An-Najah National University

Faculty of Graduate Studies

CONVERSION OF MUNICIPAL SOLID WASTES INTO FUELS AND CHEMICALS BY PYROLYSIS: TULKARM TRANSFER STATION AS A CASE STUDY

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Dedication

سبحانَ من وهبَ العقولَ جميلا فهدى الأَنامَ مُنَزِّلاً تَرتيلا

أُهْدي لِأُمي بالدَّليلِ رِسالتي و لِدَعمِها أَحني الجَبينَ دَليلا

و الشُّكرُ بَعدَ اللهِ أُهديهِ أَبي فَهو الذي في جَبهتي قِنديلا

و لخالَتي عَدولَ جُلَّ مَحبَّتي نَهرُ المودَّةِ بالصفاءِ مَسيلا

و لإِخوتي فَهم النَّجاحُ و عِزوَتي عيسى و يوسُفَ و الرَّجا اسْماعيلا

و لِخافِقي بَين الضُّلوعِ و مُهجَتي نَصّارُ زَوجي مُلهِماً و خَليلا

و لِعَمِّيَ المَرحومَ أُهْدي آيةً فيها الدُّعاءُ إلى الإله طَويلا

و لإبْنيَ المَحبوبُ أيّوبُ أرتَجي فَضلاً وآدمُ عُزْوَتي و قَبيلا

و لِمن له فضلٌ عليَّ وَسيلتي لِلرّبِّ شُكري و الدُّعاءُ سَبيلا.

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Declaration

I, the undersigned, declare that I submitted the thesis entitled:

CONVERSION OF MUNICIPAL SOLID WASTES INTO FUELS AND CHEMICALS BY PYROLYSIS: TULKARM TRANSFER STATION AS A CASE STUDY

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name: Sabreen Mousa Ibrahim

Signature:

Date: 03/08/2023

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Abstract

The implications of MSW accumulation and continuing fossil fuel consumption on the environment and human health have increased the importance of alternative energy sources around the world. Pyrolysis of MSW is regarded as an innovative method for producing biofuels that can be used in many applications, not only to produce electricity, where power production in the Palestinian territories (PT) is constrained by the political situation. Also, it is a solution of the global rise in oil prices, the lack of fossil fuel reserves in the Palestinian territories. Our case study is the Tulkarm transfer station, which in 2021 received more than 200 tons of MSW per day.

The results were obtained using the simulation program Aspen Plus, and the equations it used were developed based on numerous real-world experiments documented in the literature. Four scenarios presented in this study in order to find the best way to produce biofuels from MSW, and to understand the effect of co-pyrolysis on the process yields.

The intended MSW was subjected to a simulation of the pyrolysis process in the first scenario, with a maximum bio-oil production of 21.3wt.%. In the second scenario, pyrolysis simulation was only run for the projected MSW's biomass portion, which would yield 60.5 wt.% bio-oil. The maximum bio-oil yield was 67.82 and 82.32 wt.%, respectively, for the third scenario (50 % plastic with 50 % biomass) and the fourth scenario (100 % plastic feedstock).

These findings, along with the performed economic and environmental assessment, demonstrated that pyrolysis may be the best option for resolving the MSW and energy issues. Economically, this project has a 3-year payback period and a 31% internal rate of return. environmentally, using biofuels can significantly reduce carbon footprint. While fossil fuels emit 95.5 g of CO_2 eq per MJ in the transportation sector, transportation bio-oil emits only 9.5 g. In comparison to fossil fuels, which produce 182.8 g CO_2 eq per MJ to produce the same amount of electricity, for producing 1 MWh of energy, integrated AD and pyrolysis-gasification technologies might decrease GHG emissions by an average of 237.42 g CO2 eq per MJ.

Keywords: Pyrolysis, MSW, bio-oil, fossil fuel, energy, carbon footprint.

Chapter One

Introduction

1.1 Background

Based on a United Nations report, the world's population will rise by 2 billion individuals in the coming 30 years, from 7.7 in 2019 to 9.7 billion in 2050. The UN Department of Economic and Social Affairs' Population Division conducted a study that came to the conclusion that the world's population could peak at about 11 billion individuals by the end of the present century. Furthermore, the global population is aging, with the over-65 age group experiencing the highest growth. One in six persons worldwide will be over 65 by 2050 (16%), up from one in eleven in 2019 (9%) [1].

The population of the Palestinian Territories (PT) was 5,227,193 people in mid-2021, distributed as follows: the West Bank has 3,120,448 inhabitants., whereas 1,210,6745 live in Gaza [2]. Increased global population and urbanization, combined with rising living standards, have contributed to two of the world's most pressing issues: first, rising per capita energy consumption and worldwide dependency on fossil fuels, and second, increased per capita trash creation [3]. To overcome these issues, radical solutions are required. As a result, renewable energy is required to minimize reliance on fossil fuels and eliminate the problem of solid waste accumulation.

Renewable energy sources are classified as those naturally derived processes and renewed at a faster rate than they should be consumed, comprising geothermal, hydropower, solar, wind, ocean, and bioenergy, as well as all forms of energy generated from renewable sources in a sustainable manner [4]. The US Environmental Protection Agency (EPA) classifies MSW as a renewable energy resource because it comprises a large amount of paper, kitchen wastes, wood and yard trimmings, cotton, and leather. MSW also contains materials originating from fossil fuels, such as plastics, rubber, and textiles. The non-renewable proportion of MSW should be segregated or accepted as part of the fuel, and almost all wastes in MSW are treated as renewable after material recovery and recycling [5].

Despite municipalities and joint service councils attempt to manage and control the solid waste problem adequately (and in a safe manner) in Palestinian territories, these efforts are insufficient to keep up with the significant increase in solid waste generation. According to the Ministry of Local Government's 2019 Data Book, Production of MSW reached 2600 tons per day (or 949,000 tons annually), while production per person reached 0.91 kilogram per day. The JSC collects about 83% of the generated MSW (>2000 tons/day). The remaining quantities falling to Local Governmental Units (LGU) and the United Nations Relief and Works Agency (UNRWA) [6]. These figures are anticipated to rise as the world's population and living standards continue to rise. The rise is estimated to be 4%. MSW is almost 50% organic in terms of composition [7]. As a result of this situation, MSW in our country is regarded to be more harmful when compared to other countries that perform more scientific ways of MSW disposal. Furthermore, energy shortage and the awareness of fossil fuel depletion have made the need for a long-term solution that handles the major challenges critical. The massive rise in MSW generation, combined with the declining capacity of existing disposal sites, emphasizes the importance and urgency of a well-designed MSW management network [8].

To take benefit of the crisis, all MSW treatment processes can be turned into opportunities for long-term energy production, a process known as "waste-to-energy" (WtE). The three main categories of WtE solutions are thermal conversion techniques, biochemical conversion methods, and landfilling [9].

Since the 1970s, the basic thermal WtE methods have been incineration, pyrolysis, and gasification. Incineration is the traditional while pyrolysis and gasification were considered more innovative thermochemical conversion technologies [10]. The manner the feedstock is oxidized to produce energy identify the thermal processes; pyrolysis employs no oxidant (oxygen), whereas incineration and gasification use an excess and restricted supply of oxidant, respectively [9]. The only product of combustion is heat, which can be used to generate electricity, gasification and pyrolysis can provide better control to convert the heterogeneous solid fuel into a consistent liquid or gaseous intermediate fuel. In addition to the fact that pyrolysis produces oil which its quality can be closely monitored, and easier to transport, it is also safer for the environment than other thermal treatment systems [11].

AD and composting are examples of biochemical conversion. CH_4 gas, the major product of AD, may be utilized to replace energy produced by fossil fuels, additional nutrient-rich digestants are produced as a by-product which could be used as fertilizer. However, because to the presence of cations such as sodium, potassium, calcium, and magnesium in food waste, high salt applications in food waste inhibit AD. from a practical perspective, composting and AD facilities, in any event, are inefficient treatment alternatives for any of the waste components due to the high running costs and low revenues [12].

In developing countries, landfills are commonly used as an effective framework for accommodating waste for reprocessing and recovery. Although landfilling serves a distinct role in MSW management since it may reduce waste volume and weight by 90% and 70%, respectively, it also raises concerns about environmental degradation of soil, water, and air [13]. As a result of these concerns, several countries around the world have begun to avoid landfills in favor of more environmentally friendly solid waste disposal techniques. Pyrolysis of MSW is a crucial WtE technique for addressing both fossil fuel depletion and MSW accumulation. It is a flexible technique among other WtE techniques; it may produce heat and/or electricity as well as many types of fuel and chemicals.

The accumulation of MSW has a harmful impact on the environment and the health of citizens. In Palestinian territory, it is challenging to construct and open additional landfills to keep up with the enormous growth in MSW creation. Accordingly, a sustainable method to completely or partially eliminate quantities of MSW is required, where landfilling is the only method of MSW disposal in The PT. Indeed, the three West Bank landfills, Zahrat Al-Finjan in Jenin, Jericho landfill, and Al-menia in Beitlahm are overloaded with utilization rates of 88 %, >100 %, and 9%, respectively [7]. While the existing transfer stations are inadequate to overcome the growing volumes of MSW, as well as the difficulty and cost of collecting and transporting MSW to the few accessible landfills. These MSW are not subjected to any pre-treatment procedures before they are transported to their final landfill.

It is not necessary to focus on producing electricity in order to adopt a sustainable approach of MSW disposal, as this procedure may not be economically or politically possible for a variety of reasons. One of the key reasons is that the Palestinian Authority lacks the necessary infrastructure to profit from renewable energy in order to generate electricity. Furthermore, gathering, sorting, and pre-treatment activities prior to incineration may be costly and exhausting. It is better to focus on WtE technology to produce fuels, especially as there are no reliable amounts of crude oil in the Palestinian Territories to generate electricity, run factories, farm machinery and transportation, among other things. In addition, the Palestinian Authority does not have its own fuel reserves, similar to neighboring Arab countries, and the only source of fuel sold at gas stations comes from Israel, at a high cost. This fuel, available at petrol stations, is enough for the Palestinians to consume for only 48 hours if Israel cuts off supplies[14], [15].

1.2 Problem statement

Due to the current situation in the PT, the rapid increase in MSW generated and its negative consequences, as well as the impossibility to expand and open new landfills. In addition, Palestinian areas lack their own crude oil reserves and the infrastructure needed to generate electricity using renewable energy sources. All of these issues highlight the necessity to find a long-term solution to the critical situation in the PT. On the other hand, the absence of studies regarding the feasibility and application of pyrolysis in the PT among other WtE technologies emphasizes the necessity to concentrate on such studies. The aim of the research is to recommend an optimal WtE technology for producing valuable fuels and chemicals from MSW that may be marketed locally.

1.3 Significance of research

In light of the foregoing introduction, it may be inferred that the PT 's problems with waste buildup and the depletion of fossil fuels do not have a radical solution on the ground. This study will present the optimal solution to both problems. where the ability of MSW in Palestinian territories to produce biofuels and chemicals will be the main emphasis of this study. This is dependent on the amount and make-up of the MSW at the transfer station we've chosen as our example study. The thermochemical procedure known as pyrolysis will be discussed in this study as an alternative to the conventional methods now in use around the world for disposing of municipal solid waste (MSW) (landfilling, incineration, anaerobic digestion, and composting). Here, we will give individuals who evaluate our research a thorough understanding of the specifics of the pyrolysis process that can produce the greatest amount of bio-oil and chemicals.

1.4 Research Objectives

The following are the study's key objectives:

1. Conduct a feasibility assessment for the pyrolysis of MSW based on a simulation of an existing case in the PT as an example.
2. Proposing different scenarios for the pyrolysis process and applying a computer simulation to each scenario.
3. Analyze the energy balance and energy production potential during the pyrolysis of MSW.
4. Evaluating the economic and environmental aspects of employing this technology to dispose of MSW.

1.5 Thesis structure

This thesis contains five chapters, which are arranged under the following categories:

1. Chapter One introduces the research by providing background knowledge and outlining the research objectives.
2. Along with a comprehensive understanding of the current state of MSW in Palestinian territories, Chapter Two's literature study continues with a synopsis of WtE methodologies used around the world.
3. In Chapter Three, the literature studies continue and a more detailed summary of the pyrolysis of MSW is provided.
4. Chapter Four supplements the thesis by presenting the research methodology.
5. In Chapter 5, the study's results and related discussion are presented, along with the study's conclusions and some recommendations.

Chapter Two

Literature Review

2.1 Technologies of MSW disposal

Municipal waste deserves special attention because of its environmental consequences on a local, regional, and global scale, its proximity to humans and potential health impacts, as well as its value for prospective recycling via circular economy supply chains [16]. The composition of municipal waste varies based on topographic site, life quality, living standard, urban population, and other considerations [17].

Aside from fossil fuels, renewable sources of energy refer to energy resources that are deemed inexhaustible or replenishable by nature. Hydro, solar, geothermal, wind, and biomass are examples of these renewable resources [3]. Biomass conversion to energy has expanded rapidly due to global warming, low-cost energy, additional safety supply, and reduced environmental effect. Due to the increased cost of non-renewable energy production, developing nations are focusing on waste to energy (WtE) conversion. [17]. MSW is actually classified as biomass, and it typically contains considerable amounts of items such as food wastes, wood and yard trimmings, paper waste, and other components. MSW is also classified as a renewable resource by the US Environmental Protection Agency (EPA) because it is a continuously produced biogenic materials that would otherwise end up in landfills if not diverted to energy generation [3]. It is typically defined as waste originating from municipalities or other local governments. It mostly consists of household, commercial, and institutional trash. Biodegradable trash, recyclable resources, inert wastes, composite waste plastics, domestic harmful waste materials, and toxic waste are some of the different types of MSW [17]. Similarly, the Intergovernmental Panel on Climate Change (IPCC) reports that MSW is made up of food wastes (25–70%), plastics, metal, glass, textiles, woods, rubber, leather, paper, and other materials [18].

Since the generation of MSW is strongly linked with factors such as economic development and industrial growth, industrialised countries with higher economic levels will generate more MSW. Other factors, including as urbanization, population growth, and technological advancement, also contribute to increased MSW production in developing countries. Numerous environmental issues, including greenhouse gas emissions, air pollution, and water contamination, are associated with rising waste generation as well as unreliable energy demand [17].

The Food and Agriculture Organization (FAO) predicts that world energy demand would rise by over 60% by 2025. Many studies have predicted that, as urbanization and income levels rise, municipal soil waste (MSW) production levels will likely climb to over 2.6 billion tons by 2025, up from the current level of 2.4 billion tons [19].

Based on another forecasting:

- By 2025, worldwide MSW production might rise from 1.3 billion tons per year in 2010, averaging around 1.2 kilograms per capita per day, to 2.2 billion tons per year, with the average trash created rising to nearly 1.5 kilograms per capita per day [20].
- According to another research article, the amount of MSW produced worldwide in 2011 was 2 billion tons, with 9.5 billion tons predicted by 2050 [21].
- The International Solid Waste Association (ISWA) calculated that more than 4 billion tons of MSW are produced annually around the world. 70 % of MSW is anticipated to be disposed of in dumpsites and sanitary landfills, while 19 % is recycled or treated mechanically or biologically [22].
- According to Wilson's research, the generation of waste, i.e., unneeded or undesired byproducts, is an inescapable result of most activities. Every year, 7-9 billion tons of waste are created around the world. MSW is a type of waste generated by homes that can also include industrial and commercial wastes, based on the reporting standard. Fig. B.1 (Appendix B) illustrates the global prediction of future waste generation by type and treatment, with MSW accounting for 2 billion tons of the total waste generated in 2016 [23].

The above-mentioned statistics for annual solid waste production fluctuate from one study to the next, owing to data being assembled and harmonized from a variety of sources, including official government reports, surveys of MSW treatment facilities, meta-analyses, and measurement data of MSW, among others. Because of the stage at which data is gathered, the measurement utilized, and variable institutional capacities, the quality of reporting may be challenging to ascertain. Additionally, due to a shortage of time-series data, there may be fixed impacts that are specific to a region or country, including established policy frameworks or cultural views, that were not captured. Regardless of the different in values, these figures follow the same pattern, confirming the massive increase in the amount of MSW produced annually, as well as the harmful impacts of this on citizen health and the environment [23].

2.2 MSW sector in West bank

In 2019, the West Bank generated 2600 tons of municipal waste per day, or 949,000 tons yearly, with per capita generation reaching 0.91 kilograms per day, up 4% from the previous year. The JSC collects about 83 % of the produced municipal waste in the West Bank (>2000 tons/day), with the remaining quantities falling to LGU and UNRWA [6]. Most critically, there is no technology for disposing of domestic wastes other than landfill.

A transfer station is a station that serves as a link between the last disposal location and the collection point to improve system efficiency. If the disposal location is distant from the collection region, this is the best alternative. As the size of the collection vehicle increases, it helps to reduce the cost of driving from collection to disposal location, as well as maintenance and fuel expenses for collection vehicles [24].

15 JSCs, 13 of which are in the West Bank, oversee the solid waste management system in PT. Three MSW dumpsites are currently operational: Zahrat Al-Finjan, which serves the middle and northern West Bank (with an 88 % utilization rate), Al-Menia, which serves the southern zone (at a 9 % utilization rate), and one in Jericho (which is overloaded) [7].

Tulkarm Transfer Station (TS):

Tulkarm has 31 Local Governmental Units. The Joint Service Council (JSC) manages the Tulkarm transfer substation. JSC offers services to 27 LGUs, as well as 3 service days for Qaffin village. Staff from the United Nations Relief and Works Agency (UNRWA) have been collecting and transporting waste from the Tulkarm and Nour Shams camps since 2015. Due to the proximity to the landfill, the villages of Illar, Attil, and Baqa al-Sharqiya gather and transport their own MSW straight to Zahrat Al-Finjan dump.

The Tulkarm transfer substation is 35 kilometers from the Zahrat Al-Finjan landfill and has a total area of 5 rented donums. It received approximately 4600 tons of MSW per month in 2020 (184 tons per day excluding Friday); this amount of MSW necessitates 12 rounds by transfer vehicles to the final site. by 2021, this amount had increased to more than 200 tons per day.

JSC employs 30 collection vehicles to collect MSW from Tulkarm city and its surrounding villages, 15 of which belong to JSC and 15 to Tulkarm Municipality. JSC additionally has three transfer vehicles with a maximum capacity of 16 tons. The whole cost from MSW collection sites to Zahrat Al-Finjan landfill is 141 NIS per ton. Some Local Government Units gather their waste and transport it to the substation on their own. The station fees per ton of waste are 74 NIS/ton (17 NIS/ton for worker and guard pay, 24 NIS/ton for substation to Zahrat Al-Finjan transfer costs, and 33 NIS/ton for Zahrat Al-Finjan fees).

2.3 Health and environmental impacts of poorly managed MSW

Ground and surface water pollution, soils and air contamination, major human health concerns, and aesthetic degradation are all potential consequences of different types of MSW. Depending on the manner of disposal, plastic wastes, for example, is a growing global concern because it persists for long periods and is swallowed by organisms, producing health effects across the food chain, including people. Another notable long local impact is nitrogen pollution from waste leachate, which has the potential to cause sickness and nutrient imbalances in neighboring water bodies. Moreover, open waste burning has been demonstrated to generate considerable volumes of toxic air pollutants, posing serious health risks, particularly in developing countries [23].

In 2006, fugitive emissions through waste treatment accounted for 3-4 % of global GHG emissions. Global landfill emissions are expected to rise from 340 Mt CO_2 eq in 1990 to 1500 Mt CO_2 eq by 2030, and 2900 Mt CO_2 eq by 2050 Monni et al. [25]. According to the report by Kaza et al., emissions from solid waste treatments and disposal account for around 5% of overall global GHG emissions, mostly due to disposal in open dumpsites without landfill gas collection systems. By 2025. By 2050, emissions are expected to rise from 1600 Mt CO_2 eq in 2016 to 2600 Mt CO_2 eq [16]. Owing to differentiation by region, weather, waste type, and processing, as well as dynamic future development, Friedlingstein claimed that their predictions are estimated at a more sensitive scale than other evaluations, such as Kaza et al. and Monni et al. In 2018, MSW accounted for 1385 Mt CO_2 eq, representing for 3.7 % of worldwide CO_2 emissions. By 2050, GHG emissions will have nearly doubled, from 1323 Mt CO_2 eq in 2015 to 2383 Mt CO_2 eq. Almost all GHG emissions come from landfills and dump sites, with just little emissions from composting and incineration. This is because a significant amount of waste will still be disposed of in landfills in the future [26].

Based on the foregoing, poorly managed MSW has significant negative consequences for human health and the economy. Furthermore, improper waste management GHG emissions, which contributes to the global warming effect. To combat this, it appears that all public authorities must create the best MSW system possible [12].

2.4 MSW management and disposal

MSW has traditionally been disposed of in landfills or dumping sites in various nations across the world. However, this method of disposal has frequently caused environmental and public health problems. As a result of the worries about conventional disposal methods, many countries, particularly the developed ones, are pursuing the goal of waste management and control via a hierarchical system of priority. In one such hierarchy system, priority is given to eventually reducing waste stream. Figure B.2 (Appendix B) shows the hierarchy, which consists of five basic steps in order of priority: waste prevention, reuse, recycling, recovery (including energy recovery), and safe disposal. This hierarchy offers a vital framework for enacting waste management regulations [3].

