE) are disposed of in the landfill (Ishchenko, 2019). The high concentration of Manganese found in the leachate is likely due to iron corrosion (Rudi et al., 2020). The leachate is toxic to the environment if it is not properly treated. Therefore, it is not recommended to dispose the municipal solid waste at a dump site as the leaching from municipal solid waste will contaminate the groundwater.

There is no significant difference in heavy metal concentration in the old landfill sample and the new landfill sample except iron which was found relatively high concentration in the new landfill sample. However, it is most probably due to the sampling variation of new landfill samples which record high standard deviation. This is in line with the research study by Wdowczyk & Szymańska-Pulikowska (2020), which found a lack of significant differences in heavy metal concentration between active and non-operational landfills.

4.2.3 Chemical Analysis – ED-XRF

XRF (X-ray fluorescence) is the analytical technique which measures the emission of secondary X-ray from the sample when it is excited by X-ray. It can be used to determine the elemental composition of solid waste. The ED-XRF analysis results for the landfill sample are tabulated in Tables 4.7 and 4.8.

Table 4.7: ED-XRF Analysis for Old Landfill Sample

Parameter	Concentration (%)			
	Old Landfill Sample 1	Old Landfill Sample 2	Old Landfill Sample 3	Average
Magnesium	0.16	0.46	0.12	0.25
Aluminium	0.28	1.26	1.15	0.90
Silicon	0.62	2.12	0.89	1.21
Phosphorus	0.02	0.03	0.01	0.02
Sulfur	0.12	0.39	0.11	0.21
Chlorine	0.08	0.07	0.01	0.05
Potassium	0.14	0.16	0.02	0.11
Calcium	0.85	2.23	0.68	1.25
Titanium	0.03	0.11	0.07	0.07
Chromium	0.01	0.01	0.01	0.01
Iron	0.21	0.74	0.49	0.48

Table 4.8: ED-XRF Analysis for New Landfill Sample

Parameter	Concentration (%)			
	New Landfill Sample 1	New Landfill Sample 2	New Landfill Sample 3	Average
Magnesium	0.28	0.18	0.24	0.23
Aluminium	0.62	0.75	0.95	0.77
Silicon	0.97	0.70	0.90	0.86
Phosphorus	0.02	0.01	0.02	0.02
Sulfur	0.22	0.16	0.21	0.20
Chlorine	0.08	0.31	0.36	0.25
Potassium	0.09	0.12	0.13	0.11
Calcium	1.33	1.00	1.16	1.16
Titanium	0.08	0.04	0.05	0.06
Chromium	0.02	0.02	0.02	0.02
Iron	0.53	0.17	0.18	0.29

The XRF results reveal that both the samples from the old landfill and the new landfill contained a high fraction of Silicon, Calcium, Iron and Aluminium. These four elements are the main ingredient of cement. As suggested by Sofi et al. (2019), material high in Silica, Calcium and Iron can be treated as a value-added construction material. Zhu et al. (2020) also observed that waste containing high Calcium, Silicon and Aluminium is suitable as a substitute material for natural aggregate in road construction. Joseph et al. (2018) also suggested using municipal solid waste incineration ash in various building

materials, such as use as road construction material, cement raw meal additive or aggregate in concrete.

4.2.4 Calorific Value by Bomb Calorimeter

Calorific value is the main factor in waste-to-energy incineration plants. Table 4.9 with the calorific value for the old landfill sample and the new landfill sample. The calorific value for the old landfill sample is 2041.86 kcal/kg and the calorific value for the new landfill sample is 2891.9 kcal/kg.

Table 4.9: Calorific Value for Landfill Sample

Sample	kcal/kg			
	1	2	3	Average
Old Landfill Sample	1575.01	2041.06	2509.5	2041.9
New Landfill Sample	3274.3	2748.5	2652.9	2891.9

As reported by Liu & Nishiyama (2020), the Low Calorific Value (LCV) must be at least 6285kJ/kg for a waste-to-energy incineration plant. For incineration of municipal solid waste, also required at least 3,352 kJ/kg of LCV. Therefore, both samples' calorific values are low and not suitable for either waste-to-energy incineration plants or incineration plants. Figure 4.10 illustrates the relationship between proximate analysis and calorific value. The low calorific value is most likely due to the high moisture content of the samples. In order to convert waste to energy, pre-treatment is required to remove the moisture before it sends for incineration.

