PERFORMANCE OF VIBRATION-INDUCED ELECTRODE PLATES IN BATCH ELECTROCOAGULATION FOR STABILIZED LANDFILL LEACHATE TREATMENT

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by

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LIST OF SYMBOLS

%	Percentage
A	Amphere
V	Voltage
g/L	Gram per litre
mg/L	Milligram per litre
CH4	Methane
CO2	Carbon Dioxide
H2S	Hydrogen Sulphide
H2	Hydrogen
N2	Nitrogen
°C	Degree Celcius
$M_{(s)}$	Metal
$M^{n+}_{(aq)}$	Metallic Ion

LIST OF ABBREVIATIONS

AF	Anaerobic Filter
AC	Activated Carbon
AOP	Advanced Oxidation Process
Anammox	Anaerobic Ammonium Oxidation
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CF	Coagulation/flocculation
CCD	Central Composite Design
CSI	Class Separation Indices
CSM	Class Sample Matrix
CSV	Class Sample Vector
CWM	Class Weight Matrix
CWV	Class Weight Vector
DC	Direct Current
DOE	Department of Environment
DLVO	Derjaguin-Landua-Verwey-Overbeek
EC	Electrocoagulation
EB	Electron Beam
FA	Fulvic Acid
GAC	Granular Activated Carbon
HA	Humic Acid
Hyl	hydrophilic
IPS	Institut Pengajian Siswazah
KPKT	Department of Housing and Local Government
MF	Microfiltration
MBBR	Moving Bed Biofilm
NH_3-N	Ammoniacal Nitrogen
NF	Nanofiltration
PAC	Powder Activated Carbon
RMS	Root Mean Square
RSM	Research Surface Methodology

RBC	Rotating Biological Contactors
RO	Reverse Osmosis
SEM	Scanning Electron Microscope
TOC	Total Organic Carbon
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
UASB	Up-flow Anaerobic Sludge Blanket
UV	Ultraviolet
US	Ultrasonic
VOA	Volatile Organic Acid
VFA	Volatile Fatty Acid
WFD	Waste Framework Directive

PRESTASI PLAT ELEKTROD ARUHAN GETARAN DALAM ELEKTROKOAGULASI KELOMPOK UNTUK RAWATAN LARUT RESAP TANAH ISIAN TERSTABIL

ABSTRAK

Kekuatan tinggi larut lesap tapak pelupusan telah mengehadkan kecekapan elektrokoagulasi disebabkan oleh beberapa kelemahan seperti pempasifan elektrod dan pengumpulan buih pada permukaan elektrod yang meningkatkan rintangan pemindahan ion. Kajian ini menyiasat prestasi elektrokoagulasi kelompok dengan plat elektrod yang disebabkan oleh getaran dalam rawatan larut resapan tapak pelupusan terstabil yang diperoleh daripada Tapak Pelupusan Pulau Burung untuk menambah baik penyingkiran COD, warna dan penyingkiran NH3-N. Kajian awal tentang kesan jarak interelektrod, ketumpatan arus dan masa elektrolisis yang dikaji mendedahkan bahawa penyingkiran bahan pencemar menunjukkan trend yang meningkat sehingga mencapai keadaan optimum. Reka bentuk eksperimen lanjut yang melibatkan pH awal, keamatan getaran dan masa elektrolisis menunjukkan bahawa keadaan optimum diperoleh pada pH 4.4, 45 minit dan intensiti getaran 3.8V dengan 23.8% COD, 92.8% warna dan 43.8% NH3-N, masing-masing. Persediaan keadaan optimum telah dianalisis selanjutnya dan dibandingkan dengan elektrokoagulasi pegun dan elektrokoagulasi dengan bantuan kacau magnet pada 200 rpm. Pengimbasan mikroskop elektron (SEM) mendedahkan bahawa elektrokoagulasi dengan akibat getaran menunjukkan lekuk yang licin dan serupa berbanding dengan intensifikasi elektrokoagulasi yang lain Tahap ketidakstabilan zarah menunjukkan bahawa elektrokoagulasi akibat getaran memperoleh keadaan mantap yang lebih cepat berbanding dengan elektrokoagulasi lain. Pecahan bahan humik menunjukkan bahawa

EC sangat berkesan untuk menghilangkan COD dan asid humik. Oleh itu, aplikasi elektrokoagulasi akibat getaran boleh digunakan sebagai alternatif kepada rawatan fizikokimia walaupun masih terdapat penambahbaikan yang perlu dilakukan.

PERFORMANCE OF VIBRATION-INDUCED ELECTRODE PLATES IN BATCH ELECTROCOAGULATION FOR STABILIZED LANDFILL LEACHATE TREATMENT

ABSTRACT

The high strength of landfill leachate has limited the efficiency of electrocoagulation due to several drawbacks such as the passivation of electrodes and accumulation of bubbles at the surface of the electrode which increased the resistance of ions transfer. This study investigated the performance of batch electrocoagulation with vibration-induced electrode plates in the treatment of stabilized landfill leachate obtained from Pulau Burung Landfill to improve the removal of COD, colour and NH_3-N removal. The preliminary study of the effect of interelectrode distance, current density and electrolysis time studied revealed that the removal of pollutants showed an increasing trend until reaching optimum conditions. Further experimental design involving the initial pH, vibration intensity and electrolysis time indicated that the optimum conditions were obtained at pH 4.4, 45 minutes and vibration intensity of 3.8V with 23.8% COD, 92.8% colour and 43.8% NH_3-N, respectively. The optimum conditions setup was further analysed and compared with stationary electrocoagulation and electrocoagulation with aid of magnetic stirring at 200 rpm. Scanning electron microscopy (SEM) revealed that electrocoagulation with vibration-induced shows smooth and identical dents compared to other electrocoagulation intensification The degree of particle destabilization indicates that vibration-induced electrocoagulation obtained faster steady states compared to other electrocoagulation. The fractionation of humic substances showed that EC was particularly efficient to remove COD and humic acid. Therefore, the application of vibration-induced electrocoagulation can be

used as an alternative to physicochemical treatment although there are still improvements to be made.