In the hierarchy of priorities, recycling comes after waste prevention and reuse, which are aimed to reduce the waste stream. The energy recovery follows recycling. In terms of carbon savings and costs, various researchers have concluded that recycling would be the most environmentally beneficial waste management method. Recycling, on the other hand, does not offer the advantage of energy recovery, and materials that cannot be recycled are frequently candidates for energy recovery, which is preferable to landfilling [3]. Globally, projections indicate that the waste cycle has the potential to become more circular in the future. Paper, glass, and metal are easily recyclable, and it is anticipated that by 2030, these waste streams will account for 26% of world waste, with organic waste accounting for 44%. Recycling, on the other hand, continues to account for 13% of the total, while composting accounts for only 6%. To attempt decreasing unsustainable waste treatment (through landfills and dumps), the quantity of the recycled and composted wastes by 2030 should increase from 363 Mt in 2015 to 740 Mt, and to 1744 Mt to fulfill EC targets for the world [23].

Due to the tremendous increase in the amount of waste generated, the significance of solid waste management is growing by the day Maghmoumi et al. [27]. As a result, waste management methods are crucial for the effective and sustainable management of produced waste. Waste management methods take into account the volume and characteristics of wastes produced. WtE has recently been recognized as an MSW management approach for reducing pollutants while also generating power and/or heat from MSW [27]. WtE is a rapidly developing technique that is both ecologically and economically beneficial. It is linked to energy consumption, waste elimination, and environmental monitoring [17]. As the appeal of WtE techniques has prompted many countries and communities around the world to adopt these rapidly evolving technologies as soon as possible. Currently, the United States and other developing countries treat MSW according to a hierarchy of recommended procedures, with WtE considerably outranking landfilling [3].

WtE techniques allow for the beneficial use of waste materials in the production of electricity, transportation fuels, and chemicals. Significant quantities of these feedstocks may be accessible at negative prices, implying that a prospective bioenergy facility may receive these materials for free or be compensated for accepting them in some cases. Organic wastes can be purchased for negative prices in places with extremely high waste disposal expenses since entities often have difficulty disposing of the waste [3].

By the application of WtE processes, solid wastes can be used to produce chemicals, fuel for transportation, and electricity. Many of these feedstocks might be offered at negative pricing, which would allow a potential bioenergy factory to accept them for free or be compensated to do so in some regions. It is feasible to purchase organic wastes at negative prices in regions with exceptionally high waste disposal expenses, since entities often struggle to get rid of the material. Strict legislative restrictions or logistical needs for garbage disposal may be the cause of these challenges, however these factors tend to differ by location. The locations with the highest likelihood of these negative pricing feedstocks are those with large population densities, limitations on the disposal of organic waste, and high landfill tipping costs. In the Palestinian territories, in addition to what was mentioned above, shortage in permissible lands that lead to a shortage in landfills, and the absence of sanitary methods for the disposal of MSW other than landfills, may make the prices of MSW used for energy production negative [28].

Palestinian Territories are still highly dependent on landfills for MSW management and disposal, but with increasing the quantities of MSW and its accumulation with the inability to expand and open new landfills due to the present situation in the PT, besides, its negative impacts on the environment and citizen's health arose the need for a sustainable method to completely or partially eliminate quantities of MSW, where landfilling is the only MSW disposal approach in the PT. Because of the aforementioned, at least one method from WtE methods must be used to dispose of these wastes in a sustainable manner. The strengths and weaknesses of each WtE method must be reviewed in order to choose an appropriate method based on the data and the current situation in the PT. They must be studied in terms of energy, economic and environment.

2.5 Waste-to-Energy technologies

WtE is an attractive approach to cope with the significant growth in municipal waste production and the depletion of fossil fuels. Where it is seen as a promising method for recovering energy and valuable materials from unwanted and environmentally hazardous waste. WtE technology is being considered as a renewable energy source by several nations throughout the world, including the United States, China, Iran, and Malaysia. Sanitary landfills are one of the oldest waste management methods; they are also utilized for garbage that has no other suitable disposal option. Composting and anaerobic digestion (for organic waste) are examples of biochemical conversions that are considered environmentally friendly waste management methods. Electricity, heat, and fuel are produced by thermal operations such incineration, refuse-derived fuel generating, gasification, and pyrolysis (for flammable trash); these conversions vary depending on the by-products produced [29].

Throughout many low-income countries, choosing a fit-for-purpose WtE technology is challenging due to varying levels of risk and local context. The risk includes; Environment, Socioeconomics and Technology. Environmental risks include potential pollution, epidemics, and health and safety, while socioeconomic risks include acceptability, land use requirements, and costs, and technological risks include ease of use, practicality, expertise, and infrastructure requirements [22].

This section provides an overview of the most common WtE technologies; LFGRS, AD, Combustion, Gasification and Pyrolysis. As well as their energy, environmental, and economic (3E) impacts.

2.5.1 Landfilling process

According to the International Solid Waste Association (ISWA), landfilling is still the most common method of removing MSW on a global basis. It is commonly used in poor countries as an effective framework for entertaining garbage for reprocessing and recovery. Landfilling can play a vital role in MSW management since it can reduce waste volume and weight by 90 % and 70%, respectively. A landfill has two life stages: the operational stage, in which MSW is dumped and biogas generation starts, and the closed stage, in which the loading volume has given its maximum biogas productivity [17]. This LFG, which is formed by biological decomposition, is utilized to generate electricity or heat in internal burning machines, gas turbines, and steam boilers [17]. The most typical components of LFG are CH_4 (50–75%), NH_3 (0.1-1%), N_2 (3.9-4.1 %), O_2 (0.9-1.1 %), non-methane volatile organic compounds 0.01–0.60 %), CO_2 (25–50 %), and water vapor (6-6.5 %). The main factors affecting LFG generation are waste composition, availability of biodegradable organic materials, waste age, moisture content, pH and temperature. Fig. B.3 (Appendix B) depicts the landfill system and its process [30].

The environmental degradation of the air, water, and soil are some of the more serious issues sparked by landfilling. By anaerobic breakdown of solid waste, where bacterial decay, volatilization, and chemical reactions are significant processes that result in the creation of those landfill gases, an over reliance on landfilling has led to the emission of CH4 gas (a more potent GHG than CO2) (LFG). Around 30-70 million tons of CH4 are released from landfills each year [17]. Besides that, landfill N2O may account for up to 20% of the global warming capability of landfill gas. As a result of the leakage of leachate, which is a complex mixture of pollutants with a high chemical oxygen consumption, a high ammonium nitrogen concentration, and long-lasting toxicological features, landfilling is another key source of groundwater poisoning. Thus, contamination of water brought on by landfill leachate transportation may pose a serious environmental risk.

Leachate can contribute to the contamination with potentially harmful compounds at amounts that are above drinking water limits, especially at unlined landfills. Yet, because the liners eventually wear out, lined landfills also pose a risk to the quality of the groundwater. Chloride (Cl), sodium (Na+), ammonium (NH4+), total hardness, total dissolved solids (TDS), organic matter like chemical oxygen demand (COD), heavy metals, and phosphate are among the main groundwater contaminants from landfills, according to numerous studies [31].

Since landfills contain most of the world's garbage, the formation of CH_4 from them has attracted a lot of attention. In terms of energy, if the CH_4 produced is captured and used for energy production, landfill can be considered a WtE method. The Landfill Gas Recovery System (LFGRS) is ideally suited to biodegradable waste with a high moisture content. Average gas recovery rates for dry MSW range from 120 to 150 m3/ton corresponding to a calorific value of 2500 MJ/ton, these figures can vary significantly depending on the MSW component. However, if the proportion of non-biodegradable materials (e.g. metal, plastic, glass) in MSW is large, the potential energy output can be reduced [32]. As a result, landfilling should be used only when a large volume decrease has been achieved through WtE conversions or recycling [33].

Landfilling is the most cost-effective method of disposing of enormous amounts of waste. A universal approach as outlined by [5] provides ultimate waste disposal, comparatively inexpensive and simple to implement. Landfill works in conjunction with other technological options for residual waste treatment; it complements other technology alternatives for dealing with residual waste. On the other hand, the lack of available land for disposal purposes is a major obstacle [32], where large areas are needed for waste disposal; the site location can be limited by the local geology and the natural stability of the underground soil. As well as landfill operating costs increase significantly with liner, leachate collection and removal system. Additionally, long post-closure due diligence requirements, stringent regulations, and unknowns are major factors limiting on-site land use for landfill in the long-term. Due to public acceptability and space concerns, landfills are frequently located distant from the sources of waste, forcing waste transportation across long distances. As a result, landfilling wastes without producing energy products may have a negative economic effect attributed to transportation, tipping fees, and operation and maintenance expenses [32]. In order to use the methane gas from the landfills, a LFGRS must be installed which uses the gas to generate heat and electricity. While landfilling is generally less expensive than incinerating waste, it may also be the least cost-effective WtE technique if the amount of non-biodegradable materials (e.g. metal, plastic, glass) in MSW is large, reducing the potential energy generation [32].

2.5.2 Anaerobic digestion (AD)

In the absence of oxygen, AD is a complex biological process that requires specific environmental conditions and different bacterial populations. It is one of the promising WtE technologies because it decomposes organic matter to produce biogas and digestate. Biogas is a valuable high-energy mixture of gases (mainly CH_4 and CO_2), and the produced digestate can be used as fertilizer [32]. Biosolids, livestock manure, moist organic wastes, and MSW in general are now acceptable feedstocks. Because AD prefers high-water-content biomass, it is a superior candidate for renewable energy generation that is acceptable exclusively with source-separated organic matter in MSW. As a consequence, AD is inappropriate for wastes with less organic substance, because lignin can remain for long periods of time before degrading. Due to the presence of cations such as sodium, potassium, calcium, and magnesium in food waste, high salt applications in food waste inhibit AD [34]. Fig. B.4 (Appendix B) shows a diagram of the AD process [35].

Process variables such as temperature, pH, and C:N ratio, the creation and quality of co-substrates, microbial dynamics, and type reactors, among others, contribute to the AD process' productivity and must be tuned to achieve maximum profits [34], [36].

Several types of bioreactors are now employed to treat the AD process. However, batch, continuous one-stage, and continuous two-stage reactors are the three most used methods for dealing with methanogen variability. These processors include the up-flow anaerobic sludge blanket (UASB), continuous stirred tank reactor (CSTR), tubular reactor, anaerobic sequencing batch reactor (ASBR), and fixed-film reactor [36].

Several research have shown that AD improves biogas harvesting. Biogas is typically 40-50%, 55–75% pure CH_4 depending on the waste source material and treatment scheme. AD biogas has a greater methane (CH_4) content and a lower carbon dioxide (CO_2) content than landfill gas [36], [37]. Chemical denotes the general methods of the AD process [34], [35].

Organic matter (CxHyOz) → $CH_4 + CO_2 + H_2 + NH_3 + H_2S$ ……………. Equation 1

Biogas may have additional benefits as a source of renewable energy, particularly for power generation, because it includes a high proportion of methane. It may also be used as a cooking gas, a domestic heating fuel, and a fuel for power fuel cells [38].

AD provides a number of environmental advantages, including the production of renewable energy, the ability to recover nutrients, and the reduction of waste capacity. Furthermore, compared to incineration, AD and gasification caused less to global warming and acidification. However, when energy is generated from organic wastes by AD, gases like CH_4, CO_2, and toxic gases like NOx, SOx, and hydrogen sulfide (H_2S) leak into the atmosphere, polluting the environment. A large quantity of free ammonia (NH_3) produced by the breakdown of nitrogen-rich protein components can be harmful to methanogenic bacteria, resulting in severe effects on the AD process [17].

The key advantages of AD include co-digestion of food waste on bio-reactors with various substrates to facilitate waste management and the production of expected yields, it is suited for high moisture content waste, and it secures future energy demands by creating inexpensive biogas. Compost or digestate, a nitrogen-rich fertilizer, is also utilized in agriculture and as a soil amendment. However, low biodegradability of specific wastes, such as lignocellulosic biomass, buildup of solids, blender malfunction, slow digestion rate, incomplete decomposition of large particles, and digester shut downs pose economic hurdles for AD. Poor methane yields, low energy output, high maintenance and operating expenses, and ultimately a high methane price result from these factors instead of producing it at a low price [39].

Furthermore, an extra water supply is sometimes necessary to make diluted slurry in large and costly digestion tanks. The digestate must be processed extensively before it can be utilized in agriculture. Digesters must be heated in cold climates. Digesters have construction and gas leakage prevention issues as well. In addition, AD reduces waste volume by approximately 50% (less than incineration) and needs expensive biogas cleaning. The feasibility of AD for small-scale use on farms and with local organic waste has previously been proven; however, research and development for MSW feedstock for pilot-scale use is presently underway. Despite the fact that there are several industrial AD approaches, there is still potential for development, both in the process as well as in the pre- and post-treatment processes. Continuous monitoring and progressive automated control are required for AD [40].

2.5.3 Incineration

The attractiveness of incineration in recent years has been its ability to combine it with energy recovery. Around the world, there are around 1400 incineration facilities in operation. Incineration is the most common WtE technique for producing heat and electricity, it is the most developed and widely used of all WtE techniques, with the main differences between nations' varying levels of development serving as its defining features. Incineration is a procedure that is suitable for wastes with a high calorific value [17], it entails destroying waste in a furnace while monitoring combustion at high temperatures ranging from 750 to 1100 [41]. This method's objective is to break down and eliminate the organic materials in MSW while utilizing oxygen to make the waste lighter and smaller so that it can be used to generate heat and energy [17].

Incineration helps reduce waste from being dumped in landfills, it may reduce about 70% of overall waste mass and 90% of overall volume, or solid wastes by 80–85% [36], based on the makeup and level of recovery of particular components such as metals from ash for recycling [42]. Organic compounds recovered from wastes often contain large energy deposits, of which 65–80 % may be accessed for heat and used in thermal supply. Fig. B.5 (Appendix B) depicts a schematic of the incineration process [42]

Incineration is a fairly stable process that can burn nearly any waste and can be sufficiently managed, therefore air pollutants may be carefully controlled as well. Nevertheless, preliminary preparation and processing of the biomass is required, such as pre-drying to reduce the waste's high moisture content before it enters the combustion chamber to be combusted with air. Furthermore, the residual ash includes leachable inorganic contaminants, which must be properly disposed of and are often landfilled [39].

While there are various other types of incinerators used in the WtE process for combustion, there are three basic incinerator types employed in the combustion phase, namely: a) grate incinerators or moving grates, b) rotary kilns, and c) fluidized bed [3]. Incineration is the most advanced WtE technique. The most recent generation of incinerators features an advanced air pollution control (APC) technology, which has improved their environmental performance dramatically [43].

In terms of energy, the greatest importance of incineration lies in the generation of heat and steam from MSW [17], where the final result of waste combustion is hot combusted gas, which is largely constituted of nitrogen (N_2), carbon dioxide (CO_2), water (H_2O, flue gas), oxygen (O_2), and non-combustible leftovers. The heat from combustion can indeed be utilized to generate steam and/or electricity as an energy source [32]. WtE recovery is mostly determined by the effectiveness of the processing system and the type of energy produced. Heat generation, cogeneration (steam and electricity), and pure electricity generation have an energy efficiency of 80%, 20–30%, and 20%, respectively. The quantity and thermal potential of the collected material are defined by the waste stream's composition, particularly for MSW because it may be quite heterogeneous [19]. Incineration, in any case, is not flexible enough to provide various types of primary energy (coal, gaseous, and liquid fuels), therefore it could only be utilized to generate steam and/or electricity as a tertiary output.

One of the most significant drawbacks of incineration is the emissions of greenhouse gases and other pollutants, which negate the environmental benefits. In comparison to AD and gasification, incineration contributed far more to global warming. Sulfur oxides (SOx), carbon oxides (COx), nitrogen oxides (NOx), polyaromatic hydrocarbons (PAH), and heavy metals are harmful gaseous pollutants that require extra treatment in a state-of-the-art flue-gas cleaning system before final emission into the atmosphere Fig. B.5 (Appendix B) [36]. While WtE incineration performs better in respect of CO and particulate matter emissions than other options, it performs worse in terms of SOx, carbon dioxide (CO_2), and nitrous oxide (N_2O) emissions, which can have a significant harmful impact on the climate [19].

Cucchiella et al. found that only the electrical configuration of a WtE plant produced emissions that were 14% higher than the cogenerative configuration, resulting in environmental savings of 430 kg CO_2 eq per ton of waste against 370 kg CO_2 eq per ton of waste, respectively [44]. Furthermore, when WtE incineration is evaluated just for its ability to generate electricity, it is observed to be less efficient than fossil-fuel-based conventional electricity plants [3]. However, efficient WtE incineration plants have larger positive externalities in terms of improving energy security and reducing GHG emissions [5], [45].

One of the key public health arguments for WtE incineration has been its ability to positively contribute to health promotion by destroying pathogens and other microorganisms that can accumulate in landfill waste. On the other hand, external effects related to combustion pollution can have negative consequences for public health. The transport of dangerous heavy metals like mercury and lead, as well as other pollutants like furans and dioxins, gives fly ash from incineration the ability to cause significant health problems, including respiratory diseases. Incinerators can also be ugly and emit unpleasant odors. As with landfill, incinerators can significantly pollute water and soil through leaching [5], [45].

Incineration plants can be built close to residential areas, lowering the expense of transporting MSW to waste disposal sites and, consequently, achieving better land use and resource integration than landfilling [5]. Notwithstanding this, incineration plants overcome a variety of economic constraints, including high capital, operational, and maintenance expenses as compared to other non-incineration choices, as well as the need for extensive operator experience. Mass burn facilities necessitate costly APC systems, which are necessary to treat flue gas and may be subject to more stringent permit requirements in some countries, such as the United States [39]. Another issue is that more raw materials must be utilized to replace those that have been burned, which does not save energy in the long term because resources are not recycled. Incineration has the potential to inhibit recycling and waste reduction, as well as create a poor public perception, particularly when it comes to dioxin emissions [5]. In addition, fly ash needs to be thrown away in toxic waste landfills, which added to the previously indicated expenditures.

2.5.4 Gasification

Gasification can now be expected to be a viable a substitute for the well-known thermal therapy technologies for the recovery of renewable energy from MSW. Gasification is a third method for converting combustible MSW into a secondary energy carrier that can be burned in a turbine to generate heat, electricity, or both [46]. Secondary products include hydrocarbon gases (hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and low molecular weight hydrocarbons), as well as hydrocarbon liquids (oils) and char (carbon black and ash) [37]. Gasification occurs at high temperatures (780–1650 °C) with a controlled amount of oxygen and/or steam without combustion (Compared to what is necessary for stoichiometric combustion, there is less oxidant present). Fig. B.6 (Appendix B) depicts a gasification schematic diagram [37].

Dehydration is the earliest round of the gasification procedure, followed by pyrolysis of volatiles (which is a promising WtE approach in and of itself), and finally gasification of char. Observing the mass loss of a solid material during gasification helps to understand the process [47].

The most common raw materials used in gasification are coal, petroleum-based compounds, and organic-based materials [17]. The chemical makeup of the final products and the efficiency of gasification are both heavily influenced by the feedstock. Biosolids, in theory, are well suited to produce more energy [3]. Furthermore, improved reactor design and operating parameters of the gasification process result in the production of higher hydrocarbons (HC) in addition to CH_4 and syngas [17].

Unlike WtE incineration, which is exclusively beneficial for energy recovery, gasification can be utilized to recover the chemical value of wastes in addition to energy recovery. A syngas produced by gasification is heat enhanced, cleaned, and used according to preference; it can also be used as a feedstock in the chemical sector following sufficient processing [46].

Apart from the potential for chemical value recovery, gasification has a number of additional gains over WtE incineration. Because it is a partial combustion process, it only needs a fraction of the oxygen that incineration does. This decreases the amount of dioxins, SO_2, and NOx produced, reducing or eliminating the requirement for costly gas cleaning equipment to improve incineration's environmental performance [46]. But Gasification, like incineration, produces bottom ash (Fig. B.6 - Appendix B), which must be separated and accurately maintained [48].

In terms of waste treatment benefits, gasification is said to outperform incineration in terms of waste volume reduction and energy consumption [46]. Gasification, according to [19] can save between 1.9 and 3.8 MW for each ton of waste. Though still in its infancy compared to combustion, the above-mentioned benefits have boosted acceptance of the technique in a number of countries, albeit on a smaller scale [3].

In terms of energy, unlike WtE incineration, gasification may not only recover energy but also produce a variety of compounds, making it a method for creating common fuels or chemicals from unconventional feedstock [19]. The syngas produced by gasification is heat improved, cleaned, and used as desired; after proper processing, it can also be used as a feedstock in the different chemical sector [46]

In terms of the environment, compared to burning, gasification is a more environmentally friendly thermochemical process. The reductive reaction conditions in a gasifier avoid the evolution of dioxins, furans and NOx and improve the quality of solid by-products by preventing metal oxidation and producing inert and vitrified ash. Syngas produces the highest quality fuels and cleaner energy after thorough purification and scrubbing, but requires a sequence of syngas pre-treatment and purification steps, increasing complexity and cost. Fischer-Tropsch synthesis can convert clean syngas into liquid fuels for use in internal combustion engines. Gasification, followed by AD, incineration and finally LFGRS has the greatest potential for CO2 reduction from an environmental perspective [32].

Gasification of MSW may be an economically challenging approach since it is better suited for homogenous wastes (such as wood chips, scrap tires, paper and cardboard, and plastics), whereas MSW's heterogeneous nature makes gasification and syngas cleaning more problematic [39]. As previously noted, gasification produces syngas, which needs to go through a number of syngas pre-treatment and cleaning procedures, adding to the difficulty and cost. While using catalysts to gasify waste improves syngas yield and purity, it also raises production costs. Furthermore, the well-established technology must cope with tar, char, and particles in the syngas, which adds to the gasification process's expenses, where at low temperatures, tar can condense and choke downstream pipes and equipment [49]. There aren't many huge-scale independent waste gasification stations in the US or around the world since companies haven't yet solved the aforementioned issues [39]. Summary of the topic: Due to its large capacity and operational expenses, gasification may not be attractive. Gasification comes first in terms of cost savings, followed by incinerators, LFGRS, and finally AD [32].