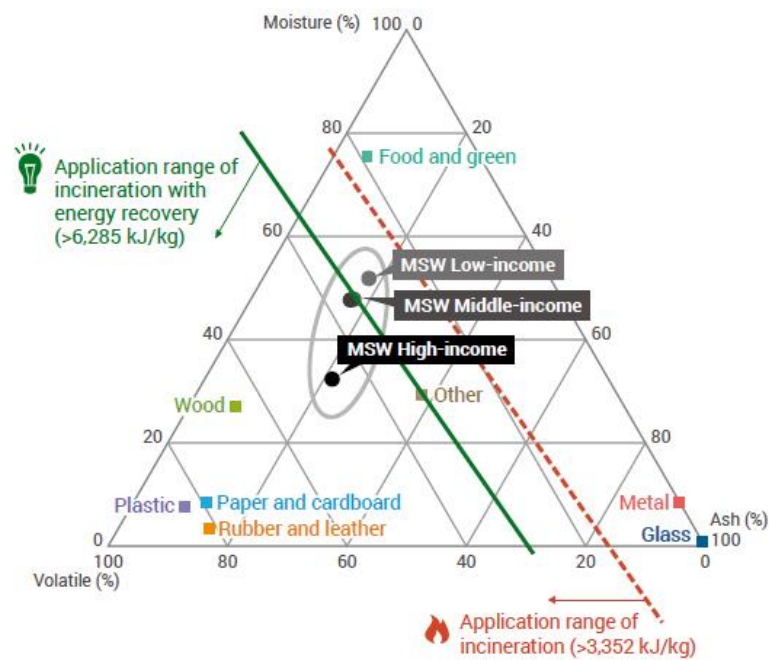


Figure 4.10: Proximate Composition of Different Country Groups and Application Range of Incineration and WtE Incineration (Liu & Nishiyama, 2020)

4.3 Solid Waste Management

4.3.1 Solid Waste Generation in Kuching

According to the Department of Statistics Malaysia (2022), the GDP of Sarawak is shown in Table 4.10. The average GDP growth rate from the year 2015 to the year 2020 is 4.5% annually. Therefore the assumption is made that GDP Sarawak will grow 4.5% annually for GDP projection.

Table 4.10: Gross Domestic Product (GDP) of Sarawak

Year	Gross Domestic Product (RM/capita)
2015	45006.081
2016	45346.404
2017	50176.923
2018	52386.947
2019	53550.762
2020	55930.524

The average solid waste generation rate is 0.88kg/person/day (Kai, 2018), or 0.3212 tonnes/year/capita in the year 2018. The projected waste generation rate for Sarawak is calculated in Table 4.11.

Table 4.11: Projected Waste Generation Rate per Capita (kg/year)

Year	Proxy Gross Domestic Product (RM/capita)	Proxy waste generation per capita (kg/year)	Projected Waste Generation Rate per capita (kg/year)
2020	55930.52	576.03	329.50
2021	58447.40	585.93	335.17
2022	61077.53	595.95	340.90
2023	63826.02	606.09	346.70
2024	66698.19	616.33	352.56
2025	69699.61	626.69	358.48
2026	72836.09	637.17	364.48
2027	76113.72	647.76	370.53
2028	79538.83	658.46	376.66
2029	83118.08	669.28	382.84
2030	86858.39	680.21	389.10

According to the Department of Statistics Malaysia, the population of Kuching is 609,205 in the year 2020 with annual growth of population 0.2%. Hence, the estimated solid waste generated annually in Kuching is shown in Table 4.12 and Figure 4.11.