CHAPTER 1

INTRODUCTION

1.1 Background of study

The generation of solid waste is undoubtedly increasing at a rapid rate without any sign of slowing down. The continuous increase in solid waste generation can be described because of the Industrial Revolution 4.0 drive which see the opening of numerous industrial zones worldwide. The revolution causes the migration of workers for job opportunities and thus occupied this area. As a result, a dense community is formed which will increase the demand and usage for various essential needs. However, as demand and usage increase, the generation of solid waste is most likely to increase. For this reason, a proper waste management and action plan are required to handle these issues from cradle to grave. Waste management is considered vital for each country to mitigate any illegal disposal and pollution. Countries spend millions of dollars on vehicles, technologies, and treatment processes to ensure that waste can be safely disposed of. Solid waste is projected to grow up to 3.40 billion tonnes globally by 2050 as described in Figure 1.1 (Kaza et al., 2018). The projection data also described that 0.74-kilogram waste per capita per day generated and accumulated around 0.11 to 4.54 kilograms per capita per day depending on the native country. The solid waste composition can be varying from one country to another. Common waste contributors include industrial, commercial, and agricultural by-products (Kamaruddin et al., 2015). Current treatment technologies vary from conventional treatment to integrated treatment methods. Treatments such as landfilling, incineration, and composting have been widely applied besides having waste minimization and recycling processes to reduce the total amount of waste. The reliance on landfilling process is still high in numerous nations especially developing countries including

Malaysia. Malaysia has regulated Solid Waste and Public Cleansing Management Act 2007 (Act 672) for almost all states in the country. As reported by (MIDA, 2022)the total of 38,427 metric tonnes per day of solid waste are generated in 2022, which 82.5% were estimated disposed to the landfill. Overall, Malaysia generates an estimation of 14 million metric tonnes per annum in 2022.

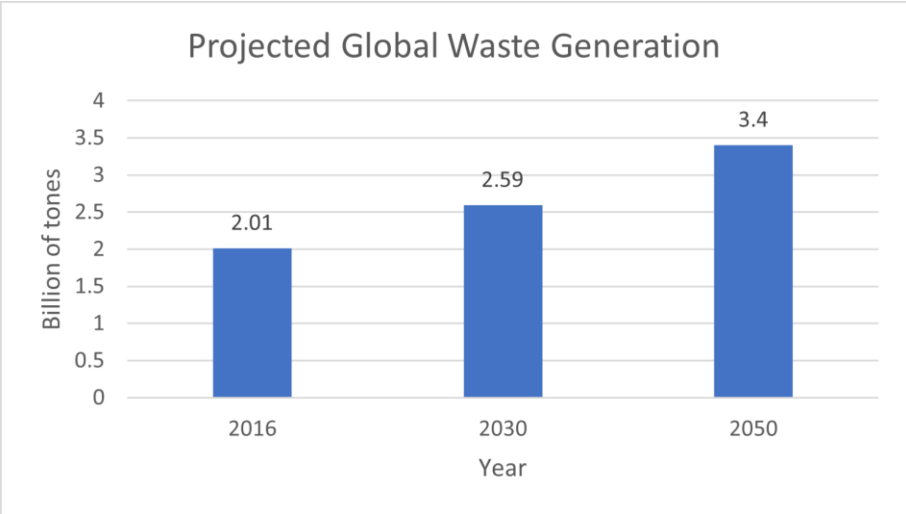

Figure 1.1 The projected global waste generation (Kaza et al., 2018)

Municipal solid waste can be best described as unwanted materials produced by human activities and the owners discard or intend to discard within the area of municipal (Abas & Wee, 2014a). In Malaysia, household waste is the most dominant waste with 65% of total waste compared to industrial or commercial and institutional waste. According to report by the Department of Housing and Local Government (KPKT, 2015), household waste compromise of food and organic, plastics, paper, diapers, gardens, and others (glass, textile, metal, e-waste, etc). Food and organic waste are undoubtedly the highest contributors because daily consumption and routines resulted in 45% of total household waste. All waste will end up in the landfill unless the waste is segregated for recycling or any waste recovery purposes. Although a recent report showed Malaysia exceeded the set target of a 28.1% recycling rate in 2019, however, the massive amount of waste is still managed using landfilling process.

Landfilling has been applied worldwide for decades. Even with the emergence of the latest technology, landfilling is still considered the main option specially to handle a massive amount of waste at once. Generally, almost all countries from developed to developing nations own various types of landfills which can be differentiated by the advancement of technologies. The recommended landfill is undoubtedly the sanitary landfill with an engineered system for leachate treatment and gas collection system. However, the cost and maintenance for this type of landfill are considered high to be implemented for all landfills. Developed countries and a small percentage of developing countries with proper solid waste management funding only could afford such a type of landfill. The main advantages of landfilling process are due to its cost-effectiveness and the ability to manage the overwhelming amount of waste daily. As one of the developing countries, Malaysia recorded a total number of 16 operating and ongoing sanitary landfill to cater huge amount of waste generation. There are numerous open dumpsites nationwide but considered unsafe and less environmentally friendly. Besides all the advantages of the landfilling process, land scarcity and low aesthetics value becoming a concern for the citizens, especially the surrounding community (Hanif et al., 2022). A landfill can only last until full capacity before being closed and recovered. The major concern in landfilling process is the generation of landfill leachate which is considered very recalcitrant and high strength. Leachate contamination in the surface and groundwater could cause serious pollution and damage the aquatic environment. The presence of toxic components in the aquatic environment due to leachate leads to bioaccumulation over long-term exposure (Mavakala et al., 2016).