2.5.5 Pyrolysis

The MSW pyrolysis process is becoming more popular as a novel distributed MSW treatment method and as a WtE converter. It is a successful WtE approach that is gaining traction in the WtE research agenda due to its great increased efficiency, as it has the ability to recover up to 80% of the stored energy in carbonaceous wastes, as well as its capacity to create a broad range of solid, liquid, and gaseous products [19].

Pyrolysis is the initial stage in the incineration and gasification process. It is a destructive distillation technique in which thermal breakdown occurs in the absence of oxygen at temperatures ranging from 300 to 1300 ° C [50]. The molecular structure of solids is altered in this process, and CO2 is produced, resulting in a 40% drop in the mass of the solids. The carbonized solids are then converted into slurry, which is subsequently dried using thermal energy and converted into solid fuels in the form of pellets [3]. Fig. B.7 (Appendix B) shows a schematic of pyrolysis and its process [17].

The feedstock, temperature range, heating rate, and type of reactor utilized all affect the pyrolysis product yield and composition of MSW [51]. The product-spreading pattern, for example, changes as the pyrolysis temperature fluctuates. Lower pyrolysis temperatures yield more liquid products and higher pyrolysis temperatures yield greater gaseous yields, respectively. Conventional pyrolysis (550–900 K), fast pyrolysis (850–1250 K), and flash pyrolysis (1050–1300 K) are the three most used pyrolysis methods [17]. Fixed-bed, rotary kiln, fluidized-bed, and tubular reactors are among the pyrolysis reactors documented, although only rotating kilns and tubular reactors are used in the scale-up plants [11].

In terms or energy, MSW is an effective pyrolysis feedstock, pyrolysis of MSW can be commercialized to provide high quality fuel [51]. Heat and/or electricity, bio-oil, reformed syngas and char are the main products of commercial pyrolysis systems. The charcoal produced by the pyrolysis of MSW has a high calorific value and low ash content, making it suitable for use in combined heat and power (CHP) plants using other fuels such as MSW or coal. In addition, the dense and porous microstructure of char is associated with a high adsorption capacity, making it ideal for filtration or soil improvers. Pyrolysis of MSW can also produce high quality crude oil with a calorific value of around 38 MJ/kg [50]. It has the potential to be used in place of fuel and refined oil as a chemical feedstock to produce valuable industrial chemicals such as aromatics and phenols. Chemically, the liquid outputs from the pyrolysis of MSW are quite complicated as they contain a significant amount of water (Dezhen Chen et al. 2015). Since the gases mainly consist of CO and H_2, they can be used in gas turbines, gas engines and fuel cells, and can also be converted into chemicals [3].

When utilized in pyrolysis, catalysts increase product yield while lowering the process's energy requirements, Nickel and ruthenium-based catalysts, zeolites, and dolomite are among these several catalysts. Pyrolysis has also gotten a lot of interest because of the high liquid yield at high heating rates, as well as the reaction temperature of 425-600 °C and the short vapor residence time in the reactor. Synergistic interactions of various MSW constituents, notably plastics, yield fuels with high calorific values equivalent to conventional fossil fuels, according to a co-pyrolysis of diverse MSW constituents [53].

Pyrolysis is one of the viable alternatives for cost-effective waste reduction and carbon recovery that also minimizes environmental impacts. Pyrolysis has several environmental benefits, including reducing the volume of residuals that must be landfilled and recovering the condensate. Pyrolysis of MSW produces less NOx, SO_2, and dioxin in an inert atmosphere than incineration, and prevents the volatilization of heavy metals and fly ash. MSW pyrolysis may have certain environmental drawbacks, such as the possibility that pyrolysis-produced charcoal may contain heavy metals and organic pollutants, and that pyrogas from MSW pyrolysis may contain undesired gases such as HCl, H_2S, SO_2, and NH_3. Despite these drawbacks, pyrolysis plants employ emission control equipment to monitor and improve the quality of gas, liquid, and char products, making municipal waste pyrolysis more ecologically friendly [51]. As a result, MSW pyrolysis is more environmentally friendly than conventional MSW disposal.

MSW pyrolysis has certain drawbacks and restrictions in terms of economics. These limitations include the need for physical separation of incombustibles (metal and glass) is required prior to pyrolysis to minimize harmful effects; this disadvantage is common to all WtE processes. In addition, catalyst requirements raise prices, where some natural or synthetic catalysts are limited by their structure, physical, and chemical qualities. Synthetic catalysts, such as nickel and ruthenium, are expensive and deactivate considerably more quickly than natural catalysts. Besides, to keep catalysts in the ideal particle size range and activated form, the temperature is kept quite high, resulting in additional costs. Furthermore, impurities and pollutants in heterogeneous MSW, for example, can deactivate catalysts in the feedstock [53]. The aforementioned drawbacks are common to most WtE technologies, however in the case of MSW pyrolysis; these issues can be overcome to produce high-quality fuel and chemicals while lowering MSW volume by 50–90% [17] making MSW pyrolysis a more attractive WtE solution.

It is worth noting that pyrolysis' flexibility extends to not only the generation of heat and power, but also to the production of fuels and precious chemicals, as its outputs can be employed in a variety of applications and industries. In comparison to gasification, while gasification processes take place at temperatures between 800 and 1100 °C, biomass pyrolysis processes happen at cooler temperatures of 400 to 700 degrees °C. Pyrolysis is the process of gasification in the absence of oxygen, i.e. using an external energy source [47].

The theme summary is that economic progress and increasing energy demand are forcing us to seek safe energy sources, highlighting the importance of solid waste as a sustainable energy source that greatly contributes to creating a safe environment and renewable energy. The Palestinian Territories face unique challenges since the primary power grid that supplies electricity to the Palestinian Territories is under Israeli control; this hinders the Palestinian Authority from constructing an adequate infrastructure to generate electricity from renewable energy. To clarify more: For alternative energy investments to be feasible, there must be a system in place that allows the consumer to use the excess energy (from a given renewable energy source) to store it on the power lines themselves, not through batteries, since batteries are very expensive and make the project uneconomical. From this situation, Any WtE method that is limited to producing electricity or heat as end products, such as LFGRS, AD, or incineration, is not feasible, whereas pyrolysis can provide a wider range of end products that can be sold and utilized for a variety of purposes, including heat and power. As a result, this research will cover everything regarding MSW pyrolysis, including settings, reactors, catalysts, product distribution, and alternative scenarios for our case study.

Chapter Three

Pyrolysis of MSW

Environmental concerns about handling rising size of MSW and the insufficient supply of municipal fuels have prompted research into converting MSW to sustainable resources. Thermal pyrolysis is a new MSW treatment that uses external energy to break down complicated organic pollutants into fragments with solid residuals [54]. Pyrolysis has recently become the focus of scientific and engineering research, according to a review of various waste-to-energy studies.

This study will focus on the pyrolysis of MSW and the resulting liquid fuel, which can be turned into chemicals or utilized as a substitute for fossil fuels, by highlighting current developments in pyrolysis research for MSW that combines several components. The energy sufficiency of MSW as a pyrolysis feedstock, pyrolysis methods, reactors, the effect of various parameters on MSW pyrolysis products, catalysts, additives, and MSW pyrolysis products will all be covered in this section. It is also essential to talk about the benefits and drawbacks of producing successful pyrolysis with the least amount of environmental impact.

3.1 Energy sufficiency of MSW feedstock

The surplus energy produced by the pyrolysis process and held in the end products is defined as the energy sufficiency of MSW feed, which is determined by the feed's original energy content (wet basis) and the reactor's energy conversion performance [55]. For example, the energy recovered from a total of 6.5 million tons of wet MSW with an average HHV of 10.4 MJ/kg was calculated using data from 24 large-scale incineration plants for wet MSW in Taiwan in 2018 [56]. In Taiwan, MSW incineration has a positive energy sufficiency rate, which accounts for 45.5% of the energy contained in the fed wet MSW counting all energy necessary to operate all facilities [55].

Waste incineration is a two-stage process that begins with pyrolysis at 500°C to produce intermediary end products, which are then entirely combusted to produce CO_2 and water while producing reaction heat. The intermediate end products have an energy content of 86%, or 84.5–91.7 %, of the caloric content of fed MSW. As a result, if 90% of the energy in feed MSW is converted to pyrolysis end products on a dry basis, and given that the entire burning process from wet MSW provides a surplus of energy that is 45.5%, the lowest amount of energy necessary to maintain the pyrolysis operation is 4.6 MJ/kg. As energy is retained in the final products, exterior energy is essential to dry and increase the temperature of MSW to the pyrolysis temperature, which has to be greater than 4.6 MJ/kg due to the irreversibility of the pyrolysis process. To guarantee energy sufficiency in pyrolysis processing, a threshold heating value of 10 MJ/kg of MSW raw materials is considered. With C=46.31%, O=16.85%, H=5.86%, and m=50%, this figure is close to that predicted for MSW gathered by N. Wang, where a larger HHV appears to correspond to increased thermal process feasibility [55].

3.2 Compositions of MSW feedstocks

The components of MSW for pyrolysis gathered from various geographic locations are dependent on regional lifestyles, and the social-geographical state of local communities, and if the obtained MSW is source separated and subjected to resource recovery as portion of its final disposition. [56].

Surplus food waste, plastics, and paper wastes are among the MSW collected from residential locations. For example, Song et al. [57] conducted pyrolysis tests on MSW collected in Taiyuan, China, it includes 57.72% kitchen wastes, 23.40% plastic, and 10.7% paper. MSW collected from Guangdong, China, includes 46.4% food waste, 30.7% PVC, and 18.2% paper, according to. Mixed MSW was collected from Lahore, Pakistan's second largest city, including 69% food waste and 26% plastics and paper. MSW samples were obtained from a solid waste management corporation in Chania and a municipal waste treatment facility in Leicester, UK. Since Chania is Crete's second largest city and its economy is based on agriculture and tourism, its MSW includes 49.0% food wastes, 31% paper, and 12% biomass. Leicester is a medium-sized yet well-developed city in the UK, with 40% food waste, 28.8% paper, and 6.5% plastics in MSW. In addition, at Joinville, Brazil, MSW contained 80% plastics and tiny fractions of paper and metal, all of which were generated by industrial manufacturing activity. likewise, [58] looked at MSW samples from Bandar Lampung, Indonesia, the capital of the Lampung province, which has a large agriculture and light industry sector, and discovered that the samples comprised % plastics and 34% biomass. A sample of MSW from Hangzhou, China was examined, and found that biomass and textiles made about 40% of the overall weight, with 15% metals, 10% rubber, 10% paper, and 10% food waste following [58].

In the Palestinian Territories, based on the Tulkarm Substation as our case study, biomass accounts for the majority of municipal waste (56 wt.%), while the percentage of plastics and rubber entering the substation is no more than 5 wt.% and 0.5 wt.%, paper and textiles also accounted for small percentages, 12 wt.% and 6 wt.%, respectively.

We will investigate the potential of MSW in our country to create chemicals and liquid fuels, as feed content has a considerable impact on product type and quality. From here, the terminology and scope of reactions that occur in a recognized pyrolysis process should be discuss, as defined by [11]:

$$CxHyOz + Q \rightarrow Char + Liquid + Gas + H_2O \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{ Equation 2}$$

Where Q: input heat, which consist of Q1, Q2 and Q3

Q1: heat needed for moisture vaporization.

Q2: caloric requirement of pyrolysis.

Q3: the radiation loss from reactor to the surrounding.

Table A.1 (Appendix A) helps to conduct the chemical formulas of the pyrolysis feedstock.

3.3 Pyrolysis of MSW components

Biomass, plastics, and rubber are the three primary components of MSW. This section details the interaction between two MSW components, as well as the losses in mass profiles, ranges of temperatures, and pyrolysis decomposition kinetic parameters for each component [59]. In order to establish the best conditions for pyrolysis of MSW based on its content.

3.3.1 Pyrolysis of MSW single components

3.3.1.1 Biomass components of waste

Chhabra et al. investigated the pyrolysis of MSW contents for biomass components including FW, YW, paper, and textile. Their results indicate that the biomass substrate decomposes primarily among 180 and 350 °C [59].

Food waste is a considerable source of fuel since it contains a variety of carbon-containing compounds. Although FW has a volatile content of 71.18 wt.% and 28.82 wt.% of char, the significant proportion of the volatiles (36.7 wt.%) are produced by hemicellulose degradation. This offers a clear vision of the indigestible hemicellulose found in discarded fruits and vegetable peels. Hemicellulose breakdown is place between 200 °C and 300 °C in FW [59]. H. Liu et al. investigated the pyrolysis of food waste received from a Chinese municipality. Plastic, shells, and fruits were separated from the raw food waste during sorting. Vegetables, rice, and meats were present in proportions of 44.23%, 32.69%, and 23.08 %, respectively. The reactor in their experiments was microwave heating, its temperature reached 600 °C, yielding 36% bio-oil, 35 % biochar, and 29 % syngas [60].

In YW, hemicellulose devolatilization begins at 189°C, followed by cellulose decomposition from 323°C to 363°C, and finally lignin decomposition begins at 484°C. According to the TGA results, YW contains up to 68.56 wt.% volatiles (excluding moisture), with cellulose breakdown accounting for 27 wt.% volatiles. The char that remains at the end of the pyrolysis reaction makes up the remaining 31.44 wt.% (moisture-free basis). The major breakdown of YW occurs between 290 °C and 360 °C [59].

Paper is a combustible substance with hemicellulose and cellulose as main components and low nitrogen and sulphur levels. It would be an excellent feedstock for WtE development. Among the biomass wastes, paper produces the least quantity of volatiles, with 60 wt.%. Hemicellulose pyrolysis yields 5.5 wt.% volatiles, whereas cellulose pyrolysis yields up to 22.6 wt.% volatiles. The majority of the paper decomposed within 320 °C and 429 °C, although a peak around 680 °C was seen in the paper sample owing to the decomposition of $CaCO_3$, which accounts for up to 22 wt.% of the total volatile material generated. These volatiles, on the other hand, do not contribute to the generation of syngas or oil. After pyrolyzing the sample to 900 °C, 18 wt.% char is produced. Some researchers used waste paper to conduct two similar investigations at a temperature of 665 °C and a heating rate of 5 °C/min. Newspapers, printing and writing papers made up the waste paper. Decomposition of the matrix began at 215 °C and was finished at 310 °C. Bio-oil production began at 290°C and reached a maximum output at 417 °C. The bio-oil compositions revealed that it comprised both hydrocarbons and non-hydrocarbons, as well as four primary components of anhydrous sugars, carboxyl, carbonyl, and aromatics, according to the research. Temperature increased the proportions of these components and volatiles [61].

The pyrolysis of MSW's paper component has been studied by. The process was carried out in a tubular pyrolysis reactor at various temperatures and heating rates to evaluate the quantity and the quality of the pyrolysis products. The moisture in the waste paper was eliminated by drying it for 12 hours at 90 °C before putting it into the reactor. When the temperature and heating rate were kept at 420 °C and 30 °C/min, respectively, the greatest yield of bio-oil produced from their experiment was 49.1%. They concluded that increasing the temperature enhanced the yield of syngas. This is due to secondary breakdown and secondary crack of biochar and syngas at high temperatures, respectively. They also evaluated the components of bio-oil and found four main components of anhydrous sugars, carbonyl, carboxyl and aromatics. In a similar sort of experiment using waste paper at 800°C, four distinct components of styrene, phenol, naphthalene, and benzene 1-ethynyl-4-methyl were discovered [62].

The pyrolysis of waste paper containing paper cups in a semi batch pyrolysis reactor was investigated at various temperatures. When the temperature was increased from 325 to 425 °C, the time it took for the full reaction to occur within the reactor was reduced from 24 to 8 minutes. When the temperature was kept at 400 °C, the greatest yield of bio-oil achieved was 52%. The chemical and physical features of bio-oil revealed that it included a high concentration of hydrocarbon components (C_6–C_{18}) and that its quality was low when compared to commercial fuels. The calorific value, moisture content, and pour point, respectively, were 23 MJ/kg, 9.1%, and -12 °C. Because of the low pour point, it was believed that this product would overcome the freezing difficulties in sub-zero climes [54].

The textile is made from cotton, which is a pure source of cellulose. As a result, textile decomposition occurred between 261 and 351 °C, with only 8.7 wt.% char remaining at the end [59].

3.3.1.2 Waste plastic components

Plastic waste has contributed significantly to the globe MSW output. Plastics can be divided into six categories based on their constituents: high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). Plastics differ from other MSW components in terms of their properties. They are difficult to decompose and include a variety of components in non-uniform ratios, as well as constantly changing internal and exterior features [54].

All of the various plastic components (PS, PET, PP, LDPE, and HDPE) breakdown in a limited temperature range of 311–480 °C, with fast hydrocarbon weight loss in a single peak. PS, PET, PP, LDPE, and HDPE decompose at temperatures of 311°C, 348°C, 380°C, 327°C, and 377°C, respectively. HDPE and LDPE generate the lowest amount of char, up to 2 wt.%, followed by PP (2.36 wt.%), PS (7.366 wt.%), and PET (15.77 wt.%) among the plastics. When comparing plastic to biomass, plastic decomposes at a greater temperature and produces more volatiles [59].

3.3.1.3 Rubber

Rubber is a heterogeneous system composed of Natural Rubber (NR), Styrene Butadiene Rubber (SBR), and Polybutadiene Rubber (BR). NR decomposes at temperatures ranging from 310 to 450° C, whereas synthetic rubbers like SBR and BR degrade at higher temperatures ranging from 410 to 500° C. The breakdown of rubber happens through three reactions in a sequence, resulting in three devolatilized zones, according to [59] experiment. The first zone ranges from 190 to 310° C, the second from 310 to 429 ° C, and the third from 577 to 660° C. The first zone yields 9 wt.% of total volatiles, which correlates to the pyrolysis of rubber additives. The degradation of rubber in the second shoulder produces the majority of the volatiles, 37.2 wt.%. The second zone's temperature range (310–430°C) is identical to that of NR. This means that the waste sample utilized in this investigation does not include synthetic rubber. The third zone (577–660°C) comprises for 11.3 wt.% of total volatiles and relates to inorganics that do not contribute to the formation of syngas or oil. The maximum quantity of char of the three MSW types is achieved at the end of pyrolysis temperature, with 40.11 % [59].

3.3.2 Interaction between binary components

Based on [59] experiment, a comparison between simulated and real experimental co-pyrolysis for various components of MSW will be presented in this section, where the theoretical and real results will be compared to get a clear idea about the synergetic effects of MSW components during the pyrolysis process.

3.3.2.1 The impact of interaction in the biomass mixture

The results of investigations and the prototype for the biomass blend sample were determined by Chhabra et al. [59]. the same amount of weight proportion of yard refuse, food refuse, paper, and texture samples are used to make the mixture. The char produced by the mixture matches the non-interactive model's prediction. As a result, when biomass samples are pyrolyzed, there is no overall synergistic impact; nonetheless, there is some physical interaction between the ingredients. The observed speed of mass loss of the cellulose pseudo- ingredient is lower than what the model predicts. Physical changes in the biomass mixture are responsible for this. Hemicellulose breaks down faster than cellulose, forming a liquid form that enwraps around cellulose and prevents it from decomposing.

The system exhibits positive synergy at 320 °C. This might be attributed to the combined pyrolysis of cellulose and lignin constituents, that has been shown to decrease the polymerisation of cellulose-derived anhydrosugar, resulting in more volatiles and less char. The catalyst impact of the inorganic extras, that is claimed to occur among 430 and 600 °C, can also be predicted to provide favorable synergy [63]. However, until 900 °C, the expected secondary interactions and left extras breakdown to reduce char creation, resulting in a 28.4% expected value [59].

3.3.2.2 The impact of interactions in a plastics mixture

This mixture was made by mixing equal weights of HDPE, LDPE, PP, PET, and PS specimens [59]. the first zone ranges from 283 to 416 °C, with a 396 °C peak temperature, whereas the second shoulder ranges from 416 to 480 °C, these two experimental zones correlate to two pseudo components. On the other hand, the model anticipates two separate peaks. As a result, an interaction-related consequence can be seen in a mixed plastic sample.

A good synergistic impact can be seen in the first zone, it also has a lower activation energy and produces fewer stable polymers than the uninteractive model predicts. This is a predictable outcome since the radical starters created by less stable compounds like PS and LDPE enable the HDPE radicals to pyrolyze quicker than anticipated. Once the PS and PET have completely pyrolyzed, the second zone over 416°C exhibits negative synergy, generating more char than expected. This is due to PET's char inhibition effect, which results in more complex pseudo-components.

Generally, the amount of char left behind after the reaction matches that anticipated by the uninteractive model, which is 4.1%. While the plastic mixture specimen does experience interactions during pyrolysis, there is no overall synergistic effect.

3.3.2.3 Impact of interactions between plastic mixture and biomass

The five plastic component parts and the four biomass component parts are blended in an equivalent ratio. The interactive and non-interactive results are compared. The plastic breakdown temperature has been changed to 420 °C, which is predicted to have a DTG peak at 400 °C. This implies that more steady substances that have greater activation energies are formed than expected. Lignocellulosic and plastic ingredients degrade via different pathways: the former pyrolyzes by ionic/non-ionic processes, whereas plastics degrade via radical interactions [64]. Because lignocellulosic material degradation produces reactive species, which can extract hydrogen from plastic polymers, plastic can’t depolymerize until more hydrogen species are generated or the lignocellulosic substances are entirely degraded, as the hydrogen is extracted early.