Table 4.12: Forecast Solid Waste Generated in Kuching (Tonne/Year)

Year	Population	Projected Waste Generation Rate per Capita (Kg/Year)	The Estimated Solid Waste Generated in Kuching (Tonne/Year)
2020	609205	329.50	200736
2021	610423	335.17	204595
2022	611644	340.90	208510
2023	612868	346.70	212479
2024	614093	352.56	216503
2025	615321	358.48	220583
2026	616552	364.48	224719
2027	617785	370.53	228910
2028	619021	376.66	233158
2029	620259	382.84	237462
2030	621499	389.10	241823

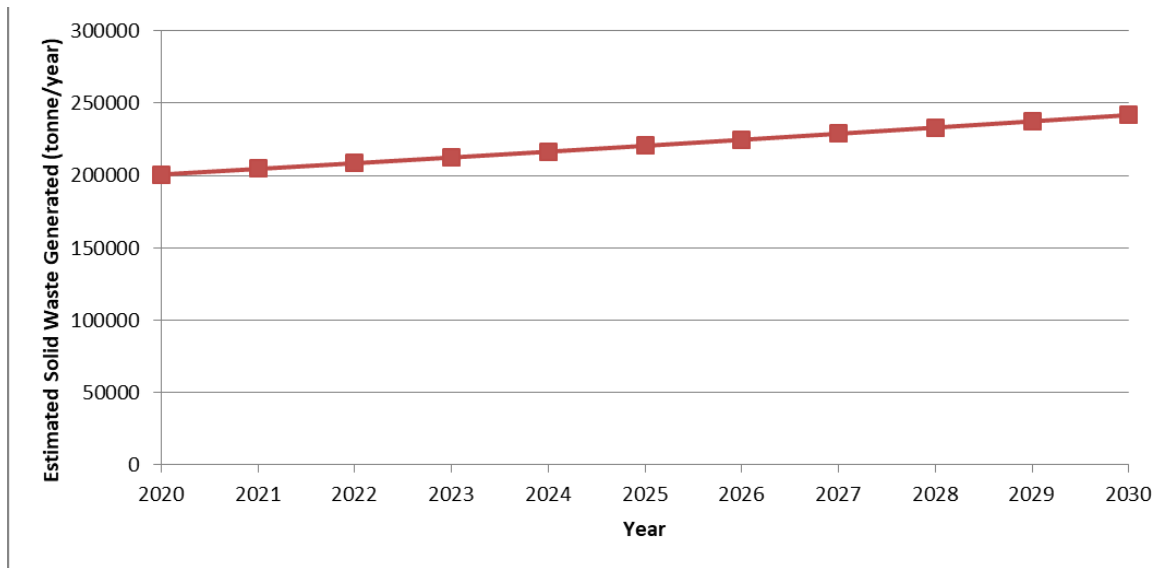


Figure 4.11: Estimated Solid Waste Generated in Kuching (The Year 2020 to the Year 2030)

4.3.2 Energy Recovery – Methane Gas

The municipal solid waste in Kuching is currently disposed of at a level 4 landfill located at Mambong, equipped with a gas flare station. From the waste characteristic study, the main fraction of solid waste is organic waste, which will generate methane gas during the decomposition in the landfill. The flare station will flare off the methane gas generated in a landfill. Figure 4.12 with the estimated landfill gas and methane gas generated by LandGEM (version 3.02) model.