Over the past decades, various technologies have been applied from biological, chemical, physicochemical and the recent membrane treatment system. However, the effectiveness and suitability of each treatment depend on the leachate ages (young, intermediate, and old). The composition for different leachate ages is different and thus requires a different method. The main goal of having treatment technology is to comply with the legislation established by the government.

Electrochemical technologies are not excluded from being utilized in wastewater treatment including landfill leachate treatment. Electrochemical treatment technologies capitalize on the knowledge of electrochemistry to remove pollutants or minimize a certain concentration level in wastewater. Various technologies can be recognized under this category such as electrochemical oxidation, electrochemical reduction, electrocoagulation/ electrocoagulation-flotation, electrodialysis, photoelectrochemical and sono-electrochemical (Feng et al., 2016a). The ultimate reason for the selection of any electrochemical technology as the main treatment process is the use of an electron as a reagent commonly praised as a “clean reagent” (Feng et al., 2016a). The flexibility and versatility of this treatment could offer treatment for various types of wastewaters. Besides, electrochemical technology also provides high removal efficiency, low cost, simple operation, and time saving. Electrocoagulation (EC) is one of the promising technologies used for wastewater treatment including landfill leachate treatment. Commonly compared to the conventional coagulation/flocculation process, EC could be described as an improvement from the previous method by producing lower sludge volume and does not consume any chemical addition. Apart from that, parallel reaction during electrocoagulation, electro flotation, would help the transportation of the flocs network upward. The ability of EC in treating landfill leachate is recognized and several intensification processes of the experimental design have been explored such as chemical or physical intensification. Vibration is one of the most interesting physical intensifications that gains attention to improve the removal of pollutants in EC of landfill leachate.

1.2 Problem Statement

The increasing waste generation and the dependence on landfilling process significantly becoming an environmental burden to society. Both factors lead to a major environmental concern, the production of landfill leachate. Leachate has gained high attention due to its high strength and various pollutants load within the wastewater. The continuous generation of leachate worsens the scenario as the leachate needs to be treated before being released back into the environment. Even though almost all modern and engineered landfill equipped with a proper leachate treatment system, leachate still poses a big risk to the environment especially when not be treated properly.

Landfill leachate can be very toxic and complex due to the presence of heavy metals and organic matter. The presence of humic substances for example causes a low degradation of the organic compound. Due to this situation, various conventional treatment technology unable to achieve effective removal (Lima et al., 2017a). In Malaysia, the landfill leachate needs to comply with the permissible limit set by the Department of Environment for final discharge. Landfill leachate in Malaysia is found to have a value much higher compared to the permissible limit in term of COD, colour, heavy metals and NH_3-N. Even after being treated by conventional technology, some parameters are still found to exceed the requirements.

Alternative treatment offered by electrocoagulation is found to be capable to remove pollutants in landfill leachate. Electrocoagulation generates in-situ coagulant formation, low sludge formation, no chemical addition and shorter electrolysis time. Electrocoagulation has been successful in treating various wastewater and landfill is one of them. Several pollutants removal have been achieved via electrocoagulation of landfill leachate.

Conventional treatment using coagulation/flocculation (CF) is formerly used as one of the technologies used in treating landfill leachate. However, CF requires the addition of an inorganic coagulant to initiate the process. As reported by Wang et al., (2005), the addition of coagulants is required to destabilize and agglomerate the particles. However, this process is considered slow and less effective especially when dealing with a large amount of wastewater or continuous treatment of wastewater. This situation creates a tremendous effect on the landfill operator to deal with a large amount of landfill leachate daily. Thus, a faster and more effective treatment landfill leachate treatment using electrochemistry has come into the spotlight. Even though electrocoagulation has been widely applied and achieved great pollutants removal, a few factors such as passivation and bubbles accumulation reduce the ability of electrocoagulation from achieving much higher pollutants removal. The accumulation of bubbles and metal oxides on the surface of electrode eventually form an oxide layer on the electrode. As reported by Asselin, Drogui, Benmoussa, et al. (2008) Sahu et al., (2014) and C.-T. Wang et al. (2009), the formation of this oxide layer will act as electrolyte resistance which eventually reduces the mass transfer between the electrodes and bulk solution. Another drawback of electrocoagulation involves the formation of a fragile flocs structure. Safwat (2020) in his study identifies that in typical electrocoagulation system, a fragile and big flocs structure was formed thus requires a series of regrowth process. The build up of flocs is unstable especially when colliding between each other during the treatment process. Hence, the flocs will break down into smaller flocs which are more compact before regrowth into a larger and stable formation. Besides a typical electrocoagulation system, an advance electrocoagulation treatment system includes the utilization magnetic stirring to enhance pollutants removal. However, the stirring conditions heavily influences the performance of EC treatment. The agitation speed show be at the optimum conditions to avoid inefficient treatment. Bayar et al. (2011) identify that a strong agitation speed will break the floc formation as there are much higher collision rate and low time of interaction between the flocs.

Physical treatment using vibration is one of the available options that can be used to prevent electrode passivation while enhancing the mixing and removal of pollutants. Although there is little work on this intensification has been found, there are still massive gaps of knowledge on the removal and mechanism of this intensification process, especially for the treatment of landfill leachate. Thus, this study will be focusing on the utilization of vibration as intensification for electrocoagulation for stabilized landfill leachate treatment.