At 550 °C, experimentally, 2 ± 0.6 wt.% more char was formed than predicted by the model. However, till 900 °C, the estimated secondary interactions and remaining extras breakdown to reduce char production, yielding the expected outcome of 14.3% [59].

3.3.2.4 Impact of interactions between plastic mixture and rubber

The five plastic sub-components and rubber are blended in a similar mass ratio. At 280 ° C, the system begins to pyrolyze, which is the estimated beginning temperature of the rubber specimen. The radicals of rubber are thought to catalyze the generation of radicals in plastic specimens, resulting in a beneficial synergistic result in the process until the temperature reaches 430 °C, at which point the entire rubber material is supposed to pyrolyze totally, leaving a considerable amount of char. This char prevents the pyrolysis of the plastic material at temperatures above 430 °C, and the volatiles generated are hypothesized to remain in the char, causing an unfavorable synergy in the framework. Experiment results in 5% higher char formation compared to expectations[59].

3.3.2.5 Impact of interactions between biomass and rubber

At an equal weight ratio, four sub-components of biomass and rubber are combined. Hemicellulose decomposes completely near temperatures up to 270°C. The cellulose and lignin portion of biomass in addition to NR pyrolyze in tandem above 270 °C till 420 °C. The characteristics of volatiles generated via the pyrolysis of diverse substances are changed as a result. Moreover, above 420 °C, the volatiles deposition inside the porous construction of the charcoal contributes to the gross charcoal outputs. Finally, between 420 and 510 °C, only 2.4 % of the leftover charcoal breaks down. Given that the reactive substances already are degraded by radical interactions between 270 and 420 °C, this pseudo-component is found to be highly stable. This combination produces 8 wt.% more char than the non-interactive model predicts. As a result, these outcomes demonstrated that the existence of rubber in a municipal waste sector reduces the generation of volatiles, and that rubber's co-pyrolysis action overcomes the catalytic effect of extras in the overall mix [59].

3.4 Categories of pyrolysis

Thermal pyrolysis can be labeled as slow pyrolysis, fast pyrolysis, and flash pyrolysis based upon the associated heating rates, as shown in the table below.

Table 1

Types of pyrolysis and the distinct characteristics that affect it

Pyrolysis technologies		Slow Pyrolysis	Fast Pyrolysis	Flash Pyrolysis
Process conditions	Temperature (°C)	400–600	400–700	400–950 or above
	Heating rate	6-48 °C/min	10-100 °C/sec	≥1000 °C/s
	Residence time	25 min-35 hr.	0.5-2 sec	< 0.5 s
	Feedstock particle size	Briquette, whole	Finally ground	As small as possible
Product yield (wt.%)	Char	25-65	<25	10-15
	Bio-oil	10-30	40-75	10-20
	Syngas	10-50	<20	60-80

[54]

3.4.1 Slow pyrolysis

Slow pyrolysis represents a batch process wherein the biochar is typically produced at temperatures that vary between from 400–600 °C and heating rates that range from 6 to 48 °C/min. Solids and gas have longer residence durations in this process, which might vary through minutes to days [65]. The majority of the research literature on the slow pyrolysis technique is focused only on its use to make biochar. However, other studies investigated the creation of bio-oil via slow pyrolysis. Slow pyrolysis yields biochar, bio-oil, and syngas in the band of 25–65 wt.%, 10–30 wt.%, and 10–50 wt.%, respectively. Carbonization is a slow pyrolysis technique in which various feedstocks are pyrolyzed without the pyrolysis products being condensed. This technique has been used for the creation of biochar for centuries, and it is used when char is required. The percentage of biochar and bio-oil generated is considerably affected by the qualities of the raw material, such as the percentage of moisture, volatile substances, fixed carbon, ash, and process temperature. 15–20 % of moisture is normal for biochar creation, according to. The size of the raw material to feed slow pyrolysis may vary from briquettes to entire logs, with wood being the most acceptable choice. Other forms of feedstocks including cashew nut shells, palm, and many more, can also be used, but yields are less than with wood [66].

3.4.2 Fast pyrolysis

The fast pyrolysis technique has been regarded as a cutting-edge technique. It has attracted much interest because of its higher bio-oil production capability than other procedures. It is a continuous task that is taking place at temperatures ranging between 400 and 700 ° C [53]. The main goal of this approach is to keep the pyrolysis output against decomposing further into non-condensable chemicals. To achieve higher bio-oil yields, the parameters in this approach are strictly monitored. This approach necessitates extremely fast heat transmission rates. The heating rates are usually among 10 and 100 °C/sec, while the residence period is between 0.5 and 2 seconds [53]. The aforementioned fast-heating rate has been attributed to the adequate grinding of the feedstock. The reaction inside the reactor in fast pyrolysis normally takes place in a relatively brief period of time. The chemistry of the pyrolysis products is determined by the kinetics of chemistry, mass, heating transfer speeds, and transition phenomenon. This technique may produce bio-oil at a maximum of 70 wt.% or 75 wt.%. Based on many investigations, the greatest number of bio-oil liters could be produced once the interaction temperature is set to 500 ° C. Fast pyrolysis additionally generates bio-charcoal and syngas, syngas yields increasing as biochar and bio-oil yields decrease. Adjustment of operation parameters can offer desired substance yield [67].

3.4.3 Flash pyrolysis

This category of pyrolysis is the most sophisticated technique for recovering a considerable volume of syngas along with high-quality bio-based oil which has low minimal water percentage. Such category of pyrolysis is performed at high temperatures of 400 to 900 °C or more and at extremely high heating rates of more than 1000 °C/s [65]. The residence duration is less than 0.5 seconds, thus being is lower when compared to fast pyrolysis method. As this method demands extremely rapid heating rates, the feedstock dimensions of the particles have to be as tiny as possible [68]. Through flash pyrolysis, yields of biochar, bio-oil, alongside syngas vary from 10–15 wt.%, 10–20 wt.%, and 60–80 wt.%, respectively. This process can convert around 80% of the energy included in the raw materials into a variety of energy products, and so the energy density of the formed products is higher than the raw feedstock. Nonetheless, the bio-oil produced by this technique contains a significant amount of oxygen, confirming that this yield is corrosive and unstable. It moreover possesses impurities like heavy metals and nitrogen, eliminating these pollutants demands an enormous quantity of hydrogen, which is very expensive [68].

3.5 Pyrolysis reactors

To qualify pyrolysis to be truly efficient, a pair of fundamental design parameters need to be considered: the reactor ought to indeed ensure high heat transfer to the raw materials alongside a brief residence duration. If the heating transfer rates are low plus the residence time is lengthy, significant amounts of bio-charcoal and syngas might be produced [54]. To produce bio-oil, several types of pyrolysis reactors are employed, the most common of which include fixed-bed, fluidized-bed, rotary kiln, auger or screw, alongside ablative reactors. Here's a brief overview of the reactors listed above:

3.5.1 Fixed-bed reactor

Fixed-bed reactor is the oldest form among reactors, it is commonly run-in batch manner. It is simple to construct and has been demonstrated to work well with uniformly sized MSW as a feedstock. Charcoal is the major product of this sort of reactors. Fig. B.8 (Appendix B) depicts a typical fixed-bed reactor. This type of reactor has several drawbacks, including slow heating rates, lengthy residence duration, along with non-uniform temperatures of the substance within the reactor. On top of that, this reactor is economically untenable due to its batch nature. As a result, this sort of reactor provides possibilities in research along with small-scale heating and electricity production [54].

3.5.2 Fluidized-bed reactor

The most widespread form of the reactor is the fluidized-bed reactor, which can be used in an extensive range of applications, from experimental to manufacturing scale. Such reactors are widely utilized in the oil and chemical industries. Besides from creating bio-oil, the fluidized-bed reactors have been more productive owing to the continuous nature of feedings. This reactor can be classified as either bubbling (Fig. B.9 - Appendix B) or circulating (Fig. B.10 - Appendix B) [54].

- Bubbling fluidized-bed reactor:

For bubbling fluidized-bed reactors, MSW particles are put into the hot sand and perhaps other solid bubbling beds. The bed is fluidized with an inert gas. Low flows of air can also be utilized as long as the volume of oxygen is assured to be stoichiometrically modest, preventing full oxidization of the substance. Competent blending of the inert bed solids is necessary to ensure effective and uniform temperature regulation. Typically, bio-oil fraction of the product produced by this reactor system is 50–55 %. These reactors have the benefit of being relatively simple to scale up [54].

- Circulating fluidized-bed reactor:

The circulating fluidized-bed reactors operate on the same principles as the bubbling fluidized-bed reactors. The main distinction resides in the circulating reactor, the bed is substantially enlarged, as well solids are continually circulated circa an interior loop that includes a cyclone and a loop seal. This reactor's riser uses a unique hydrodynamic technology known as a fast bed. The circulating fluidized bed reactor does in fact ensure uniform mixing and temperature control. The superficial gas velocity is higher with this type than with the bubbling sort. The high gas speed along with efficient blending allows the circulating sort to handle a large supply of raw material. Once gas along with solids move within the reactor, an interior refluxing phenomenon occurs. Consequently, the residence period of a typical feedstock is longer compared to that of the gas. The difference, however, is not as great as it is in the bubbling reactors. The crucial benefit of this design of reactors is the ease with which the embedded bio charcoal is able to be separated [69].

3.5.3 Rotary kiln reactor

A rotary kiln is a form of pyrolysis reactor that is greater in effectiveness than fixed-bed reactors, particularly with regard to heating the raw material. Fig. B.11 (Appendix B) depicts a typical rotary kiln reactor. By virtue of its inclination ceramic-lined cylinder and the slow rotation, the rotary kiln reactor efficiently mixes MSW. It has a broad range of applications. However, this form of reactor employs a slow pyrolysis process, signifying its heating rates are likewise slow. The heating rate cannot exceed 100 °C/min, and the residence period is 1 hour. The low heating rate is caused by a variety of factors, encompassing the fact that heat is delivered to the feedstock exclusively via the reactor wall, the wall surface contact area with the feedstock is minimal, as well as the particle size is rough. The chopped municipal waste is fed into the reactor via its frontal end. The kiln's rotation facilitates the optimum mixing of MSW. Then it is slowly heated as pyrolytic gaseous substances are emitted whilst it shifts down the cylinder and carbonizes.

Rotary kiln reactors are the most frequently reported reactor for MSW pyrolysis thanks to some distinctive features [11]. Some of these features include appropriate MSW mixing, flexibility in residence period alteration, the capability to introduce heterogeneous substances, the lack of MSW pre-treatment requirements, and easiness of maintenance [54].

3.5.4 Auger reactor

Augers are employed in this sort of reactor to transport biomass substrate via a heated, free-of-oxygen cylinder tube. Fig. B.12 (Appendix B) depicts a typical Auger reactor. The feedstock devolatilizes and gasifies when heated up to the necessary pyrolysis temperature, which ranges from 400 °C to 800 °C, by passing within the tube. Char is created, gases are condensed into bio-oil, and bio-gas is recovered from non-condensable vapors. In this arrangement, the heated region by which vapor passes before reaching the condenser train can be changed to alter the vapor residence period [70].

3.5.5 Ablative reactor

Due to the method of heat transmission via a melted layer across the heated reactor surface alongside the lack of the fluidizing gas, ablative pyrolysis differs significantly from fluid bed procedures. The biomass is pressed against a hot reactor wall using mechanical pressure. When something touches a wall, it "melts" in a sense, and as it is pulled afar, any remaining oil vaporizes to be pyrolysis vapors. Ablative processors have the beneficial characteristics of not requiring excessive cutting of the input material and of allowing significantly bigger biomass particle sizes than other kinds of pyrolysis processors. However, because the procedure is mechanical, this setup is a little bit more complicated. Since this structure is surface area regulated, scaling is a proportional function of heat transmission. So, unlike other reactor designs, ablative reactors cannot take advantage of the same economics of scale [70]. Fig. B.13-(Appendix B) depicts a typical Ablative reactor.

3.6 A literature review of parameters affecting pyrolysis efficiency

3.6.1 Effect of temperature

Biomass decomposition takes place via three consecutive stages during pyrolysis. At 122 to 202 °C, some interior rearranging occurs, including moisture removal, bond fracture, the emergence of free radicals, and the generation of carboxyl, carbonyl, and hydroperoxide groups [71]. Pyrolytic products such as charcoal, bio-oil, and gases begin to represent in the second stage (200–600 °C). The third stage (over 600 °C) involves the slow breakdown of char, resulting in carbon-rich residual solids [72]. Dehydration as well as decarboxylation reactions lead to an increase in the concentrations of polar, aliphatic, and aromatic molecules at temperatures above 600 °C. The yields of various gas compounds also change [73]. Temperature significantly affects the amount of water generated as well. Water production increased substantially at temperatures up to 360 °C, but not at higher temperatures. However, after 580 °C, water production begins to decline [74].

It was noticed an improvement throughout the carbon content alongside a reduction in both oxygen and hydrogen levels through promoting the temperature. Demirbas et al. also evaluated the influence of temperatures on reaction output from biomass. They found that when pyrolysis temperature rises, the amount of char produced decreases. Between 376.85 and 526.85 °C, the highest possible bio-oil output was attained. Furthermore, the heating value for the yielded fuels had been linked to the pyrolysis temperature [71].

Elevated temperatures cause volatile cracking processes, which minimize bio-oil yields and foster gas production, whilst lower temperatures cause substantial amounts of biochar to develop. Temperatures within the range of 450 to 550 °C are ordinarily ideal for producing liquid biofuel [75]. Since temperature is among the most crucial factors influencing the pyrolysis procedure, it can affect bio-oil yield by 10–20 %. A number of research have looked into the effect of temperature on MSW pyrolysis. Some researchers performed thermal pyrolysis on MSW samples in a fluidized bed reactor, keeping all process variables constant except the temperature, which fluctuated from 350 to 500 °C. They discovered that the highest biooil output was attained alongside the lowest char yield. The yields of bio charcoal, bio-oil, and syngas had been 18 (wt.%), 50 (wt.%), and 32 (wt.%), respectively. However, the grade of bio-oil in relation to hydrogen, oxygen, calorific value, alongside the quality of bio charcoal in regards to calorific value plus ash content, were found to be finest at 500 °C. Li et al used an externally laboratory-scale rotary kiln reactor to pyrolyze mixed MSW. With a temperature increase from 550 to 850 °C, bio-oil generation was lowered from 65 to 36 % while syngas generation was increased from 27 to 63 % [76]. This research also found that the heating value of bio-oil elevated until it reached a particular pyrolysis temperature limit, beyond which it began to decline when the temperature was raised further. Similar tendencies were discovered for aliphatic hydrocarbons, but aromatic rings showed the opposite trend.

3.6.2 Effect of heating rate

Another key parameter that influences the patterns of breaking down within pyrolysis reactors is their heating rate, which differentiates slow pyrolysis from fast pyrolysis. Fast pyrolysis causes rapid depolymerization of cellulose and hemicellulose of MSW, resulting in larger yields of volatile compounds. It additionally reduces the residence period of volatiles within the reactors as well as secondary interactions [77]. The cracking reactions were enhanced by the short duration of secondary reactions, which resulted in more volatiles (bio-oil) and less char. Slow pyrolysis, on the other hand, contributes to considerable bio charcoal production due to the progressive degradation of MSW. Slow pyrolysis procedures require heating rates of 1 to 100 °C/min, whereas fast pyrolysis operations demand heating rates of more than 1000 °C/min [78].

Heating rates has a direct effect on the content and qualities of bio-oil, charcoal, and gas components. Because secondary processes such volatile dehydration are inhibited at higher heating speeds, the water content of the bio-oil drops. At high heating rates, CO and CO_2 levels also boost. High heating rates result in a char with a reduced pore capacity [79].

The implication of heating rates on mixed MSW pyrolysis was explored experimentally by many researchers. The trial was carried out in a horizontal tubular reactor with varying heating rates of 5, 20, 90, and 350 °C/min, an extremely high temperature (800 °C), along with a long vapor residence duration. There was no observable effect when the heating rate was increased from 5 to 20 °C/min. However, increasing the heating speed to 350 °C/min raised the syngas output from 15% to 47% and reduced the bio-oil output from

53% to 23%. Biochar has been steadily declining, owing to the heat degradation of higher molecular weight hydrocarbons inside the charcoal [80].

3.6.3 Effect of residence time

The residence time is the period of time the raw material is exposed to a specific temperature. For batch processing activities to achieve the desired pyrolysis output, this time must be adequate. The residence periods of vapor alongside solid within the reactor have a substantial influence on the yields and properties of biomass pyrolysis output. A lower vapor residence time favors bio-oil generation and reduces cracking responses. Biomass, on the contrary hand, requires a longer residence time to guarantee complete breakdown [54], [78].

Cai et al. focused on the impact of the duration of residence on biomass pyrolysis. TGA was adopted to investigate the pyrolysis kinetics of biomass at a variety of retention times in their research. They discovered that as the residence duration increased, cracking interactions increased and the amount of more weighty species in the bio-oil decreased [77].

3.6.4 Effect of feedstock particle size

Due to MSW's poor thermal conductivity, the particle size of the raw material is also another significant factor to consider for pyrolysis. When the size of the particles changes, temperature gradients within the particles shift, resulting in variations in the pyrolysis products. Several research teams investigated the effect of feedstock particle dimensions on pyrolysis and expenses. Their results reveal that larger particle sizes result in increased char and gas production, while bio-oil output decreases. Furthermore, after a certain degree of particle dimensions increase, the yield of the products is unaffected. More curiously, as the particle size gets bigger, so does the yield of water production. Lu et al. explored the effects of particle dimensions and shape on biomass particle devolatilization. The size along with the shape of the particles had an effect on the reaction rate, according to their findings. Indeed, by reducing the particle size, the volatile yields were decreased. Furthermore, particle shape possesses an effect on product yields and compositions. As an illustration, biomass with a spherical shape produced fewer volatiles than biomass with a cylinder or plate shape [81]. Lu et al explored the influences of particle size and shape on biomass particle devolatilization. So according to their observations, size as well shape of the particles had an impact on the reaction rate. The volatile yields were indeed diminished by minimizing the particle size. Additionally, particle form alters product yields and structure. As an example, sphere-shaped biomass yielded lesser volatiles compared to cylindrical or plate biomass [81]. Conversely, Nurul et al. found an opposing pattern of bio-oil output in municipally waste papers pyrolysis at 450 °C via a fixed-bed reactor using nitrogen as a carrier gas [82]. Three substrate sizes were used: lower than 10 mm, 10–20 mm, along with ordinary or typical sizes (as gathered from municipalities). As the size of the feed particles got larger, so did the generation of bio-oil. Bio-oil production went up from 43% to 54% when particle size went up from less than 10 mm to normal sizes. Smaller particles were excessively heated or easily blown away, leading to lesser quantities of bio-oil, according to the authors.

3.6.5 Effect of reaction atmosphere

Biomass pyrolysis is often done in an inert atmosphere. Carrier gases including N_2, H_2, CO, CO_2, CH_4, along with steam can be employed. The utilization of steam provides a number of benefits. It is capable to enhance the production of bio-oil by reducing the rates of secondary cracking reactions, but it can also promote the growth of organic oxygenates by avoiding some secondary interactions. As a result, the carrier gas may change the pyrolysis reaction mechanism by affecting the productivity, functional categories within products, the content of energy in bio-oil, and so on. With respect to CH_4, it is suitable to produce a large yield of bio-oil [77]. It has been discovered that adding CO_2 to the pyrolysis environment changed the amount produced and the structure of the all products. The addition of CO_2 to a nitrogen medium increased CO production. When compared to pure nitrogen, it resulted in a reduced charcoal yield. The presence of CO_2 in the atmosphere causes a carbon-rich char to form [77]. Kwon et al. also discovered that adding CO_2 to the pyrolysis environment increased gas yield while decreasing oil yield [83].

3.7 Catalytic pyrolysis

Catalysts enhance the pyrolysis operation and production efficiency by accelerating the decomposition of feedstock, leading to an increase in the yields as well as the grade of the products or a specific product [84]. Plenty of studies have investigated the quality enhancement of MSW pyrolysis products using various types of catalysts.

In plastic waste pyrolysis, Cai et al. employed a Ni-Al-Mg catalyst to break down alkanes alongside alkenes (C_2 to C_4) to H_2, CO, along with CO_2. The gaseous output boosted the electricity production via a solid oxide fuel cell that got the acquired syngas from 710 W/m2 to 2800 W/m2 at 800 °C with the application of the applied catalysts. also, to promote gas output plus raise the H_2 content of the syngas output, Chai et al. added a Ni-CaO-C catalyst to LDPE and pine sawdust mixes [85].

Onwudili et al. employed Y-zeolite (ZY-1) as well as ZSM-5 zeolite (ZS-1) just like catalysts in order to improve the gaseous yields from pyrolysis of plastic mixes (PP, PE, PS, and PET) at 600 °C by factors of 1.5 and 1.8. At 500 degrees Celsius, the ZY-1 along with ZS-1 catalysts decreased oil production by 24% and 37%, respectively, compared to typical pyrolysis of blended polymers, but boosted the gaseous yields by 2.5 and 1.5 times, respectively [86].

3.8 Various pretreatment methods to improve pyrolysis efficiency

Pretreatment of feedstock is required for a successful pyrolysis operation. Pretreatment is capable of enhancing the efficiency of the process by destroying the lignocellulosic composition [77]. Pretreatment procedures will be described in the following sections: physical, chemical, thermal, and biological.