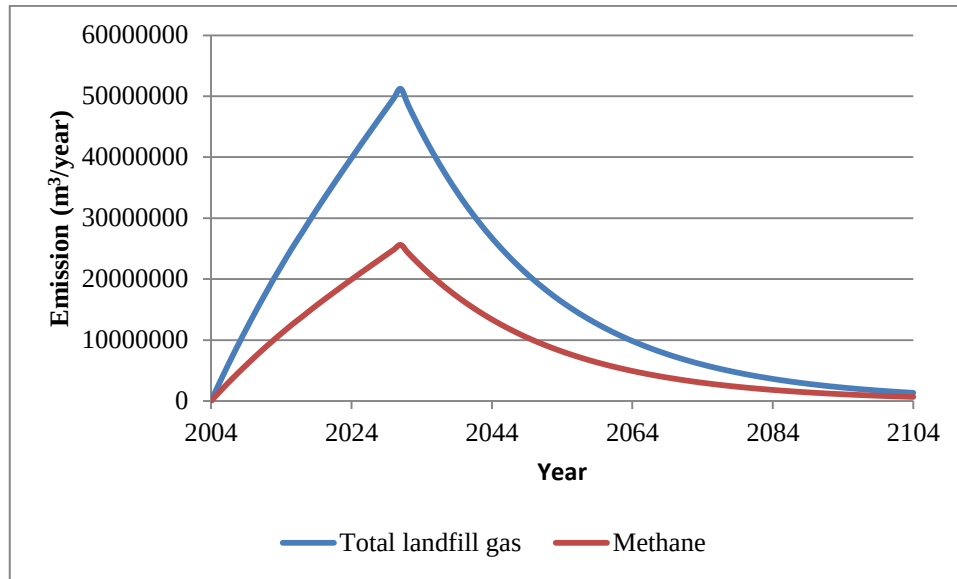


Figure 4.12: Estimated Landfill Gas and Methane Gas Generated

In the year 2021, it is estimated $17400792 \text{ m}^3/\text{year}$ of methane gas is generated at the landfill, or $47673 \text{ m}^3/\text{day}$. The energy released from burning methane gas with oxygen is about $39 \text{ MJ}/\text{m}^3$ or $10.83 \text{ kwh}/\text{m}^3$. Assuming the gas engine efficiency is 40%, 516.3 MWh can be generated every day.

4.3.3 Life Cycle Assessment (LCA)

Although there is a very limited option from the free license LCA software, especially the lack of a recycling database, however, it can be used as a qualitative study in evaluating the alternative MSW treatment method. Table 4.13 shows the impact analysis of two types of disposal methods, which are landfill and incineration.

Table 4.13: LCA Analysis by Different Disposal Methods

Impact Analysis	Landfill	Incineration	Unit
Acidification - CML-IA Baseline	0.32	0.39	kg SO ₂ eq /t
Eutrophication - CML-IA Baseline	1.99	0.08	kg PO ₄ --- eq /t
Global Warming (GWP100a) - CML-IA Baseline	570.62	215.99	kg CO ₂ eq /t
Human Toxicity - CML-IA Baseline	1.97	4.25	kg 1,4-DB eq /t

Overall, it is found that landfilling the biodegradable waste will contribute to global warming gas and eutrophication while incineration of the waste will increase Human Toxicity due to the incinerated plastic waste. Therefore, it is suggested that composting biodegradable waste and recycling plastic waste is the best option to minimize the negative impact on the environment.

Despite the incineration of solid waste being able to reduce the amount of solid waste disposed of in the landfill and also reduce greenhouse gas emission, however, there is some negative impact of the incineration process. Carcinogenic substances such as dioxins are emitted from the incinerator.

4.3.4 Field Observation in Landfill

Field observation was conducted at the landfill. The solid waste collected by the collection truck was discharged into the landfill. The solid waste was then compacted by

heavy machinery. For the fresh discharged solid waste, the waste was in wet condition. Organic food and soft plastic bags were the main items being seen in the landfill. The area is an open, unshaded area which is exposed to rain and shine throughout the year. On the other hand, the waste disposed of years ago is temporarily covered by HDPE sheets before being used as a new platform for solid waste discharge. The main component that was observed in this area is plastic bags. Figure 4.13 illustrates the municipal solid waste disposed at the landfill.



Figure 4.13: Field Observation in the landfill

As discussed earlier in section 4.1.1, the main component of the solid waste in Kuching is organic waste, which increased the moisture content of the waste, which made the solid waste is not suitable for incineration. However, for the solid waste disposed of for years, most of the organic waste is biodegraded and leftover plastic waste is contaminated with mud. If the solid waste disposed of can be collected without exposing it to fresh solid waste and rain, it might be the feedstock for incineration.