1.3 Research Objectives

1.3.1 Objectives 1

To study the effects vibration-induced electrocoagulation via experimental design modelling.on the operating parameters (current density, electrolysis time and vibration intensity) and its optimum condition for COD, colour, and NH_3-N removal.

1.3.2 Objectives 2

To study the vibration-induced electrocoagulation and conventional electrocoagulation (stationary and magnetic stirring electrocoagulation) on the morphological changes and the effects on the electrocoagulation plates.

1.3.3 Objectives 3

To study the vibration-induced electrocoagulation and conventional electrocoagulation (stationary and magnetic stirring electrocoagulation) on the fractionation of humic substances and particle destabilization.

1.4 Scope and limitation of the study

The scope of this study focused on the treatment of stabilized landfill leachate by primary treatment using vibration-induced electrocoagulation. Stabilized landfill leachate was collected from Pulau Burung Sanitary Landfill. Preliminary studies were done to assess the effect of variables such as interelectrode distance and current density to identify suitable ranges. The limitation of this study is the batch treatment of stabilized landfill leachate using vibration-induced electrocoagulation without having any prior pre-treatment process.

In this study, the works will be carried out using the EC process followed by process optimization based on one factor at time experiments were performed. The focus of this study is the removal efficiency of the EC on COD removal. Colour and ammoniacal nitrogen are also included in this study. Metal electrodes is used in this study as suggested by the literature review. The introduction of vibration will have a significant impact on the morphology of electrodes and the flocs structure. Thus, the structural changes will be observed and compared to the typical electrocoagulation system. The electrocoagulation treatment system optimized using Response Surface

Methodology (RSM) consisting of factors such as initial pH, vibration intensity and electrolysis time. The optimized electrocoagulation conditions will be further characterized and compared to the predicted value based on the statistical model prediction. Vibration intensity, electrolysis time, and current density will be carried out to assess the effects of each parameter based on the optimized conditions for the removal of COD, colour, and NH_3-N.

1.5 Organization of the Thesis

The organization of this thesis can be divided into five chapters which are constructed in an orderly manner.

Chapter one introduces an overview of the waste management system in Malaysia especially landfilling process that leads to the generation of landfill leachate. The detrimental effects of leachate have been further explained especially if not treated properly as risks that may arise to water security. The comparison of conventional coagulation/flocculation and electrocoagulation is also mentioned in this chapter as well as the need for electrocoagulation treatment for landfill leachate treatment. Problem statement, objectives, scope and limitation of the study, and the organization of the thesis.

Chapter two presents a literature review that covers the landfill management system and the leachate formation throughout the process. This chapter also covers the previous and available treatments used for landfill leachate varying from biological, chemical, and physicochemical treatment performance. Information on electrochemical technologies is also mentioned and the focus is ultimately given to electrocoagulation. The operating parameters are elaborated in detail based on the previous studies. Process intensification is honourably mentioned and discussed to provide insight for better removal efficiency. The last section then focused on the optimization and characterization of the optimized parameter.

Chapter three presents the list of materials and chemical reagents used in the research work. The experimental procedure for research work is explained in detail for each experiment including the instrumentation. The schematic flow diagram shows the overall activities carried out in this research.

Chapter four presents the results from the experimental works for one factor at time. Further data collected from the experiment were used in variables for modelling. The data collected from the experimental works were analysed using the model. The later part of this chapter presents the comparison of an optimized vibration-induced electrocoagulation compared with normal electrocoagulation and electrocoagulation with aid of magnetic stirring. The comparison were shown in term of the effect all electrocoagulation system toward the morphological of the electrode, the flocculation index and also the fractionation of humic substances.

The last chapter, chapter five concludes the overall performance of the experiment based on all objectives. Recommendations for future research work are also mentioned which may help for improvement in the treatment system.

CHAPTER 2

LITERATURE REVIEW

This chapter will be divided into several sections which provide the background information of this study. The chronology of this chapter in general are as follows: (i) solid waste management practise via landfilling; (ii) landfill leachate generation and its composition; (iii) methods of landfill leachate treatment; (iv) electrochemical treatment process and its contributing factors; and intensification of electrocoagulation.

2.1 Landfilling

Waste management can be divided into several methods and landfilling is one of the options available. The United States Environmental Protection Agency (USEPA) had come out with a waste management hierarchy that lists several techniques from the most environmentally friendly to the least environmental practices as shown in Figure 2.1.

Figure 2.1 Waste management hierarchy (United States Environmental Protection Agency, 2019)

The hierarchy was established in the appreciation that no particular waste management solution is appropriate for all materials and waste streams in all situations. As part of a sustainable materials management strategy, the hierarchy emphasizes minimizing, reusing, and recycling. The European Union through Directive 2008/98/EC of the European Parliament 2008 or known as the Waste Framework Directive (WFD), is an aggressive approach to dealing with solid waste in the European region. The European member states are required to construct and plan the structure for sustainably handling municipal solid. Aspects that need to be considered include reduction of waste, recycling, recyclability, recovering electricity, and disposal in a landfill.

Based on the waste hierarchy, landfilling sits at the bottom which is deemed to be the least preferred method compared to others. However, landfilling is still considered the most applicable method due to its financial capability and the ability to treat an abundance of waste at the time. Even though the concept of landfilling process does not vary from the past until the present, the design for modern engineered landfills has improved the safety aspects and provided better environmental monitoring. Figure 2.2 has conceptualized the comparison between the old-style sanitary landfill and the modern type of sanitary landfill. In the modern type of sanitary landfill, improvements have been made to the base of the landfill which theoretically prevents the diffusion of landfill leachate from reaching the groundwater. Gas and water monitoring are major upgrades that able the landfill operator to indicate any non-compliances that happen within the landfill operation. Landfill leachates are properly collected and supplied for treatment before discharge. Gases produced from the degradation activities within the landfill cells can be recovered for further use. The solid waste collected from the municipalities occupies each cell in the landfill until reaching the limit. Each cell is filled until full capacity before being covered by soil to prevent any bad odour or presence of pesticides. In addition, a protective clay cap is applied once the landfill reached full capacity to reduce surface runoff and excessive water percolation via the soil matrix.