3.8.1 Physical pretreatment

Because biomass has a low heat conductivity, temperature gradients within it influences the pyrolysis mechanism. In pyrolysis, the larger the feedstock particles size, the more char is created. Furthermore, reducing the size of biomass particles raises the cost of operating. As a result, considering the cost, choosing the right sized particle might have a big influence on pyrolysis efficiency [87].

- Shredding the feedstock to change the particle size:

Several research groups investigated what effect of feedstock particle sizes on pyrolysis as well expenses. Their findings, as previously stated, showed that larger particle sizes result in increased char and gas generation while bio-oil yield decreases. Furthermore, after a certain degree of particles size increase, the yield of the products is unaffected. More intriguingly, as particle size increases, so does the yield of water production.

- Densification

The biomass density influences the amounts and compositions of pyrolysis products. Palletization of partitioned agrarian straws and high-pressure densification of wood waste was investigated in several studies to generate an inexpensive feedstock for pyrolysis reactors. Their findings revealed that compacting biomass can increase biooil output. Pellet grinders, cubers, briquette presses, screw extruders, tabletizers, and agglomerators are all common biomass densification technologies. Pellet grinders, briquette presses, and screw extruders are the utmost popular pyrolysis equipment [87].

3.8.2 Chemical pretreatment

Inorganic minerals found in biomass may result in a substantial influence on the pyrolysis technique. Chemical treatment could reduce their effects [77]. This section will go through various important chemical pretreatment procedures, such as acid and alkali prior treatment, hydrothermal, steam explosion, along with ammonia fiber expansion prior treatment.

- Acid and alkali pretreatment

Carbonates, sulphates, chlorides, along with phosphates are actually the most common species that compose biomass, all of those having a significant impact on pyrolysis. Metals like sodium, for example, mostly remained in charcoal after pyrolysis, posing a challenge throughout char burning process. It could also make the reactor more corrosive. Cations likewise catalyze charcoal production interactions and inhibit the production of biooil. Furthermore, the presence of them in bio-oil speeds up the bio-aging oil's procedure [88].

Acid treatment is a typical means of removing minerals out of biomass prior to pyrolysis. Dilute acids, like sulfurous or chloric acid, are utilized in such procedure. The acid treatment could boost bio-oil yields from 19 to 27 wt.%. Hemicellulose, which is the origin of hydroxyl acids, can also be dissolved or removed by acid. Alkaline solutions, such as NaOH, were also employed to partially extract hemicellulose along with lignin out of biomass at low temperatures. Acidic substances could interact with alkaline throughout pretreatment, causing the formation of salt, which can catalyze the formation of charcoal, reducing the output of bio-oil [89].

- Hydrothermal pretreatment

Hydrothermal pretreatment (likewise known as wet torrefaction) of biomass is as well used to improve both the carbon as well as energy content in the biomass. This procedure was normally executed at a temperature range of 18–260 °C and up to 4.69 Mpa of pressure. Compounds like acetic acids, pentoses, hexoses, furfural, phenolic substances, and sugars are formed during the hydrothermal process. During the thermal processing, almost all hemicellulose decomposes, whereas cellulose degrades just partially [77].

Meng et al investigated the influence of the torrefaction of the biomass on the characteristics of the bio-oil generated. They came to the conclusion that employing torrefied biomass lowered the O/C ratios in bio-oil. It was found that increasing the torrefaction temperature enhanced char yield while decreasing bio-oil production. Along with that, the oxygen content of the bio-oil was reduced. Some researchers employed torrefied biomass as a feedstock for fast pyrolysis. They demonstrated that torrefaction may boost the efficiency of fast pyrolysis via reducing the amount of energy required to crush biomass particles and boosting the characteristics of bio-oil [77].

- Steam explosion

The fibers in biomass are opened up during this procedure, making their polymers better accessible for following processes such as fermentation, hydrolysis, or densification. The mechanical strength of biomass, particularly woody biomass, is great due to the closely packed cellular structures (fibers) found within the biomass. The tough structure of biomass is a significant technological challenge for the majority of biorefinery operations, including pyrolysis. Sugars and other valuable compounds can be extracted from biomass using steam explosion. To enhance the calorific value, a steam explosion is able as well to generate biomass pellets. In comparison to other pretreatments, this process does not necessitate the utilization of chemicals. Chen and colleagues According to their findings, combining steam explosion with other pretreatments might notably change the characteristics of biomass as well as change the product distribution through pyrolysis or hydrolysis [77].

- Ammonia fiber expansion

Ammonia fiber expansion serves as an essential pretreatment approach that uses the two physical and chemical operations to attain successful pretreatment. Physical processes are represented by raising temperature and pressure, while chemical processes are represented by adding ammonia. For ammonia fiber expansion treatment of biomass, anhydrous ammonia, elevated pressure (~2 MPa), and temperatures of 60–120 °C were utilized. During the treatment, hemicellulose was decomposed into oligomeric sugars, lignin was depolymerized, and cellulose was recrystallized [87].

3.8.3 Thermal pretreatment (drying)

The dehydration of the biomass before pyrolysis serves to conserve energy. During pyrolysis, water found in biomass demands a significant supply of heat to vaporize. It is possible to minimize the energy necessitate to raise the raw material temperature to reach the reaction temperature with faster ramping rates by reducing the water content in the biomass. As a result, drying should be considered a vital pretreatment for pyrolysis with the goal to minimize energy demand and create fewer water in bio-oil [77]. Wang et al. investigated the leverage of biomass drying in microwaves on biomass pyrolysis. Via drying the biomass prior to pyrolysis, they were able to enhance the outputs of charcoal and bio-oil whilst decreasing the amount produced of the gaseous product. Furthermore, the CO_2 concentricity in the gas got higher. The organic component concentration of the char was found to be lower. Chen et al. also looked at how drying biomass affects devolatilization. They demonstrated that humidity has no effect on the composition and structure of biomass [90].

3.8.4 Biological pretreatment

Another environmentally friendly option is biological pretreatment, which employs rot fungi that decompose some of the organic substances thus rendering it simpler to pyrolyze. Rot fungi of several varieties, which include brown, white, and soft rot fungi, might be employed. In the biomass, they mostly breakdown lignin and hemicellulose. Water and carbon dioxide are the major byproducts of this procedure. In terms of energy conservation, this approach compacts the biomass and makes it more appropriate for pyrolysis. Furthermore, rot fungi reduces the emission of SOx, a harmful gas in the atmosphere [91].

3.9 End products: Yields and quality

3.9.1 Syngas

Syngas comprises the light portions of the pyrolyzed segments, such as H_2, CO, and CO_2. Since the production of syngas from biomass is extremely endothermic, Onwudili et al. found that increasing the temperature boosted gas yields. [86]. As an instance, Veses et al. found that syngas with >80% CO+H_2 and a calorific value of 16 MJ/Nm3 was produced at >700 °C [92]. It has been demonstrated that co-pyrolysis of only certain sorts of biomass produces H_2 more rapidly than mono-pyrolysis of a single waste sort. In addition, CO_2 increased the CO amount found in syngas produced through the pyrolysis of sewage sludge by promoting reforming reactions with steam [93]. It is widely assumed that combining reforming and pyrolysis reactions will increase syngas output and quality [55]. The Ni catalyst, employed by Chai et al. was demonstrated to successfully speed the reforming interaction, increasing syngas produced along with H_2 content [85].

3.9.2 Pyrolysis oil

Hydrocarbons, aromatic hydrocarbons, benzene derivatives, along with oxygenates are all found in pyrolysis oil [94]. The amount of bio-oil created from a variety of biomass feedstocks is generally in the scope of 50–75 wt.%. Ordinarily, increasing cellulose proportion increases bio-oil productivity, but higher lignin content decreases bio-oil productivity. The characteristics of bio-oil tend to be influenced by a variety of variables, which involve the reactor's heating rates, residence duration, raw material particle size, temperatures, along with the kind of the raw material employed. The proper pyrolysis temperatures must be adjusted for oil production because temperature represents one among the most essential variables in the pyrolysis operation. Al-Salem discovered that the majority (> 96 %) of the oil from pyrolysis produced by pyrolyzing PDFE at temperatures ranging from 500 to 800 °C was aliphatic C_8–C_{12}, with additional C_{13} at higher temperatures [95]. Sotoudehnia et al. found that the amount of methanol contained within the pyrolysis oil created through the demethylation of hemicellulose along with lignin at 350 °C was about six times that of the pyrolysis oil formed at 400–450 °C [96]. The metals produced by pyrolyzed materials may boost the pyrolysis oil output [97]. The structure of the raw material has a big impact on the oil grade. Lam et al. produced pyrolysis oil from co-pyrolyzed plastic wastes alongside cooking oil with up to 84 % output and a greater heating value (HHV) of 49 MJ/kg than diesel as well gasoline [98].

Kumagai et al. found that co-pyrolysis of beech wood within the PE melt increased the synthesis of levoglucosan alongside methoxyphenols by factors of 1.7 and 1.4, respectively, compared to mono-pyrolysis testing [99]. When 25% tire trash was added to pyrolysis oil, the proportion of polycyclic aromatic hydrocarbons (PAHs) in the oil went down from 17 to 10.8%. Certain molecules, among them HCl from PVC polymers, decreased the oil's grade by lowering aromatic compound yields or promoting the synthesis of dioxins along with furans. W. Wang et al. demonstrated that co-pyrolyzing xylane with PVC successfully reduced the releasing of HCl [100].

3.9.3 Bio-char

The solid leftovers from MSW pyrolysis are in the form of charcoal, which is mostly composed of carbon, inorganic compounds, metals, and transition elements. The production of solid residues is hampered by an extremely high temperature. Tokmurzin et al. found that pyrolysis of municipal waste at 800 °C produced 39.2% charcoal [101], while pyrolysis of nine woody wastes at 400 °C resulted in 10–15% more bio charcoal than pyrolysis at 600 °C. Bio charcoal is mainly made up of carbon, with a C concentration of >60% or up to 95%. The C-rich structure that has the minimal ash concentration could have excellent heating values, making it appropriate to be employed as alternate fuels. chars were generated with HHVs ranging from 20 to 26 MJ/kg, covering for 84.5–91.7% of the potential in MSW substrates prior to pyrolysis. By including an additional supply of carbon in the pyrolysis operation, the proportion of char created can be enhanced. The solid leftovers trapped surplus Ca, K, and Mg inside the matrix, according to Kim et al. [93]. As a result, solid residues might be employed as soil amendments.

Chapter Four

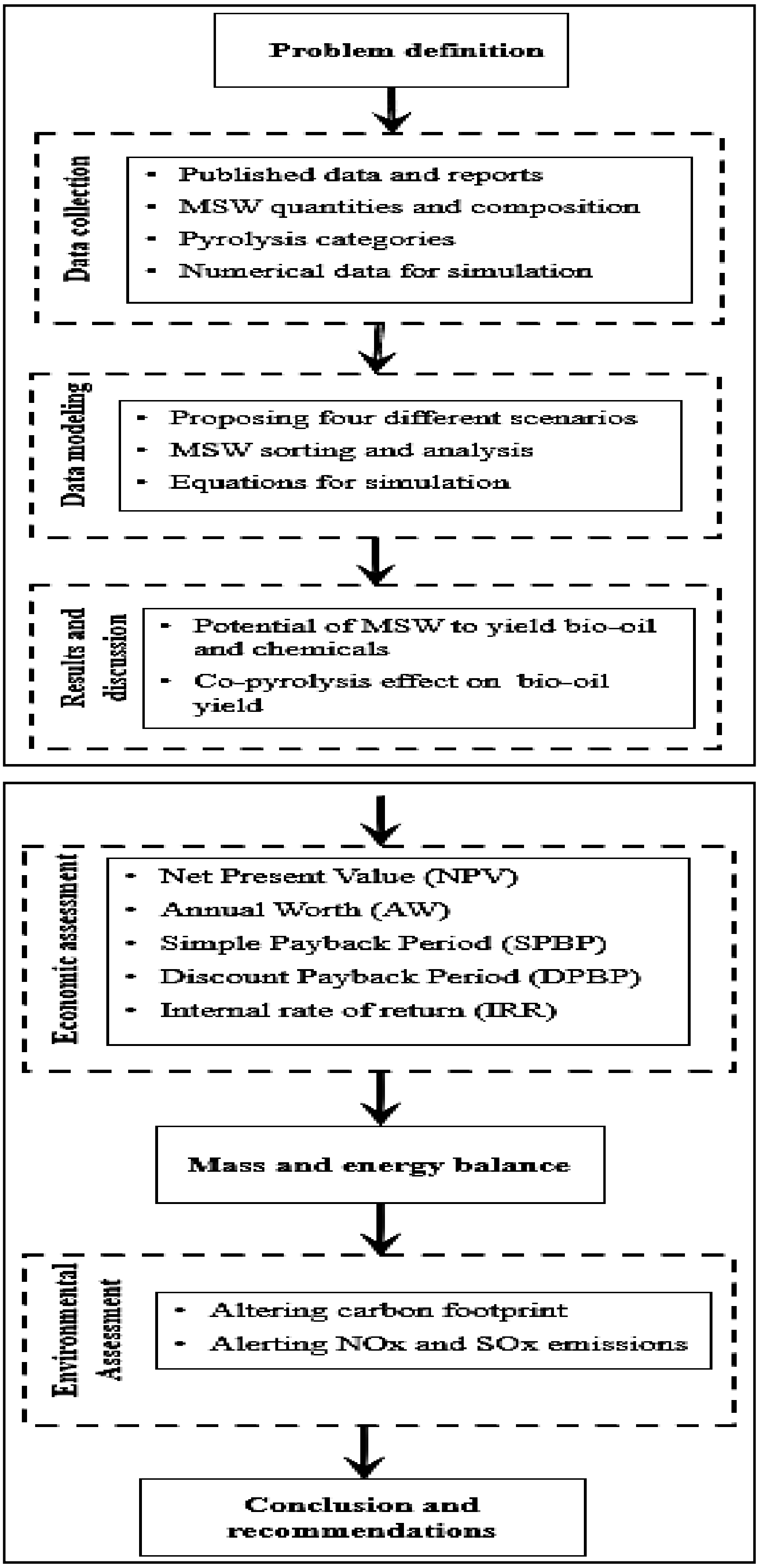
Methodology and assessment approach

4.1 Research Methodology

This research employs a rigorous modeling approach depends reliable process simulation, where the reliability of this research' results is due to that this simulation is fully dependent on the actual results of other researchers working in the same field and conditions. This study will serve as the foundation for numerous future investigations into WtE, particularly thermal pyrolysis, which can yield valuable chemicals and biofuel. It demonstrates the potential of MSW to yield bio-oil and chemicals because it will provide exact details on the slow pyrolysis of MSW and serve as a framework for several studies in this field to be conducted throughout the West Bank (other case studies and conditions). The findings of this study are extremely reliable, despite the fact that they are based on a computer software and have no practical application in the PT. This study will rely on both qualitative and mostly quantitative data collecting and analysis. The qualitative approach includes one interview with the key person at the JSC in Tulkarm, as its TS is our case study, and extensive research to determine the optimal pyrolysis features to reach our goal. The quantitative approach will involve analyzing the numerical MSW quantity data that Tulkarm TS has received and creating the necessary equations and parameters for the process simulation. The methodology is depicted in Figure 1 in order to demonstrate the desired results of the research.

Figure 1

Methodology flowchart



4.2 Data Collection

For the aim of obtaining data, JSC in Tulkarm was utilized to obtain broad details like the size of Tulkarm TS, the number of LGUs it serves, and the procedure of gathering MSW. The amount and nature of garbage the TS receive, however, are of vital importance. To acquire a thorough picture of the situation in the PT with regard to MSW management., several kinds of literature in addition to national reports from the Palestinian Central Bureau of Statistics (PCBS) were also viewed. A comprehensive investigation of thermal pyrolysis to produce bio-oil and chemicals, as well as its simulation, was conducted.

4.3 Analysis Criteria

This study's analysis was conducted using a quantitative methodology. To establish the proper equations and parameters for modeling, as will be demonstrated in this part, the quantitative approach will first be utilized to assess the composition of MSW for ultimate and proximate analyses as well as its heating value for each scenario. Four different scenarios will be adopted in this study to investigate the pyrolysis temperature at which the maximum yield of bio-oil occurs, and to comprehend how the feedstock composition affects the pattern of biofuel production. The four scenarios are described in more detail below.

4.3.1 Scenario NO.1: Unmodified MSW

In this scenario, pyrolyzing the intended MSW with all of its components (biomass, paper, plastic, rubber, and textiles) without any alterations is proposed; after screening materials such as glass, metals, and rocks, the main contents and percentages are presented in Table 2.

The percentages of the employed MSW components must be adjusted because materials like metals, glass, and others will be scrubbed and not used in the pyrolysis process. Biomass, paper, plastics, textiles, rubber and moisture fraction will be 49.31 wt.%, 15.09 wt.%, 6.29 wt.%, 7.55 wt.%, 0.63 wt.%, 21.13 wt.% respectively.

Table 2

Composition and quantities of the real MSW (Scenario No.1)

MSW component	Real mass ratio (wt.%)	Adjusted mass ratio (wt.%)	Mass ton/day
Dry Biomass	39.2	49.31	78.4
Paper and cardboard	12	15.09	24
Plastics	5	6.29	10
Textiles	6	7.55	12
Rubber	0.5	0.63	1
Metals	3	Not included	6
Glass*	2	Not included	4
others	15.5	Not included	31
Moisture	16.8	21.13	33.6
		Total mass	200 ton/day

- Analysis of MSW components

In order to figure out the overall MSW ultimate and proximate analysis, a cumulative average is calculated based on the ultimate and proximate analysis of the MSW's single components [102] as well as the percentages of its components (Table 3). An illustration of how to determine the projected MSW's overall ash weight percentage is given below.

Sample calculation:

Ash wt.% = Ash fraction in biomass * Biomass fraction in MSW + Ash fraction in Paper * Paper fraction in MSW + Ash fraction in Textiles * Textiles fraction in MSW + Ash fraction in Plastic * Plastic fraction in MSW + Ash fraction in Rubber * Rubber fraction in MSW

Ash wt.% = (36.09*0.4931) + (16.30*0.07545+10.89*0.07545) + (1.52*0.025167+ 0.14*0.025167 +0.49*0.025167) + (0.18* 0.0157 + 0.00* 0.0157 + 0.09*0.0157 + 0.02*0.0157) + (47.03*0.0063)

<u>Ash wt.%</u> = 20.20 wt.%

Paper is separated into two equal parts: paper and cardboard; textiles are classified into three equal parts: cotton fabric, absorbent cotton gauze (ACG), and terylene (TE); and plastic is divided into four equal parts: HDPE, LDPE, PET, and PP.

Table 3

Ultimate and proximate analysis of MSW components in addition to its heating value (Scenario No.1)

Proximate analysis (wt.% dry basis)		Ultimate analysis (wt.% dry basis)	
Ash	20.20	C	41.15
VM	50.08	H	5.00
FC	7.85	N	1.43
Moisture	21.87	S	0.67
		O	31.55
HHV (MJ/kg)		14.59236	

The pretreatment processes:

The pretreatment processes. which must be applied before pyrolysis:

- Screening MSW from solid components like glass, metals and rocks.
- The screened feedstock must be dried (expose MSW to 105°C temperature for 24 hours)
- The feedstock must be shred to the appropriate particles size, according to findings by [54], [55], a particle size of 10 mm was used.

Co-pyrolysis reactor and characteristics:

- A rotary kiln reactor has been proposed since it is often used for the industrial-scale pyrolysis of MSW and offers sufficient heat transfer with comparably little energy usage [54].
- We recommend using a heating rate and residence duration of 15°C/min and 30 min., respectively, based on experiments conducted by many researchers [55], [57], [58].
- Pyrolysis simulation has been performed over a wide range of temperatures, from 300 to 800 °C.

Preparing for simulation:

Aspen Plus might be simple to utilize for well-known chemical processes, but for a procedure like pyrolysis, it might provide a significant challenge. because pyrolysis is a difficult process that involves extensive chemical interactions as well as mechanisms for the transmission of heat and mass. These reactions and yields are influenced by a variety of variables, including the kind of feedstock, temperature, and other pyrolysis variables. In order to obtain results from the Aspen Plus, we, therefore, created the necessary variables and equations for each and every output material in the simulation we did using the experimental data that was provided. It's also important to keep in mind that Aspen Plus is a precise program, meaning that even the smallest error in the user's input results in an error and occasionally prevents the program from moving on to the next phase. In conclusion, the Aspen Plus user needs to have all the necessary input settings ready and needs to exercise caution when using it.

In our simulation, we relied on the pyrolysis temperature among other parameters to study the optimization of the pyrolysis potential and quality yield. Since it is the most crucial factor that affects the pyrolysis process and there is a wealth of information about this aspect in the literature. The type of reactor selected will determine how to set up the simulation's key equations and parameters; in our case, the stoichiometry reactor (RStoic) was used. For each of the proposed reactions in the pyrolysis process, this sort of reactor necessitates the insertion of a reaction coefficient and a fractional conversion in addition to pyrolysis pressure and temperature. Simply put, the reaction coefficient is constant regardless of the temperature of pyrolysis and equals the multiplicative inverse of the substance that results. Conversely, figuring out the conversion factor is a more complicated procedure. the conversion factor for each product was calculated, which will change depending on the temperature of pyrolysis, using formulae based on the realistic outcomes of various pyrolysis studies for circumstances similar to our own [54], [103]. In Table 4, the calculated reaction coefficients and fractional conversions equations are illustrated.

Table 4

Reaction Coefficients and Fractional Conversions equations (Scenario No.1).