4.3.5 Sustainable Solid Waste Management System with Zero Waste Management

Figure 4.14 depicts the proposed solid waste management in Kuching by using the data obtained from the waste composition study and lab analysis.

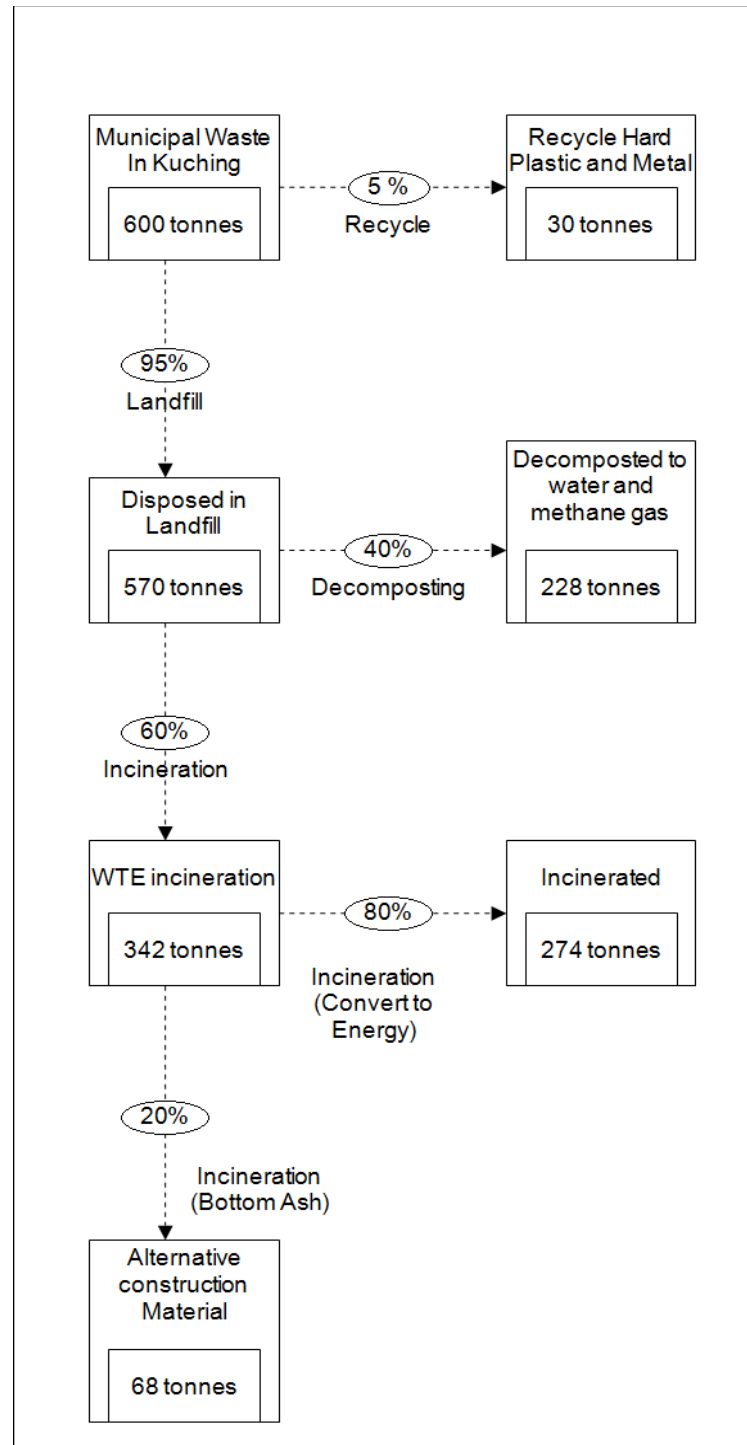


Figure 4.14: Proposed Solid Waste Management in Kuching

The solid waste generated in Kuching which can be collected is estimated at daily 600 tonnes/day. Recycle items such as hard plastic, and metals are sorted out and recycled. In this study, the amount of recycled items found in residential waste ranged from 7% to 20%. It is not feasible that all of the recycled items be sorted out, hence it is set 5% of total waste is sorted and recycled. The remaining waste such as organic waste, and soft plastic waste will send for disposal.