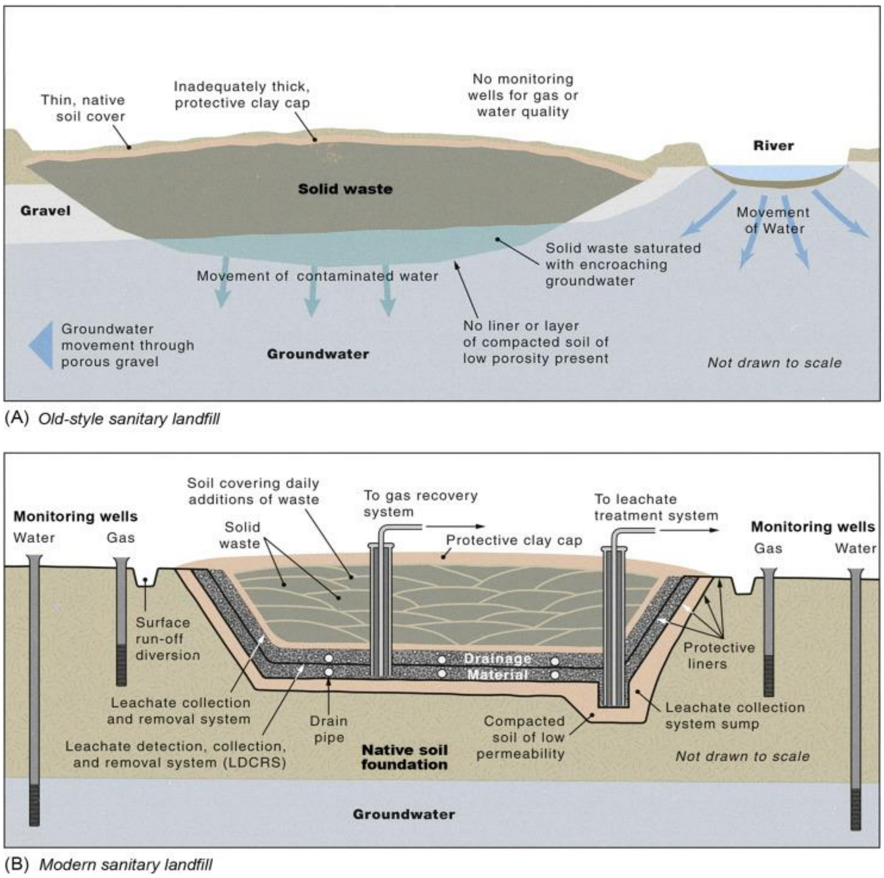

Figure 2.2 Difference between traditional landfill’s plan and modern constructed landfill

The presence of a sanitary landfill system has replaced the old-fashioned open dumpsite system. The sanitary landfill can be classified as an engineered waste disposal method compromising technical aspects such as sitting, design, operation, and long-term environmental impacts (Kamaruddin et al., 2017). Unlike modern landfill systems, open dumpsite does not consider and cover the management of landfill leachate, landfill gas, and odour management. Thus, the sanitary landfill system does not consider the non-engineered landfill system such as open dumpsite as one of the levels in the landfill hierarchy which consist of four different levels (Level 1-4) based on their operational status. In Malaysia, according to the Technical Guideline for Sanitary Landfill, Design and Operation by the Department of Housing and Local Government (KPKT, 2006), open dumping has been included as a level 0 landfill. Malaysia via KPKT has classified landfill leachate as follows:

Table 0.1 Landfill hierarchy (KPKT, 2006)

Level of the landfill	Description
Level 0	Open dumping
Level 1	Controlled tipping
Level 2	Sanitary landfill with a bund and daily cover soil
Level 3	Sanitary landfill with leachate recirculation
Level 4	Sanitary landfill with leachate treatment

Table 0.2 Statistic for the sanitary and non-sanitary landfill in Malaysia (MHLG, 2022)

State	Disposal Site			
	Sanitary	Non-sanitary	Inert	Total
Johor	1	7	-	8
Kedah	3	1	-	4
Kelantan	-	10	-	10
Melaka	1	-	-	1
Negeri Sembilan	1	2	-	3
Pahang	3	7	1	11
Perak	1	15	-	16
Perlis	1	-	-	1
Pulau Pinang	1	-	1	2
Sabah	1	21	-	22
Sarawak	3	43	-	46
Selangor	3	2	3	8
Terengganu	1	8	-	9
W.P. Kuala Lumpur	-	-	-	-
W.P. Labuan	1	-	-	1
W.P Putrajaya	-	-	-	-
Total	21	116	5	142

Malaysia has recorded a significant increase in the opening of sanitary landfills. Data recorded by Malaysia Open Data Portal and verified by the Malaysia National Solid Waste and Management Department has shown the number of sanitary landfills doubled from 2016 to 2017. The increasing number of sanitary landfills has increased water security and provided mitigation measures to control landfill leachate. The statistics for both sanitary and non-sanitary landfill in Malaysia is shown in Table 0.2 (MHLG, 2022). Even though most of the landfills in Malaysia are considered level three sanitary landfill systems, the facilities equipped are still not up to the required specification. As a result, almost 80% of the total amount of landfills in Malaysia are still being controlled tipping or open dumping practices due to lower cost operation and maintenance. To improve the landfill management system, some approach has been taken by the government such as the privatization of the landfill (Abas & Wee, 2014b). Pulau Burung Landfill and Kundang Landfill are among the earliest landfill that benefits from privatization. Through this initiative, the landfill's facilities have been upgraded to comply with level 3 and level 4 requirements.