Yield category	Reaction coefficient	Fractional conversion relevant equations
Gaseous Yield	0.66	FC (gas) = 0.000002 x^2 - 0.0023 x + 1.0556
Liquid yield	0.08	FC (oil) = = 0.0028x2 - 2.4707x + 553.06
Biochar yield	1.00	FC (biochar) = the summation minus one.

Note: x represents the pyrolysis temperature in degrees Celsius.

Sample calculation:

As mentioned before, reaction coefficient is equal to the multiplicative inverse of the product. Since the assumed gaseous yield composed of CH_4, H_2, CO, C_2H_4 and C_2H_6 compounds, then the total reaction coefficient is equal to the summation of the above-mentioned compounds coefficients. Same way to calculate Liquid product coefficient where C_6H_6, C_7H_8 and H_2O are the assumed contents. To make it clearer Table 5 can help.

Figure 2

Trending line of liquid yield from MSW

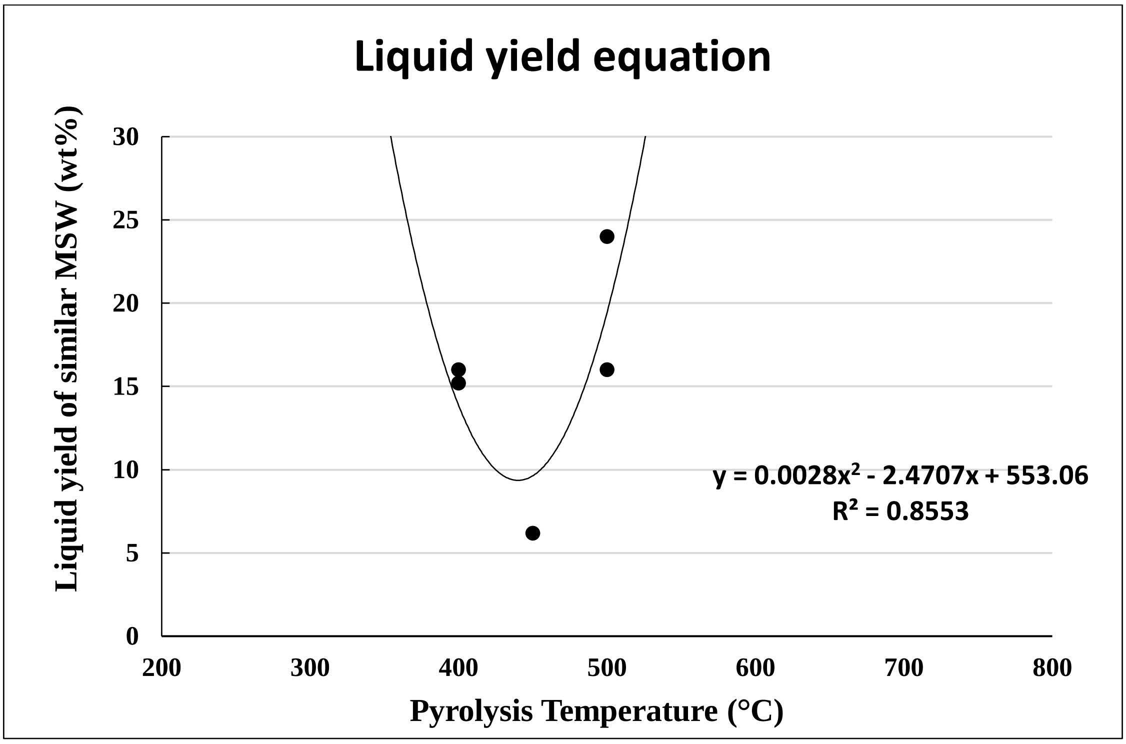


Table 5

Calculations of reaction coefficients in detail

Product	Molecular weight (MW)	Coefficient for each substance = 1/MW
Gaseous yield		
CH_4	16.04276	0.062333414
H_2	2.01588	0.496061273
CO	28.0104	0.035701025
C_2H_4	28.05376	0.035645846
C_2H_6	30.06964	0.033256135
Reaction coefficient of Gas yield		0.662997693
Liquid yield		
C_6H_6	78.11364	0.012801861
C_7H_8	92.14052	0.010852988
H_2O	18.01528	0.055508435
Reaction coefficient of the Liquid yield		0.079163285

To construct fractional conversion equations for any product type, the gathered findings from works of literature were plotted, then the desired equation was established from its polynomial trending line, as illustrated in Figure 2.

4.3.2 Scenario NO.2: Just biomass

In this case, the majority of the specified MSW, which is biomass and excludes paper, plastic, rubber, and textiles, is advised to be pyrolyzed. Table A.2 (Appendix A) shows the main constituents and percentages after screening items like glass, metals, and rocks:

Analysis of MSW components:

Since the assumed feedstock's composition shifted from one scenario to the next, the ultimate and proximate analyses also changed accordingly. The planned raw material analysis is shown in Table A.3 (Appendix A).

Pretreatment processes and pyrolysis characteristics:

The pretreatment processes, as well as the reactors and features of pyrolysis, are the same for all scenarios, as they are required for all pyrolysis processes, regardless of feedstock.

Preparing for simulation

The type of reactor is the same for all scenarios, where a stoichiometry reactor (RStoic) was used. Fractional conversion equations were created using the pyrolysis results of biomass as summarized in some studies [104], [105]. In Table A.4 (Appendix A), the calculated reaction coefficients and fractional conversions equations are illustrated.

4.3.3 Scenario NO.3: 50% Biomass with 50% Plastic

In this scenario, the MSW biomass fraction and plastic trash are co-pyrolyzed in a 50/50 ratio. According to latest statistics from Europe, LDPE, HDPE, PP, and PET are the most usable types of plastic trash [106]. Table A.5 (Appendix A) shows the main constituents and percentages after screening items like glass, metals, and rocks:

Analysis of MSW components

Table A.6 (Appendix A) provides an illustration of the suggested raw material ultimate and proximate analysis.

Pretreatment processes and co-pyrolysis characteristics

The pretreatment processes, as well as the reactors and features of pyrolysis, are the same for all scenarios, as they are required for all pyrolysis processes, regardless of feedstock.

Preparing for simulation

The type of reactor is the same for all scenarios, where a stoichiometry reactor (RStoic) was used. Fractional conversion equations were created using the co-pyrolysis results of biomass and plastics (at a 1:1 mixing ratio) as summarized by [104]. In Table A.7 (Appendix A), the calculated reaction coefficients and fractional conversions equations are illustrated.

4.3.4 Scenario NO.4: Just plastic

The pyrolyzing raw material in this scenario is exclusively made up of plastic waste; the polymers used are LDPE, HDPE, PP, and PET. The primary components and proportions of the raw material are displayed in Table A.8 (Appendix A).

Analysis of MSW components

The proposed raw material analysis is depicted in Table A.9 (Appendix A).

pretreatment processes and pyrolysis characteristics

The pretreatment processes, as well as the reactors and features of pyrolysis, are the same for all scenarios, as they are required for all pyrolysis processes, regardless of feedstock.

Preparing for simulation

The type of reactor is the same for all scenarios, where a stoichiometry reactor (RStoic) was used. On the basis of the actual plastic pyrolysis results, as summarized by [107], fractional conversion equations were developed. In Table A.10 (Appendix A), the calculated reaction coefficients and fractional conversions equations are illustrated.

4.3.5 Simulation of pyrolysis

The model of a pyrolysis reactor presented in this study is based on a stoichiometry model technique used in Aspen Plus. In certain of its routines, Aspen Plus gives the user the option to apply an equation-based methodology, making it simple to use design. The equations utilized in our simulation are based on actual results from many research for the pyrolysis of MSW components or biomass-plastic mixes. The base property method for the entire system is Peng Robinson cubic equation of state with the Boston-Mathias alpha function (PR-BM). Based on their ultimate analysis, which included C, H, O, N, S; Cl and Ash elements, and their proximate analysis, the employed feedstock, and char components were classified as non-conventional components (as shown in each scenario). Since the utilized equation was developed based on experiments performed at temperatures in the range of 300-800 °C, the pyrolysis process was intended to be carried out at temperatures in this range and atmospheric pressure (1 bar). The pyrolysis process produced three main by-products: gas, bio-oil, and char, these by-products will be stated as a weight percentage (wt.%). The simulation specifications are briefly displayed in Table 6.

Figure 3

P & ID of decomposition and pyrolysis of MSW components

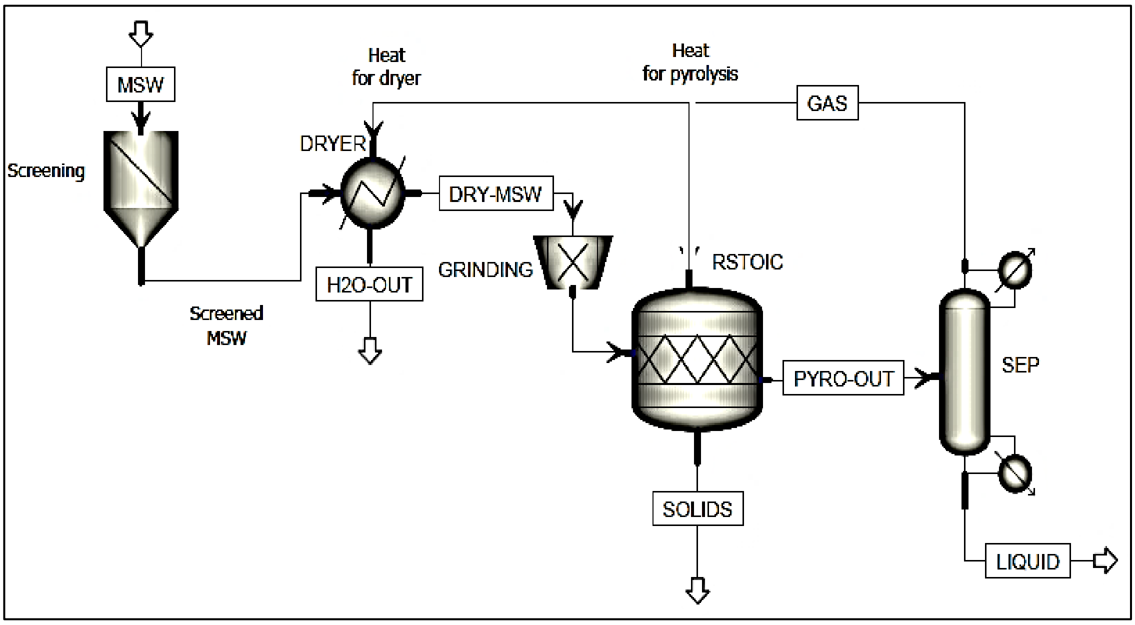


Figure 3 depicts the production piping and instrumentation diagram for bio-oil. In the RStoic reactor, the MSW was decomposed. In the RStoic reactor, the solid waste was divided. The vapor-liquid combination was cooled and separated into gas and liquid yields in a separator. The gas created during pyrolysis was crucial because it provided the necessary heat for both pyrolysis and drying the feedstock.

Table 6

Simulation specifications for the proposed scenarios

Common specifications between the four scenarios	
Property Method	PR-BM
Reactor type	RStoic
Pyrolysis Temperature	300-800 °C
Pyrolysis pressure	1 bar
Reactions coefficients	
Gaseous Yield	0.66
Liquid Yield	0.08
Biochar Yield	1
Reactions Fractional conversions of Scenario NO.1	
Gaseous Yield	FC (gas) = $0.000002 x^2 - 0.0023 x + 1.0556$
Liquid Yield	FC (oil) = $0.0000007 x^2 - 0.0011 x + 0.6196$
Biochar Yield	FC (biochar) = the summation minus one.
Reactions Fractional conversions of Scenario NO.2	
Gaseous Yield	FC (gas) = $0.0008 x^2 - 0.6643 x + 154.57$
Liquid Yield	FC (oil) = $-0.0013 x^2 + 1.4061 x - 316.52$
Biochar Yield	FC (biochar) = the summation minus one.
Pyrolysis pressure	1 bar
Reactions Fractional conversions of Scenario NO.3	
Gaseous Yield	FC (gas) = $0.0002 x^2 - 0.1476 x + 49.571$
Liquid Yield	FC (oil) = $-0.0007 x^2 + 0.7682 x - 141.53$
Biochar Yield	FC (biochar) = the summation minus one.
Reactions Fractional conversions of Scenario NO.4	
Gaseous Yield	FC (gas) = $0.0002 x^2 - 0.1176 x + 34.929$
Liquid Yield	FC (oil) = $-0.0005 x^2 + 0.4889 x - 24.775$
Biochar Yield	FC (biochar) = the summation minus one.

Note: x represents the pyrolysis temperature in degrees Celsius.

Chapter Five

Results and discussion

In this study, various assumptions were made about four alternative scenarios with the goal of analyzing the potential for creating biofuel and chemicals from MSW. The difference between these scenarios is the feedstock employed. The planned feedstock in the first scenario is Tulkarm transfer station's MSW as it is currently composed. The second scenario evaluated the bio-oil production if only the organic matter from the aforementioned MSW will be employed and the rest of its components will be left out, like paper and plastic. A primary material made up of 50% organic matter and 50% plastic was used in the third scenario, while plastic simply is used in the fourth. All of the presented scenarios have the same pretreatment procedures and pyrolysis conditions. where screening, drying, and shredding of the raw material are required. The residence duration and the heating rate, which are 30 min and 15 °C/min, respectively, are the pyrolysis conditions. In our research, the rotary kiln is the suggested reactor to apply slow pyrolysis at temperatures ranging from 300 to 800 °C and a pressure of 1 bar. Prior to conducting the pyrolysis simulation, the ultimate and proximate analysis of the raw material based on its constituent parts were identified. then the preferred Aspen Plus reactor was selected, which is RStoic. Finding the fractional conversions and coefficients for RStoic's reactions is necessary. It is important to reiterate that the analysis of the raw material and the fractional conversions vary depending on the scenario and the raw material. The pyrolysis results for each scenario will be detailed and discussed separately in the following sections.

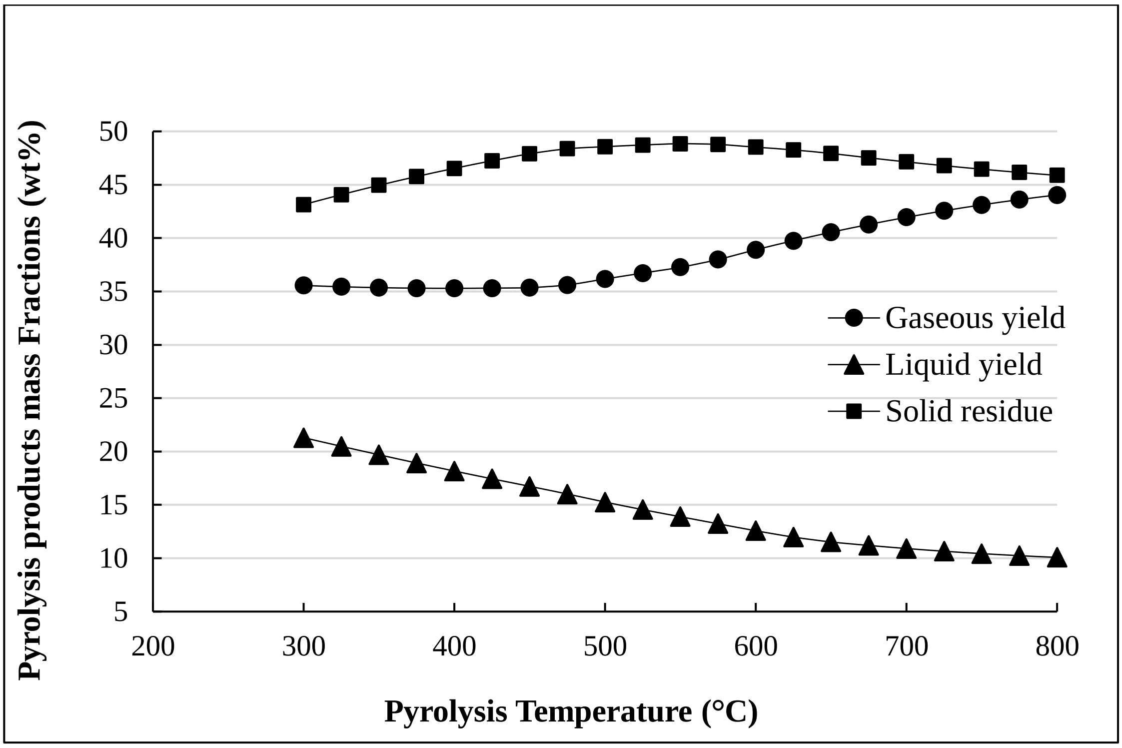
5.1 Scenario NO.1: Unmodified MSW

Figure 4 displays the yields of the pyrolysis products (gas, liquid, and solid). At 300 °C, the gaseous yield is at its lowest. The largest quantity of liquid yield was close to 21.29 wt.% at 300 °C. At temperatures of 800 and 550 °C, respectively, the largest yields of gas and biochar are produced, with weight percentages of 44.04 and 48.84. With rising temperatures, oil production declined but gas production rose. Despite the fact that the product distribution of MSW pyrolysis varies depending on the employed MSW contents, which varies from case to case, our simulated results are consistent with some of other studies. Wang et al., for instance, acquired a liquid yield of 13-32 wt.% from pyrolyzing MSW up to 700 °C, similar to Song et al., whose liquid yield ranged from 18-32 wt.%, while Gandidi et al. obtained a maximum liquid yield of 15.2 wt.% at 400 °C [55], [57], [58], [103].

The majority of the proposed feedstock is biomass, and its degradation begins at low temperatures (at 180 °C, as we indicated in Chapter 2), thus in this scenario, it is evident that bio-oil production began early and at low temperatures. Since the novel equations that were employed in the Aspen Plus program are accurate for the temperature range between 300 and 800 °C, pyrolysis yields before this temperature are not simulated in our research

Figure 4

Effect of pyrolysis temperature on Pyrolysis products mass fractions for the unmodified MSW



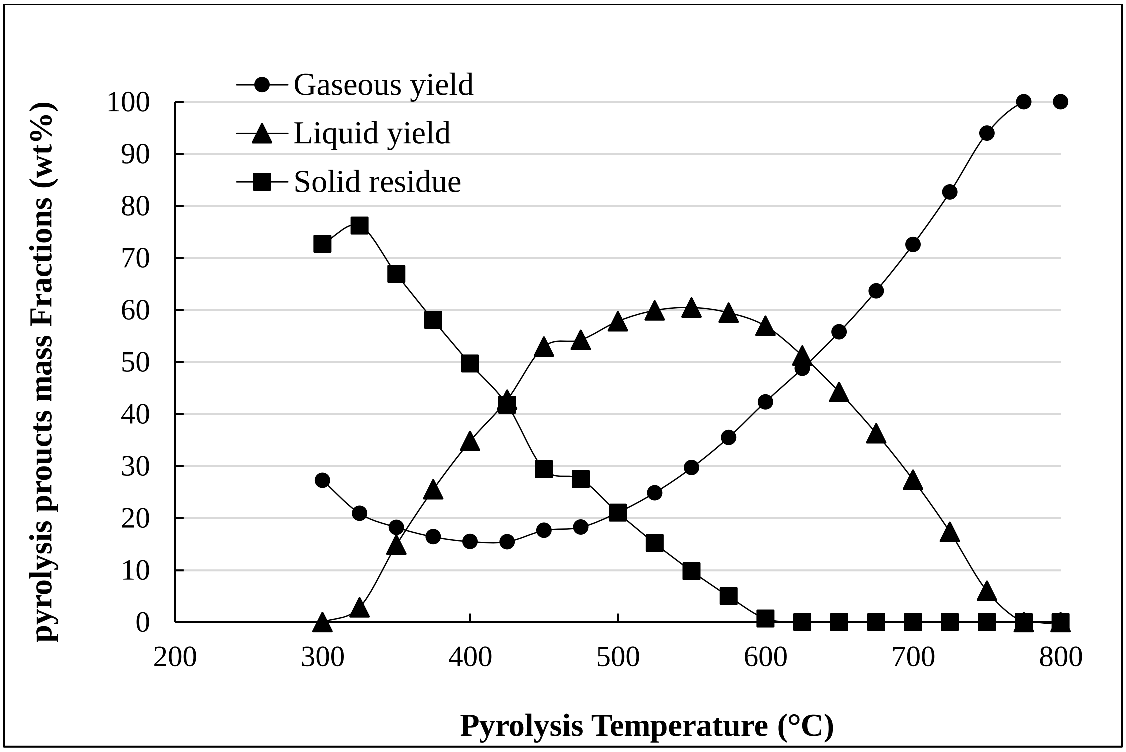
5.2 Scenario NO.2: Just biomass

The yields of the pyrolysis products are shown in Figure 5 (gas, liquid, and solid). The formation of liquid yield begins a little after 300 °C; the highest amount of liquid yield was 60.5 wt.% at 550 °C, which is close to the findings of various researches. The pyrolysis results of several types of biomass were summarized by Uzoejinwa et al. and Yang et al. Cedar, for instance, could produce 64.57 wt.% liquid yield at 600 °C, whereas sunflower's liquid yield was equal to 57.56 wt.% at the same temperature [104], [105].

The highest yields of biochar and gas are generated at 325 and 800 °C, respectively. Production of biochar and bio-oil both came to an end around 600 and 800 °C, respectively.