As the segregation of the organic waste at the source is not feasible at the moment, the remaining waste after the recycling activities is disposed of in the landfill, which is equipped with a landfill gas harvesting system for recovering energy. As reported by Ignatowicz et al. (2023), biogas from landfill can be one of the alternative fuels for replacing fossil fuels in an environmentally friendly manner. The organic waste composition is found 61.58% in this study. Therefore an estimated 40% of the waste (organic waste) will be decomposed in a landfill after several years. Leachate water will be treated and methane gas generated in the decomposition process can be harvested for generated energy.

Plastic waste which does not decompose will remain in the landfill. Therefore, landfill mining will be done to the old waste in the landfill. The waste which contained higher composition of plastic and lower composition of organic matter will have higher volatile matter and calorific value. It will be sent for waste-to-energy incineration. Although there is a risk of human toxicity from the incineration process, however Tang et al. (2022) suggested that there are no significant health risks to the surrounding population if there is a proper flue gas treatment equipped at the incinerator.

The ash content of the old landfill sample is found at 18.67%. Therefore it is estimated about 80% of the waste will be incinerated and generated energy and an estimated 20% of bottom ash will be generated from the incineration process. The bottom can be used as construction material.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions and Recommendations

The waste composition of municipal solid waste is the most crucial element in the waste management system. During this study, organic waste is discovered to be the dominant waste generated by the resident of Kuching, followed by plastic waste. Organic waste should be segregated and waste composting should be encouraged in order to reduce organic waste. Currently, there is no legislation yet against the food waste problem in Sarawak. For commercial waste, waste segregation is found done by the company which generated a large amount of recyclable items, but not for small enterprises, most probably due to small profit gain from the recycling activities. High organic waste is found in the market as well. Currently, there is a Green Technology Tax Incentives by the government for a company that uses green technology, but there are no incentives for the company that practice recycling activity or market which practice waste composting. Such measures should be considered to improve the recycling rate in the commercial sector. Else legislative action to enforce recycling activity in the commercial sector should be implemented. For institutional wastes especially from the education sector, a large amount of recyclable items is discovered although recycling awareness campaigns and activities in school have been promoted long ago. This substantiated that the students might still lack reusing and recycling awareness. Thus, emphasis on reused and recycling awareness campaigns and activities in schools and universities should be prioritised for environmental sustainability.

The municipal waste from a landfill either from a new landfill or an old landfill is not suitable for incineration due to high moisture content and low calorific value. The leaching water from landfill is toxic to the environment as it contains a high concentration of heavy metal. The study shows that the moisture content which is most probably generated from the organic waste should be removed or reduced in order to use the municipal waste as biofuel for incineration to generate energy.

The amount of solid waste generated in Kuching city is increasing in trend as the population in Kuching city is increased. In a circular economic cycle, waste composition study is only the first step in waste management followed by waste sorting and separation. For sustainable waste management, the waste has to be recycled or treated so that all the recyclable items will channel back to production.

A sustainable waste management system with a zero-waste approach is feasible in Kuching city. Recycle items such as hard plastic, and metals should be sorted out and recycled. The waste which contained higher composition of plastic and lower composition of organic matter should be directed for waste to energy incineration. The implementation of the sustainable waste management system with a zero-waste approach in Kuching will require support from the government as this sustainable direction requires massive capital investment and minimal return on investment.

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APPENDICES

Appendix A: Journal Publications

1. **Lee, Y. W.**, Lim, S. F., Chow, T. P., & Chua, D. S. N. (2022). Quantification assessment of municipal solid waste as an evaluation apropos of sustainable waste management in Kuching. *Journal of Sustainability Science and Management*, 17(6), 128-151.