In some states, the local authorities have established waste transfer stations to assist solid waste management, especially for segregation and transportation purposes. Penang, Selangor, Kuala Lumpur, and Johor are states that adopted this approach to increase the efficiency of waste transportation. In a dense city with high traffic amount, transportation and collection of solid waste are crucial and time-consuming. As the generation of waste in business districts and facilities might be double the usual waste source, an efficient model for waste transportation is required. A typical compactor unit requires several trips from the waste source to the landfill to cover the massive amount of waste generated. Hence, an integrated and systematic approach such as a waste transfer station is required to collect all waste generated. Besides, the waste transfer station function as a waste recovery facility to retrieve valuable materials from solid waste. Another bright sight of the waste recovery facility includes the compaction of unwanted waste into the silo which is then transported to a nearby landfill without creating any bad. The purpose of compaction is to reduce the size of solid waste before being disposed of at the landfill to maximize the space of the landfill (Abas & Wee, 2014b).

Besides of operational status of the landfill, the landfill in Malaysia can also be classified according to the decomposition process. Microbial activities, aeration system and leachate collection system are the main components that are used to distinguish between these landfills. Aerobic, semi-aerobic and anaerobic landfill are three classes that are used to differentiate the landfill system. Further description of the landfill classification system on the decomposition process has been explained in detail in Table 0.3. According to KPKT (2006), a semi-aerobic type of landfill is the most desirable landfill design for Malaysia. The semi-aerobic landfill also known as the passive aeration mechanism which first developed and tested in Fukuoka, Japan (Theng et al., 2005). This method of landfilling is called the Fukuoka method which is taken from the name of the location the pilot project is carried out. In general, the Fukuoka method has been designed to suit the temperate climate and has been adopted in countries such as China, Sri Lanka, Iran, and Southeast Asia countries including Malaysia. Practically, this system operates by passing oxygen into waste mass via a leachate piping system by passive ventilation process. This situation helps aerobic microbial to increase the decomposition rate in the bulk waste as well as improve leachate quality. The benefit of implementing this type of landfill is because of its simple operation and being considered environmentally friendly. Besides, it can also be considered economically friendly and easy to maintain.

Table 0.3 Landfill classification system based on the decomposition process employed.

Landfill type	Characteristics
Anaerobic landfill	Solid wastes are filled in the dug area of the plane field or valley. Waste is commingled with water in an anaerobic condition.
Anaerobic sanitary landfill covered daily	Solid waste is covered in a sandwich shape.
Improved anaerobic sanitary landfill	A leachate collection system is installed at the bottom of the landfill site. The conditions are still anaerobic, but the moisture content is much less than the anaerobic sanitary landfill.
Semi-aerobic landfill with natural ventilation and leachate collection facilities	The leachate collection duct is bigger than the one of an improved sanitary landfills. The opening of the duct is surrounded by air and the duct is covered with small, crushed stones. Moisture in solid waste is low. Oxygen is supplied to the solid waste from the leachate collection duct.
Aerobic landfill with forced aeration	The leachate collection pipe and air supply pipes are attached. Air is forced to enter solid waste causing it becomes more aerobic than a semi-aerobic landfill.

2.2 Landfill leachate composition

Landfill leachate generation and composition are much influenced by the amount of waste dumped. Generally, landfill leachate is known as a derivative from the decomposition of heterogenous waste by physicochemical and biological means resulting in the production of highly concentrated liquid containing organic and inorganic compounds. According to Kamaruddin et al. (2017), the author describes that the chemical and physical changes in the landfill cause the degradation process of solid waste to refuse with the soil matrix once the landfilling is complete. The author also indicates that the liquid percolates through the solid waste matrix and assists with rainwater's biochemical, chemical, and physical reactions within solid waste refuse directly influencing the quantity and quality of the leachate. The decomposition of waste in landfill can be divided into three types (physical, chemical, and biological decomposition). Physical decomposition starts as early as the segregation of waste and the mechanical size reduction process. Chemical decomposition is considered during the process of combustion, pyrolysis, and gasification. Once the waste is transferred into landfill cells, biological decomposition takes place. According to Theng et al. (2005), the biodegradation process is considered the most concerning process due to the nature of producing hazardous leachate and gases. Complex interactions between the components of solid waste contribute to a variety of pollutants. Certain parameters have been used as an indicator to measure the pollutants level such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen, heavy metal, turbidity, suspended solids, and others.

Several other factors are heavily linked to the production of landfill leachate quality and quantity. Landfill age, precipitation, weather variation, waste type, cover materials and composition are among the contributing factor that influences landfill leachate. The degree of compaction at some point can be considered to influence the leachate production and composition (Raghab et al., 2013). Figure 2.3 exemplify factors that contribute to the quality and quantities of the leachate (Schiopu & Gavrilescu, 2010). The volume of leachate produced is significantly related to the amount of precipitation, evapotranspiration, surface runoff, infiltration, and groundwater intrusion into the landfill (Renou et al., 2008). Hence, the use of the right cover material, lining as well as degree of compaction is important. A suitable cover layer may be able to control the entrance of waste into landfill cells as well as further reduce the volume of leachate produced (Dajić et al., 2015). As reported by Kamaruddin et al. (2015), the use of an impermeable type of cover material will retain the generated leachate produced and inhibit leachate movement within the cell which eventually reduces the effectiveness of landfill cells. As the world is divided into several regions and climates, the process of degradation of waste and leachate generation might be different. In a tropical climate, elevated temperatures and high amounts of precipitation lead to an increase in waste degradation and leachate formation (Tränkler et al., 2005). According to Vaccari et al. (2019), 46.24% of the landfills in the Asia region including Malaysia recorded an annual rainfall of over 1500 mm. This amount is considered high and leads to high production of landfill leachate. The author also described that the massive production of landfill leachate caused a higher degree of solubilization and enhanced heavy metals transportation. However, in a country with high temperatures and dry conditions, leachate production is considered low because of low precipitation (Kamaruddin et al., 2015). Waste composition is another significant factor that influences leachate production. Waste generated varies depending on the different regions which can be influenced by lifestyle and consumption patterns. As reported by (Wilson et al., 2016), the level of income of any country influenced the waste composition along with the per capita generation of solid waste.