Figure 5

Effect of pyrolysis temperature on products mass fractions for 100% biomass feedstock



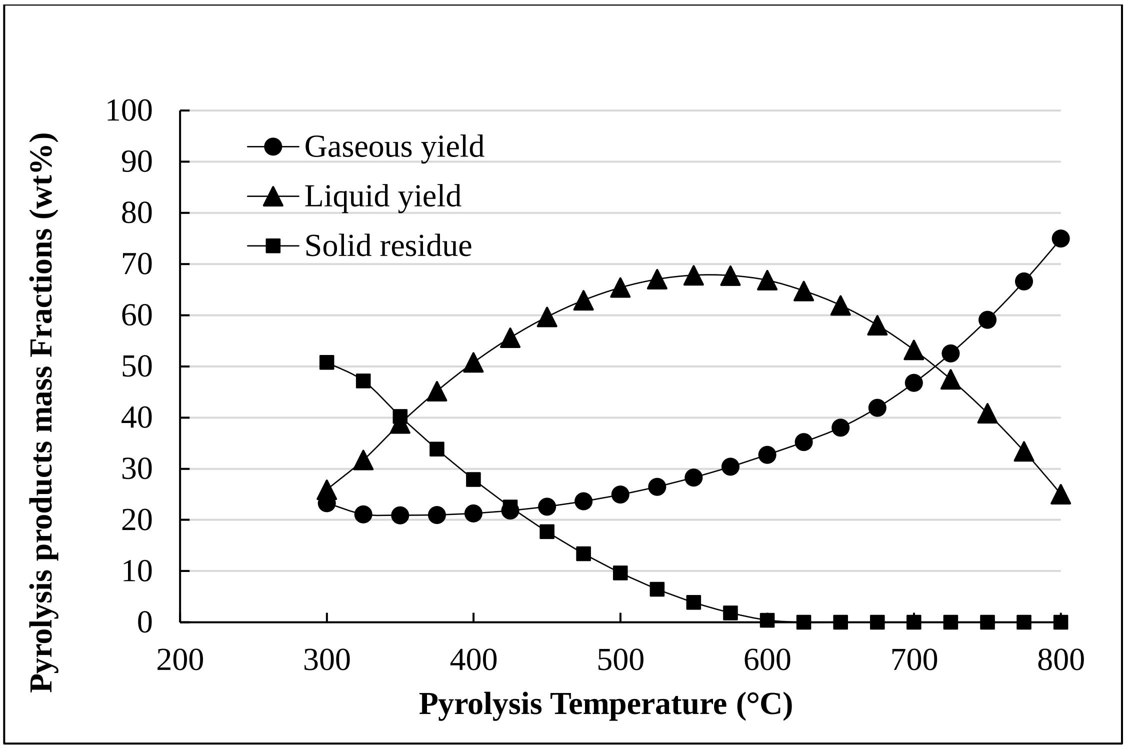
5.3 Scenario NO.3: 50% Biomass with 50% Plastic

The outcomes of the third scenario followed the same pattern as those of the second, but with higher bio-oil productivity and generally lower production of gas and biochar. Gas production started at the same temperature as bio-oil production, which was 300 °C with a weight ratio of 25.93 wt.%. However, the lowest gas production was at 350 °C with a ratio of 20.92 wt.%. Similar to the previous case, the highest oil yield occurs at 550 °C, but with a 7 wt.% higher yield, or 67.82 wt.%. These results are extremely similar to the actual results of previous studies. While our investigation concluded that the maximum liquid production is 67.82 wt.% at 550 °C, the highest yield from cedar and LDPE co-pyrolysis is 64.08 wt.% at 600 °C. Additionally, at a temperature of 500 °C, the maximum yields from co-pyrolysis of pine cones with LDPE, PP, and PS are 63.9 wt.%, 64.10 wt.%, and 69.7 wt.%, respectively. Uzoejinwa et al. and Yang et al. reviewed a number of co-pyrolysis results; depending on the feedstock composition and the pyrolysis process settings, some of these results are comparable to ours and some are not [104], [105]. At a temperature of 800 °C, the yields of bio-oil and gas were equal to 25 wt.% and 75 wt.%, respectively. For coal, output peaked at 300 °C and ended when the temperature reaches 600 °C.

Figure 6 depicts the product yields from the pyrolysis process.

Figure 6

Effect of pyrolysis temperature on products mass fractions for 50% biomass and 50% plastic feedstock

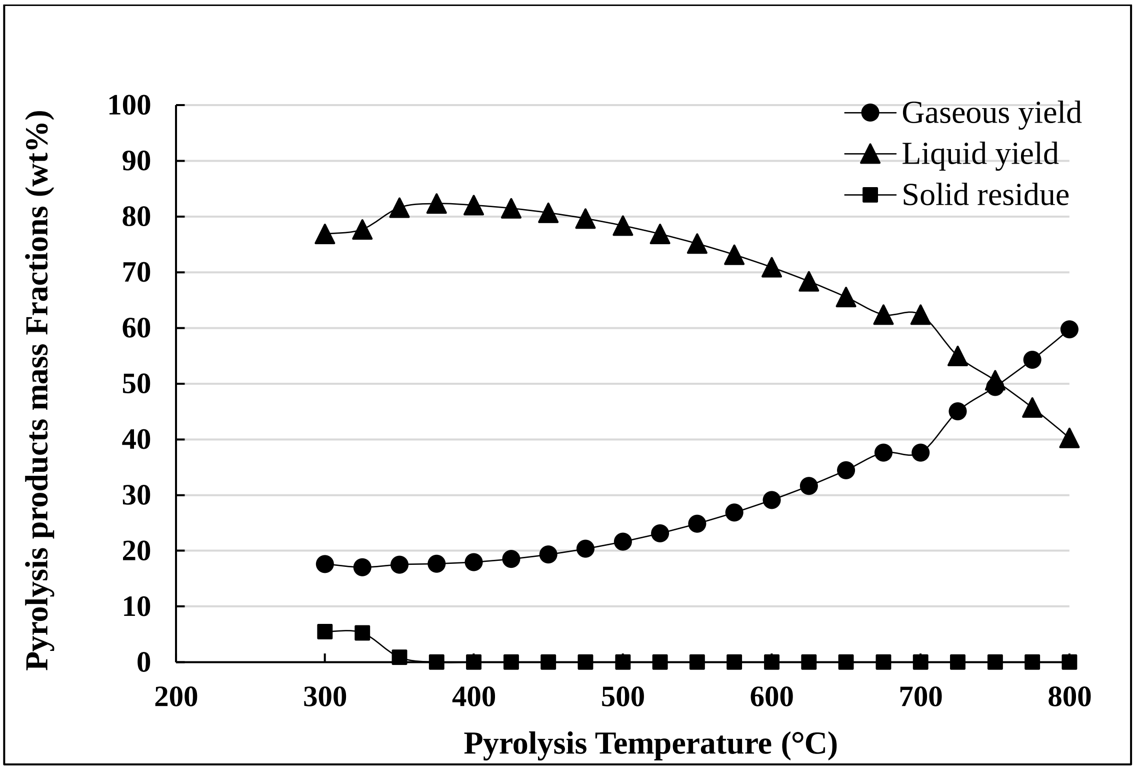


5.4 Scenario NO.4: Just plastic

As illustrated in Figure 7, the outcomes of pyrolysis employing only plastic as a raw material are reported in this section. The production of bio-oil is at its peak and significantly higher than it was in the previous scenarios. Indeed, its productivity began at a temperature of 300 °C with 76.85 wt.%, increased to reach its maximum yield at 375 °C with 82.32 wt.%, then decreased to reach its minimum productivity at 800 °C with 40 wt.%. The largest and lowest gaseous yields, with 59.77 wt.% and 17.04 wt.% respectively, are produced at temperatures of 800 and 325 °C. The amount of charcoal created during the slow pyrolysis of plastic is quite modest, beginning and ending before 400 °C temperature. There is much research regarding the thermal pyrolysis of plastic wastes to make bio-oil in the literature, and our findings trend and the results in the literature share a lot of characteristics. The greatest yields from the pyrolysis of HDPE, LDPE, and PP are 80.88 wt.%, 80.41 wt.%, and 80.1 wt.%, respectively, at temperatures of 350, 500, and 380 °C, according to Anuar Sharuddin et al's summary of many of these experiments [107]. The proposed plastic feedstock in our study is made up of HDPE, LDPE, PP, and PET, which is worth emphasizing.

Figure 7

Effect of pyrolysis temperature on products mass fractions for 100% plastic feedstock



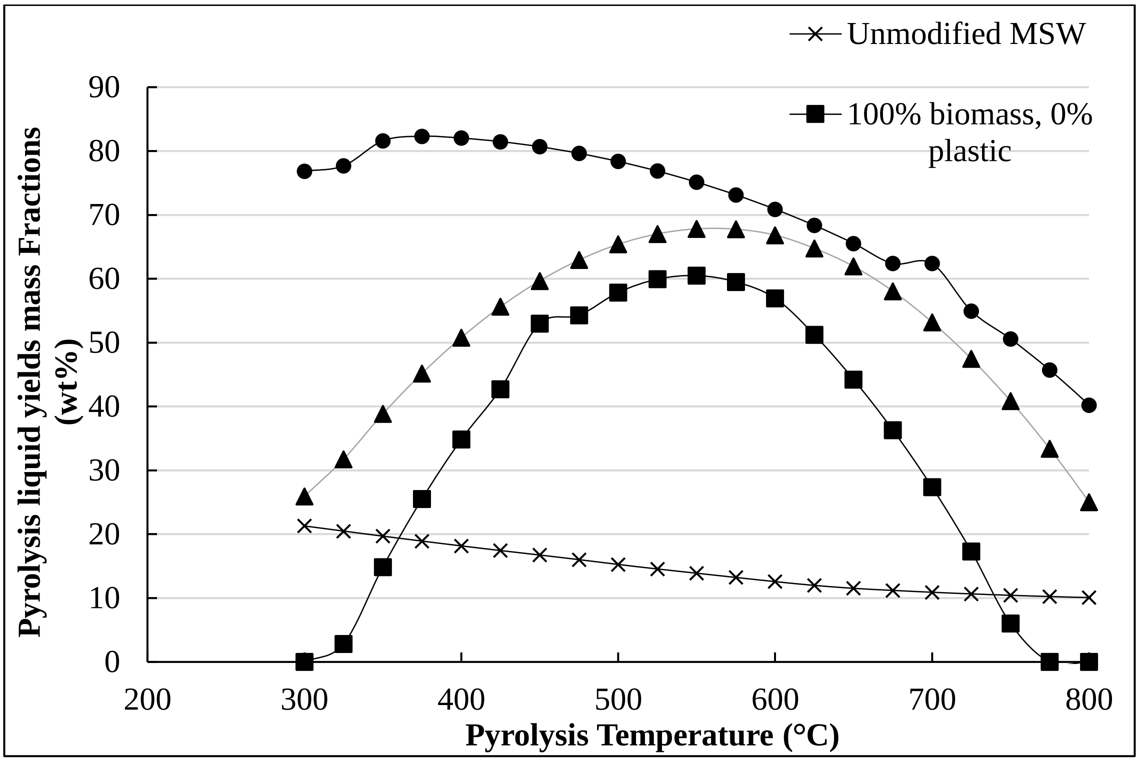
5.5 Liquid yield in all scenarios

Given that the goal of our research is to examine the possibility for creating bio-oil and chemicals from MSW, it is essential to review the liquid yields that was calculated using Aspen Plus simulation for the four scenarios that were put out. Through the suggested scenarios, Figure 8 illustrates the anticipated liquid yields. The unaltered MSW produced the least amount of liquid product, as shown in Figure 8, while the pyrolysis of only plastic wastes produced the most.

The high yields of liquid products produced by pyrolysis of biomass and biomass/plastic are produced in a converging range of temperatures and amounts. However, it should be mentioned that the liquid yield from the pyrolysis of the biomass/plastic mixture is of higher quality than the other one, where it had a lower amount of water. For instance, when cedar was pyrolyzed without the use of plastic, the yield of liquids was 64.57 wt.% at 600 °C, of which 25.74 wt.% was water. The liquid yield, on the other hand, was 80.02 wt.% with 15.94 wt.% after pyrolyzing a mixture of equal parts biomass and plastic at the same temperature [105]. The "maximum oil yield" temperature changed from 300 °C in the first scenario to 550 °C in the second and third scenarios as a result of the varied feedstock compositions between the first scenario and both the second and third scenarios. In the first scenario, the feedstock was made up of a number of different components, which had a synergistic effect on the optimal temperature in contrast to what happened in the second and third cases.

Figure 8

Effect of pyrolysis temperature on liquid yields mass fractions for the proposed scenarios



Pyrolisis of plastic wastes, as shown in Figure 8, yielded the highest liquid product comparing to the other scenarios. This highest yield occurred at lower temperature range comparing ti the second and the third scenario. This can be explained by that plastic types (PS, PET, PP, LDPE, and HDPE) breakdown in a limited temperature range of 311–480 °C [59].

5.6 Economic feasibility assessment

Conducting an economic analysis of the pyrolysis process, where the production cost of pyrolysis has a substantial share, is crucial to testing the commercial viability of any process. The cost and profit are both taken into account in the economic analysis; the profit comes from selling the pyrolysis products, which are primarily bio-oil and some charcoal. while pyrolysis plant's production costs can be roughly divided into two categories:

- Capital costs or fixed costs that comprise a pyrolysis module, necessary tools, a facility's development, feed handling, and storage. The technology, plant size, and biomass feedstock are the main determinants of the fixed cost.
- Operating costs include the cost of biomass harvesting or feedstock, maintenance, product transports, labor, utilities, and transportation. Table 7 lists the estimated percentages of contributions made by various components to variable costs [68].

Table 7

A rough estimate of each component's contribution to the variable cost

Items	Percentages %
Biomass harvesting or feedstock	23-30
Maintenance	17-24
Utilities	22-25
Labor	12-19
Grinding	7-9
Transportation	5-7

Note: R. Kataki *et al.*, “Waste Valorization to Fuel and Chemicals Through Pyrolysis: Technology, Feedstock, Products, and Economic Analysis BT - Waste to Wealth,” R. R. Singhania, R. A. Agarwal, R. P. Kumar, and R. K. Sukumaran, Eds. Singapore: Springer Singapore, 2018, pp. 477–514.

The reactor is the key part of pyrolysis plants, even though it only accounts for 10% to 15% of the entire capital expense. The remaining costs cover things like product collection and storage, biomass collecting, storage, and handling, biomass cutting, dying, and grinding. Kataki et al. summarized several criteria for pyrolysis facilities of various sizes, including feedstock type and price, estimated bio-oil cost, and capital expenditure, as shown in Table 8, which is derived from numerous publications [68]. Cost of biomass pyrolysis energy conversion is also influenced by a number of variables, such as process technology, operational scale, feedstock, year of construction, etc.

Table 8

The assumptions and expenses of the main parameters used to calculate the unit production costs for pyrolysis plants of various sizes

Plant Size (ton/day)	Feedstock	Capital Investment (million $)	Annual Operating Costs (M $)	Feed Costs ($/ton)	Production Costs ($/gal)
2000	Corn Stover	200	12.3	83	0.26
1650	Wood pellet	180	12	--	0.24
1000	Dry wood	68	10.6	44	0.41
1000	Wet wood	72	11.3	30	0.6
1000	Peat	76	10.2	20	0.61
1000	Staw	82	10.2	42.5	0.64
900	Wet wood	46	9.9	34	0.5
550	Dry wood	84.2	9.6	45	0.71
4000	Wet wood	14.3	8.8	36	1.02
250	Dry wood	14	8.92	44	0.55
200	Wet wood	8.8	4.84	36	1.11
100	Wet wood	6.6	2.84	36	1.48
24	Rice husk	3.89	0.17	22	0.82
2.4	Rice husk	0.97	0.034	22	1.73

Note: R. Kataki *et al.*, "Waste Valorization to Fuel and Chemicals Through Pyrolysis: Technology, Feedstock, Products, and Economic Analysis BT - Waste to Wealth," R. R. Singhania, R. A. Agarwal, R. P. Kumar, and R. K. Sukumaran, Eds. Singapore: Springer Singapore, 2018, pp. 477–514.

The assumptions and expenses of the main factors utilized in this economic study to assess the viability of the selected pyrolysis plant, with a capacity of 200 ton/day, are shown in Table A.11 (Appendix A) [70].

The project's viability will be evaluated using a variety of feasibility tests in this section, all of which must provide the same outcome. There are several ways to determine the feasibility of a project:

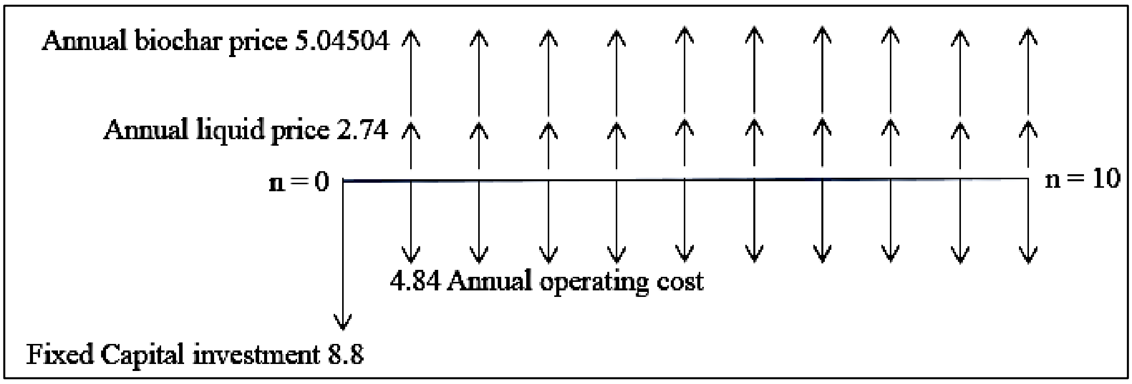
- Net Present Value (NPV)
- Annual Worth (AW)

- Simple Payback Period (SPBP)
- Discount Payback Period (DPBP)
- Internal rate of return (IRR)

It is simpler to implement a cash flow diagram for the pyrolysis process in order to apply our economic assessment. The cash flow diagram for the first scenario, in which the actual MSW without any modifications were pyrolyzed, is shown in Figure 9 with the aid of the data previously stated.

Figure 9

Cash flow diagram of pyrolysis plant implementation, costs are in million $



Net Present Value (NPV)

The difference between the current value of cash inflows and withdrawals over a period of time is known as net present value (NPV). To evaluate the profitability of a proposed investment or project, NPV is used in capital budgeting and investment planning. The NPV is today’s value of current and future cash flows which can be given by:

$$\sum_{n=1}^{t} \frac{CFn}{(1+i)^\wedge n} - I_\circ \quad \text{……………..………………. Equation 3}$$

Where t represents the investment's life in years, CFn represents the cash flow, or the difference between revenues and expenses after taxes, in year n, and $I_\circ$ represents the expense associated with the initial investment in year zero.

Simply by using the compound interest tables, the proposed project's net present value (NPV), which is equal to 9.33 and greater than zero, was computed. This value leads us to the conclusion that the planned project is anticipated to be profitable.

Product Cost per Unit

Cost per unit can aid in improving business comprehension of the costs and profitability. Calculating this cost per unit is usually preferable because it may be used to determine the right selling price for the finished product. The following equation can be used to calculate this cost on a per-unit basis.

$$Product\ Cost\ per\ Unit\ Formula = \frac{Total\ Product\ Cost}{Number\ of\ Units\ Produced} \text{ ……….. Equation 4}$$

Where total product cost includes direct labor hire cost, direct feedstock cost, and factory overheads. The cost per unit (cost per ton of bio-oil), based on the assumptions in Table A.11, is 182 US $.

Levelized cost of energy (LCOE)

The levelized cost of energy is a key concept in the energy and power industries. It essentially enables the comparison of alternative technologies with different lifetimes and capabilities without the need to create a comprehensive project finance model.

The LCOE can be calculated using the following equations [108]:

$$LCOE = \frac{FCI * CRF + OC}{E} = \frac{A}{E} + \frac{OC}{E} \text{ ……………………… Equation 5}$$

$$CRF = \frac{r}{1-(1+n)^{\wedge}-n} \text{ ……………………………………. Equation 6}$$

Where FCI, CRF, OC, A, E, r, and n represent the Fixed Investment Cost, Capital Recovery Factor, Operating cost (fixed and variable cost), Annualized capital cost, net sold electricity, interest rate (%/year) and lifetime of the project in years, respectively.

Based on the amount of produced bio-oil and biochar (Fig. 10), the 3120 yearly operation hours (Table A.11), and the 34% efficiency of the power generation system for both bio-oil and biochar, the "net sold electricity" was calculated. By using the previous equations and energy output of the first scenario, the LCOE is 0.176 US$/kWh

Additional economic evaluations AW, SPBP, DPBP, and IRR

For further clarification, the results of the other economic test AW, SPBP, DPBP, and IRR were calculated and reported in the table below.

Table 9

Results of the proposed project's economic analyses

Net Present Value (NPV)	9.33 million $
Annual Worth (AW)	1.52 million $
Simple Payback Period (SPBP)	3 years
Product Cost per ton of bio-oil	182 $
Discount Payback Period (DPBP)	3.71 year
Internal Rate of Return (IRR)	31.32 %
LCOE	0.176 US$/kWh

The proposed project is clearly profitable, and since its internal rate of return is high, it has the capacity to handle unexpected costs, as shown by prior research. Additionally, it must be mentioned that the used biochar pricing, in this case, is lower than market rates, this is because the quality of the produced biochar can vary depending on the type of feedstock used and the pyrolysis process's specifics.

In this research, we have made the economic evaluation for the first scenario because, in terms of raw material availability, it is the most realistic one since the raw materials are readily available and there is no effort involved in purchasing or collecting it. Regarding the viability from an economic standpoint, the first scenario might be the least feasible because the proposed feedstock by its very nature produces less bio-oil and more bio-char than the other scenarios, as well as the fact that this scenario produces fuel of the lowest quality compared to the others. In other words, if the first scenario is possible, the other scenarios will also be possible.