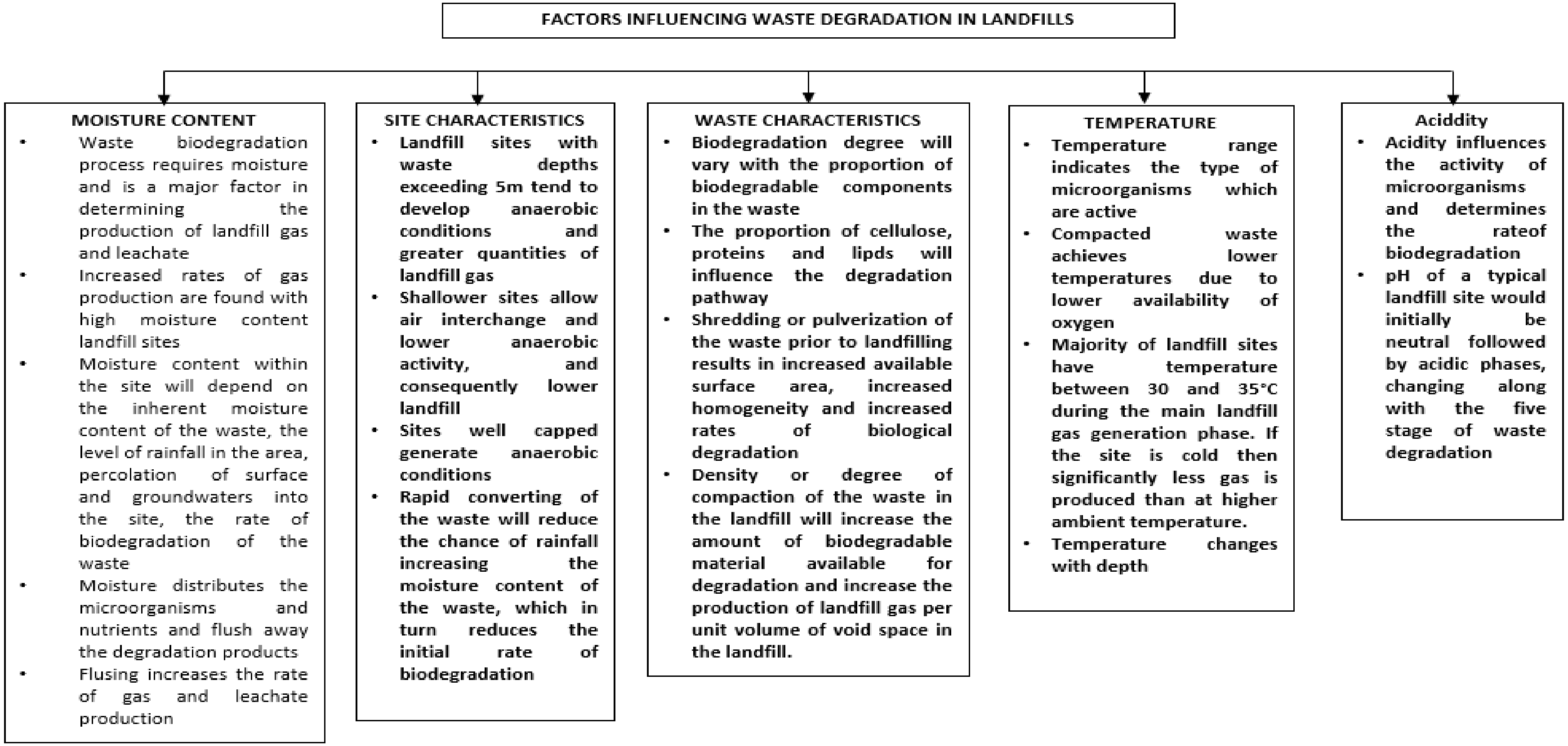

Figure 2.3 Factors affecting waste degradability in landfills (Schiopu & Gavrilescu, 2010)

In addition, leachate can be characterized depending on its composition and decomposition material. Leachate can be categorized into three types, young, intermediate, and old. This category is based on the parameters value range. The worldwide sanitary landfill shows variations in leachate composition. Table 0.4 Composition of constituents in a different state of leachate (Alvarez-Vazquez et al., 2004) provides brief information on the composition of constituents in a different state of leachate. Young landfill leachate poses low pH and can simply degrade volatile acids and organic matter. As for mature landfill leachate, a higher pH can be found and is mostly contributed by the presence of humic and fulvic fractions.

Table 0.4 Composition of constituents in a different state of leachate (Alvarez-Vazquez et al., 2004)

Parameters	Young	Intermediate	Old
Age (Years)	<5	5-10	>10
pH	<6.5	6.5-7.5	>7.5
Biodegradability	Important	Medium	Low
Kjeldahl Nitrogen (g/L)	0.1-0.2	-	-
Ammonia Nitrogen (mg/L)	<400	-	>400
TOC/COD	<0.3	0.3-0.5	>0.5
Heavy Metals (mg/L)	Low to Medium	Low	Low
BOD5/COD	0.5-1.0	0.1-0.5	<0.1

2.3 Waste decomposition process in landfills

The degradation of waste may lead to waste stabilization and the formation of less or more hazardous by-products. The waste transformation undergoes a series of complex physical, chemical, and biological processes over time. The age of the landfill is considered a significant factor. The decomposition of waste produced by by-products such as biogas is different from one phase to another. This is due to the microorganism activities in the landfill phase as well as the environmental conditions within the landfill cells. Landfill cells and sections may undergo different pressure conditions simultaneously. The process of waste decomposition in the landfill can be divided into five stages: aerobic phase, anaerobic phase, Acetogenesis phase, methanogenesis phase, and maturation phase.

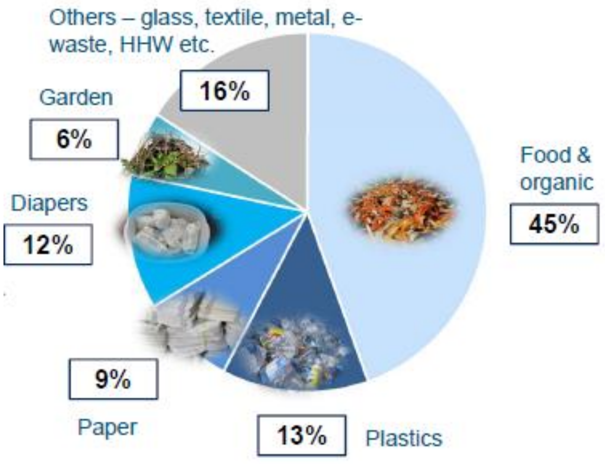

Figure 2.4 Composition of household waste(KPKT, 2015)

2.3.1 Aerobic Phase

The decomposition of waste started straight after the waste is buried. The first phase of the decomposition process is known as the aerobic phase as it consumes the available oxygen until depleted. The aerobic phase normally can be considered short and brief. Several factors contribute to the shortcoming duration such as the degree of compaction and the moisture content which eventually fill the gap initially filled by air within the landfill cell. Leachate formation during this phase is mainly due to the moisture content in the waste and short-circuiting of precipitation through the buried refuse but not the result of waste decomposition. The applied pressure during compaction will squeeze the moisture out of waste. Common contents of the leachate include suspended fine particles, highly soluble salts, and microbes (Mor et al., 2006). The accumulation of moisture is a crucial part of this phase to trigger microbial activities. The changes will provide a suitable condition for biochemical disintegration to take place.

The presence of anaerobic bacteria will hydrolyse the complex and long-chain molecular constituents of organics waste into simple constituents via the consumption of oxygen (Joshi & Pant, 2018). The ultimate end products that can be found from this phase include ash, carbon dioxide (CO_2), and H_2O which is a result of biological aerobic decomposition (Adhikari & Khanal, 2015). Organics are partially degraded during this phase as the overall decomposition cause a temperature rise within the landfill cell. According to Renou et al. (2008), the contribution of decomposition products from this phase is low and poses a minimal risk towards pollution.

2.3.2 Anaerobic Phase

Once the oxygen level within the landfill is depleted, the decomposition of the landfill moves to the anaerobic phase. The heat produced during the aerobic phase will be utilized in this phase and eventually decrease the moisture content to accommodate the anaerobic condition. The electron acceptors will swift from oxygen to nitrate and carbon dioxide converted from oxygen. The by-product of this phase can be divided into two, volatile organic acids and gases. Common gases formed such as methane (CH_4) and carbon dioxide (CO_2) while hydrogen sulphide (H_2S), hydrogen (H_2), and nitrogen (N_2) can be found in a low amount.

Microbial activities play a significant role during this phase. Environmental factors that affect all biological activity have a big impact on the nature, rate, and extent of biological decomposition in a fill. The breakdown products' nature is determined by the type of biological decomposition. Moisture, temperature, microbial nutrition content, and waste resistance to microbial attack are the main elements that determine biological decomposition in a typical fill. At moisture content levels of 55% to 60% or lower, moisture is a limiting factor in a fill because the microbial activity is restricted as moisture falls below the 55% level. Most microorganisms' activity increases as the temperature rises until it reaches around 40°C. The upper-temperature limit for several microorganisms is between 55°C and 65°C. Decomposition is likely to occur more quickly and to a greater extent in tropical climates due to warmer temperatures. In terms of nutrients, wastes with a high percentage of putrescible matter come close to being perfect in terms of decomposition. Bacteria will degrade organic constituents and convert them into simpler compounds, which are mainly acidic. The acids shall serve as substrates for methane-producing microbe (Adhikari & Khanal, 2015). Any disturbance to the landfill and exposure to oxygen will revert this phase to the aerobic phase. To conclude this phase, the amount of COD concentration shall be around 480-18000 mg/L while volatile organic acids (VOA) are up to 100-3000 mg/L within the landfill leachate. The anaerobic decomposition of the waste creates an unfavourable impact towards the environment and should be closely monitored.

2.3.3 Acid Formation Phase

The hydrolysis and biodegradation of organic matter by microbial activities result in high production of VOAs, ammonia, carbon dioxide and hydrogen. Barjinder, (2013) stated that the early acidogenic phase contains a large amount of readily biodegradable organic matter. Anaerobic fermentation will reduce the complex organic compound into soluble organic acids such as free volatile fatty acids (VFAs), amino acids, and other low molecular weight compounds and gases. These facultative bacteria aid in the disintegration of waste, lowering the redox potential of the waste and promoting the growth of methanogenic bacteria. As a result, the pH value of the chemically active leachate drops, lowering the leftover waste's capacity. A high