5.7 Mass and energy balance

As previously indicated, according to the Lu et al. research [103], 4.6 MJ/kg of energy is the absolute minimum needed to enable the pyrolysis process. Since energy is stored in the final products, additional energy must be used to dry the MSW and raise its temperature to that required for pyrolysis, which must be greater than 4.6 MJ/kg. To ensure energy sufficiency for the whole pyrolysis process needs, a threshold heating value of 10 MJ/kg of the MSW feedstocks is considered. The energy and mass flow of the pyrolysis process were explained in this section. The table below provides a summary of the information used and the presumptions made regarding the proposed pyrolysis plant.

Table 10

The proposed pyrolysis plant's employed data and assumptions

Specific heat of water at a normal boiling point (i.e., 100 ◦C)	Cp_w = 4.22 kJ/kg. K	Source
Specific heat of MSW at a normal boiling point (i.e., 100 ◦C)	Cp_{msw} = 1.39 kJ/kg. K	[109]
Specific heat of gaseous yield at constant pressure	Cp_{gas} = 0.399 kJ/kg. K	
Specific heat of bio-oil at constant pressure	$Cp_{bio\text{-}oil}$ = 2.4 kJ/kg. K	
Specific heat of biochar at constant pressure	$Cp_{biochar}$ = 1.5 kJ/kg. K	
Temperature difference for drying MSW	ΔT = 80 °C	
Water enthalpy of evaporation	hfg_w = 2256.4 kJ/kg	
Gaseous yield mass fraction and HHV	35.35 wt.%, HHV = 12.95 MJ/kg	[9]
Liquid Gaseous yield mass fraction and HHV	19.7 wt.%, HHV = 15.4 MJ/kg	[110]
Biochar yield mass fraction and HHV	44.95 wt.%, HHV = 14.06 MJ/kg	[55]
Mass rate of MSW	$\dot{m}_{msw}$ = 15.9 ton/hr.	
Mass rate of water content	$\dot{m}_{water}$ = 3.36 ton/hr.	
Mass rate of dry MSW	$\dot{m}_{dry\ msw}$ = 12.54 ton/hr.	

With 10 operational hours and 159 tons of MSW per day, 15.9 tons of MSW were intended to be pyrolyzed each hour. Calculations used for 15.9 tons of MSW per hour are depicted in the Figure 10. The used formulae to apply our calculations are listed below. From Braimakis et al. study, we assumed that the needed power for grinding MSW is equal to 1.28% of the input feedstock heating value [110], which is explained in Equation. 6.

$H_{msw} = HHV_{msw} * m_{msw}$ ……………………………………………… Equation 7

$H_1 = [(\dot{m}_{moisture}*Cp_w*\Delta T) + (\dot{m}_{moisture}*hfg_w) +(\dot{m}_{dry\ msw}*Cp_{msw}*\Delta T)] * \dot{m}_{msw}$ ...Equation 8

$H_2 = 1.28\% * H_{msw}$ ……………………………………………………Equation 9

$H_3 = 35.35\% *$ HHV of gaseous yield $* m_{msw}$ …………………. Equation 10

$H_4 = 19.7\% *$ HHV of liquid yield $* m_{msw}$ ……………………… Equation 11

$H_5 = 44.95\% *$ HHV of biochar yield $* m_{msw}$ ……………….……..Equation 12

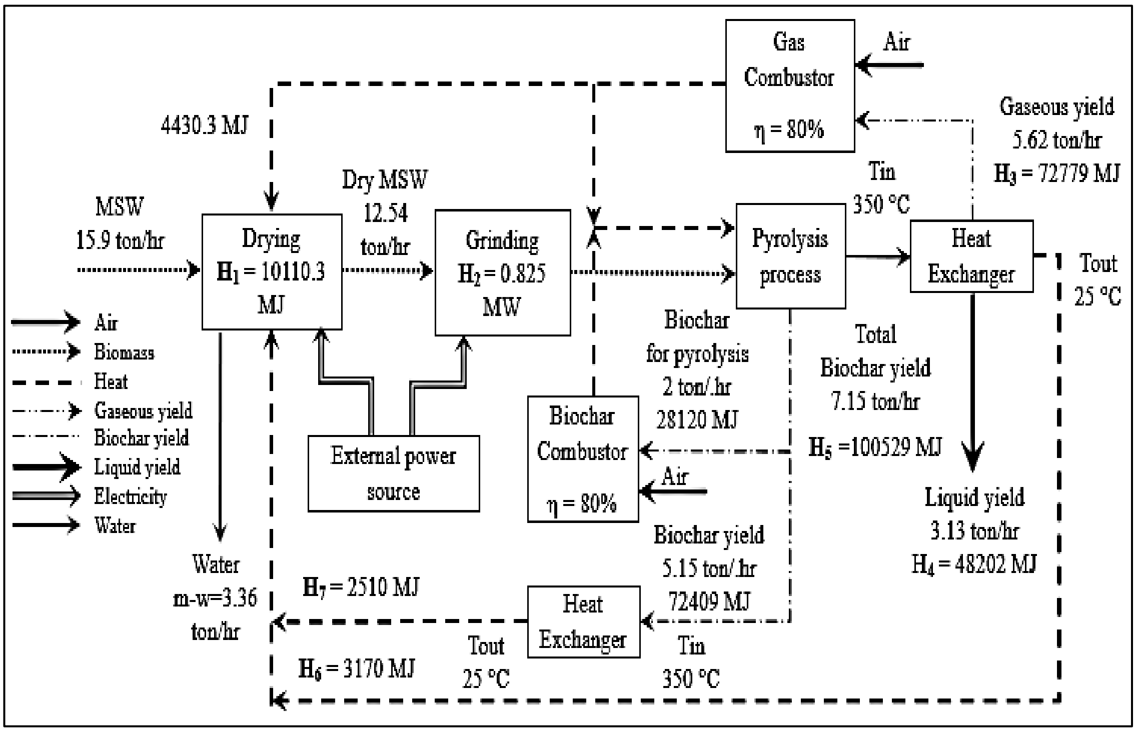
$H_6 = \dot{m}_{gas} * Cp_{gas} * (350-25) + \dot{m}_{liquid} * Cp_{bio\text{-}oil} * (350-25)$ …….Equation 13

$H_7 = \dot{m}_{char} * Cp_{biochar} * (350-25)$ …………………………………Equation 14

Where H_1 and H_2 are the necessary heating and electrical energies for drying and grinding MSW, respectively. The heating values of the total pyrolysis yields of gaseous, liquid, and biochar are H_3, H_4, and H_5, respectively. The potential heating energy that could be obtained from gas and biochar, which were produced at 350 °C, respectively, is H_6 and H_7. Moreover, H_{msw} denotes the higher heating value of the entire MSW used.

Figure 10

Block diagram illustrating the pyrolysis process's mass and energy flows



5.8 Environmental Assessment

MSW pyrolysis is regarded as an efficient method to develop treatment, management, and disposal technologies for MSW since the accumulation of MSW in the open-air causes health and environmental difficulties, such as pollution in the air, land, and water, due to bacteria and insects. Degradable materials make up the majority of MSW, which contributes significantly more to greenhouse gas (GHG) emissions. Another major issue that requires a long-term solution is the depletion of fossil fuels, which also has dangerous environmental effects on land, water and air and climate change. In light of this, the pyrolysis of MSW has a significant deal of potential to be an efficient solution for those problems and be applied in the recycling sector. It is seen that the synergistic interactions of different MSW components, particularly plastics, yield fuels with heating values similar to those of traditional fossil fuels.

As a clean fuel produced by pyrolysis, bio-oil provides significant environmental advantages over fossil fuels. Biofuels have a CO_2/GHG neutrality, they can therefore earn carbon dioxide credits. In terms of transportation, transportation bio-oil made from MSW's organic material sequesters 9.5 g of CO_2 equivalent per MJ of biofuel, compared to the 95.5 g of CO_2 equivalent released by existing fossil transportation fuels [111]. Compared to savings related to the production of power, the GHG reductions associated with transportation fuels are modest. Based on a study by Rajaeifar et al, the production of 1 MWh of electricity from fossil fuels results in an average environmental impact of 658.1 kg CO_2 eq (182.8 g CO_2 eq per MJ). The average amount of GHG emissions to the environment could be reduced by 700.4 kg CO_2eq (194.56 g CO_2 eq per MJ) and 854.7 kg CO_2 eq (237.42 g CO_2 eq per MJ), respectively, when generating 1 MWh of electricity from MSW utilizing combination of AD and incineration technologies or by utilizing the combination of AD and pyrolysis-gasification technologies [112].

Since the sulfur content of plant biomass is negligible, no SOx emissions are produced. In a gas turbine, bio-oil fuels produce NOx emissions that are more than 50% lower than those from diesel fuel. Bio-oils are therefore less polluting and cleaner. However, bio-oil must be upgraded before it can be utilized as a liquid fuel or chemical feedstock in a variety of applications. Since bio-oil has a limited ability to directly replace petroleum fuels and chemical feedstocks due to its high viscosity, high water and ash ratios, moderate heating value, instability, as well as high corrosiveness [113].

Pyrolysis is a more environmentally friendly method of manufacturing charcoal than traditional methods, which have a bad reputation due to the volatiles they leak into the environment during production. Corrosion and pollutants are much easier to reduce and get rid of with advanced pyrolysis techniques. This is achieved by retaining alkaline, heavy metals, sulphur, and chlorine in feedstock leftovers and limiting the creation of big chlorinated aromatic compounds. Additionally, because NOx is produced at a very low temperature during the pyrolysis process, there is very little NOx emission. Moreover, the gas generated during the pyrolysis process requires lower-dimensional gas cleaning equipment, which lowers the cost and operating expenses [54].

However, the solid, liquid, or gas products of pyrolysis may still include certain pollutants. S, N, and Cl are volatile elements. As a result, MSW pyrolysis is associated with emissions of these components. The effects of pyrolysis on the environment can be reduced in a number of ways. The use of catalysts to improve product quality, the interception of HCl, SO_2, and NH_3 in the gaseous phase, and the omission of some particular feedstock constituents are among these procedures [54].

5.9 Conclusion

The purpose of this research was to examine MSW's potential as a reliable renewable energy source from which we could produce chemicals and bio-oil. We can accomplish this by outlining a reliable approach that might provide a radical solution to the accumulation of MSW and the depletion of fossil fuels. Exact research was done on the pyrolysis of particular solid wastes. In this investigation, four scenarios were created. The ratio of plastic utilized in the feedstock was the biggest variation across the scenarios.

The maximum yield of bio-oil in the first scenario, at a temperature of 350 °C, was 19.7 wt.%. This ratio is not high since the majority of the feedstock is biomass and there is only a little amount of plastic and rubber; plastic promotes the generation of bio-oil while rubber inhibits it. Furthermore, despite the fact that the MSW samples used in the literature comprised larger percentages of plastic and comparable percentages of biomass, bio-oil production didn't exceed 32 wt.% yields. In the second scenario, only the biomass component was investigated as the pyrolysis process' feedstock, with a maximum bio-oil production of 60.49wt.% at 550 °C. While the third scenario produced a maximum output of 67.82 wt.% of bio-oil at 550 °C, in this scenario, the biomass and plastic content of the employed feedstock was equal. The best oil output was attained by the fourth scenario, which used just plastic as a feedstock (82.32 wt.% bio-oil yield at 375 °C).

The prior findings make it evident that the proposed MSW has a respectable potential to produce chemicals and bio-oil, particularly with modest adjustments. The proportion of produced bio-oil increases as the proportion of plastic increases. Furthermore, less organic component in the feedstock results in less water in the oil, which improves the oil's quality. The outcomes also enhance the concept of sorting in order to lower the expense and labor needed for the pretreatment procedure.

A pyrolysis plant can be established with a payback period of 3 years and an internal rate of return of 31% to address the problems of MSW and fuel depletion. It is economically possible to set up a pyrolysis plant to address the problems of MSW and fuel depletion; the project's payback period was 3 years, and its internal rate of return was 31%. On the other hand, MSW pyrolysis is environmentally friendly since it reduces carbon emissions, and controls SOx and NOx emissions, but mostly S, N, and Cl chemicals have the potential to cause pollution.

5.10 Recommendations

In this study, we attempted to gather the finest characteristics of the pyrolysis of MSW and derive the results in accordance with temperature variation. The following suggestions may be considered in future work:

1. Do more thorough research on the pyrolysis process's variables, such as heating rate and residence time, which are not limited to the temperature.
2. Study more about catalytic pyrolysis to optimize the pyrolysis process and advance one sort of product over the others.
3. Research the possibility of pyrolyzing MSW in combination with some other feedstocks such as sewage sludge, paper sludge, microalgae, or chlorella vulgaris.
4. Expanding the usage of simulation software and employing more challenging equations to get more precise results. Equations may also be expressed in terms of residence time, heating rate, and feedstock particle size in addition to temperature.
5. Study the pyrolysis of MSW at various transfer stations in the PT and evaluate how different they are from one another. What advantages can these disparities offer us?
6. With the help of the local community and the relevant government agencies, boost the concept of waste sorting, and work seriously to develop innovative ways to make the concept a reality.
7. Conduct real-world experiments to investigate the possibility of using MSW pyrolysis to create biofuels and chemicals, commencing with an experimental analysis of the suggested feedstock and ending with an experimental determination of the biofuel grade.

List of Abbreviations

Abbreviation	Meaning
°C	Degree Celsius
3E	Energy, Environmental, and Economic impacts
ACG	Absorbent Cotton Gauze
AD	Anaerobic Digestion
APC	Air Pollution Control
ASBR	Anaerobic Sequencing Batch Reactor
AW	Annual Worth
BR	Polybutadiene Rubber
C:N	Carbon-to-Nitrogen ratio
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CH_4	Methane
CHP	Combined Heat and Power
Cl	Chlorine
Cl-	Chloride ion
CO2	carbon dioxide
CO_2 eq	Carbon dioxide equivalent
COD	Chemical Oxygen Demand
COx	carbon oxides
CSTR	Continuous Stirred Tank Reactor
DPBP	Discount Payback Period
DTG	Derivative Thermogravimetry
EC	European Commission
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FC	Fractional Conversion
FCI	Fixed Capital Investment
FW	Food Waste
GHG	Greenhouse Gases
H_2	Hydrogen
H_2S	Hydrogen sulfide

Abbreviation	Meaning
HC	higher hydrocarbons
HCl	Hydrogen chloride
HDPE	High-Density Polyethylene
HHV	Higher Heating Value
i.e.,	for example.
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
ISWA	International Solid Waste Association
JSC	Joint Service Council
K	Kelvin
K	Potassium
LDPE	Low-Density Polyethylene
LFGRS	Landfill Gas Recovery System
LGU	Local Governmental Units
LHV	Lower Heating Value
m	Moisture content
Mg	Magnesium
MJ	Megajoule
mm	Millimeter
MPa	Mega Pascal
MSW	Municipal solid waste
Mt	Mega ton
MW	Mega Watt
N_2 or N	Nitrogen
N_2O	Nitrous oxide
Na+	Sodium ion
NH_3	Ammonia
NH_4+	Ammonium ion
Ni	Nickel
NIS	New Israeli Shekel
NOx	nitrogen oxides
NPV	Net Present Value
NR	Natural Rubber

Abbreviation	Meaning
O_2 or O	Oxygen
P & ID	Piping and Instrumentation Diagram
PAH	Polyaromatic Hydrocarbons
PCBS	Palestinian Central Bureau of Statistics
PET	Polyethylene Terephthalate
PP	Polypropylene
PR-BM	Peng Robinson cubic equation of state with the Boston-Mathias alpha function, a property method in Aspen Plus
PS	Polystyrene
PT	Palestinian Territories
PVC	Poly Vinyl Chloride
RStoic	Stoichiometry Reactor in Aspen Plus.
S	sulphur
SBR	Styrene Butadiene Rubber
SO_2	Sulfur dioxide
SOx	Sulfur oxides
SPBP	Simple Payback Period
TDS	Total Dissolved Solids
TE	Terylene
TGA	Thermogravimetric Analysis
TS	Transfer Station
UASB	Up-flow Anaerobic Sludge Blanket
UK	United Kingdom
UN	United Nations
UNRWA	United Nations Relief and Works Agency
US	United States
wt.	Weight
WtE	Waste-to-Energy
YW	Yard Waste

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Appendices

Appendix A

Tables

Table A.1

The chemical formula and molar mass of seven model components

Model components	Chemical formula	Molar mass (g·mol^{-1})
Food	$CH_{1.79}O_{0.65}N_{0.07}S_{0.004}Cl_{0.008}$	25.62
Green wastes	$CH_{1.49}O_{0.59}N_{0.03}S_{0.001}Cl_{0.002}$	23.44
Paper	$CH_{1.58}O_{0.79}N_{0.006}S_{0.002}Cl_{0.002}$	26.37
Textiles	$CH_{1.30}O_{0.53}N_{0.03}S_{0.002}Cl_{0.002}$	22.25
Rubber	$CH_{1.81}O_{0.006}N_{0.001}S_{0.0002}$	13.92
Chlorine-free plastic	$CH_{1.22}O_{0.04}N_{0.009}S_{0.007}Cl_{0.007}$	14.41
PVC	$CH_{1.48}O_{0.01}N_{0.002}S_{0.002}Cl_{0.45}$	29.56

Note: P. Xu, Y. Jin, and Y. Cheng, “Thermodynamic analysis of the gasification of municipal solid waste,” *Engineering*, vol. 3, no. 3, pp. 416–422, 2017.

Table A.2

Composition and quantities of the proposed feedstock (Scenario No.2)

MSW component	Mass ratio (wt.%)	Mass ton/day
Dry Biomass	70	78.4
Moisture	30	33.6
	Total mass	112 ton/day

Table A.3

Ultimate and proximate analysis of the proposed feedstock in addition to its heating value (Scenario No.2)

Proximate analysis (wt.% dry basis)		Ultimate analysis (wt.% dry basis)	
Ash	25.3	C	37.723
VM	37.4	H	4.6
FC	7.4	N	1.85
Moisture	29.9	S	0.88
		Cl	1.047
		O	28.6

Note: HHV (MJ/kg) 11.956.

Table A.4

Reaction Coefficients and Fractional Conversions equations (Scenario No.2)

Yield category	Reaction coefficient	Fractional conversion relevant equations
Gaseous Yield	0.66	FC (gas) = $0.0008 x^2 - 0.6643 x + 154.57$
Liquid yield	0.08	FC (oil) = $-0.0013 x^2 + 1.4061 x - 316.52$
Biochar yield	1.00	FC (biochar) = the summation minus one.

Note: x represents the pyrolysis temperature in degrees Celsius.

Table A.5

Composition and quantities of the proposed feedstock (Scenario No.3)

MSW component	Mass ratio (wt.%)	Mass ton/day
Dry Biomass	35	78.4
Moisture	15	33.6
Plastic wastes	50	112
Total	100%	224 ton/day
Dry Biomass	35	78.4

Table A.6

Ultimate and proximate analysis of the proposed feedstock in addition to its heating value (Scenario No.3)

Proximate analysis (wt.% dry basis)		Ultimate analysis (wt.% dry basis)	
Ash	12.66	C	54.083
VM	66.24	H	7.13
FC	4.89	N	0.98
Moisture	16.21	S	4.5
		Cl	1.047
		O	19.6

Note: HHV (MJ/kg) 26.12.

Table A.7

Reaction Coefficients and Fractional Conversions equations (Scenario No.3)

Yield category	Reaction coefficient	Fractional conversion relevant equations
Gaseous Yield	0.66	FC (gas) = $0.0002 x^2 - 0.1476 x + 49.571$
Liquid yield	0.08	FC (oil) = $-0.0007 x^2 + 0.7682 x - 141.53$
Biochar yield	1.00	FC (biochar) = the summation minus one.

Note: x represents the pyrolysis temperature in degrees Celsius.

Table A.8

Composition of the proposed feedstock (Scenario No.4)

Feedstock component	Mass ratio (wt.%)
HDPE	35
LDPE	29
PP	21
PET	15

Table A.9

Ultimate and proximate analysis of the proposed feedstock in addition to its heating value (Scenario No.4

Proximate analysis (wt.% dry basis)		Ultimate analysis (wt.% dry basis)	
Ash	0.06	C	73.62
VM	95.841	H	8.26
FC	2.534	N	1.08
Moisture	1.565	S	0.023
		Cl	0
		O	16.957

Note: HHV (MJ/kg) 36.8.

Table A.10

Reaction Coefficients and Fractional Conversions equations (Scenario No.4)

Yield category	Reaction coefficient	Fractional conversion relevant equations
Gaseous Yield	0.66	FC (gas) = $0.0002\ x^2 - 0.1176\ x + 34.929$
Liquid yield	0.08	FC (oil) = $-0.0005\ x^2 + 0.4889\ x - 24.775$
Biochar yield	1.00	FC (biochar) = the summation minus one.

Note: x represents the pyrolysis temperature in degrees Celsius.

Table A.11

Parameters used in the economic assessment

Plant capacity	200 ton/day
Plant life	10 years
Annual operating time	3120 h @ 10 h/day
Maintenance labor	1% of FCI
Maintenance materials	3% of FCI
Overheads	2% of FCI
Insurance	2% of FCI
Other fixed operating costs	1% of FCI
Interest rate	10%
Feedstock cost	20 US$/ton
Labor hire rate	2.8 US$/h
Number of labors	70
Bio-oil selling price	304 US$/ton [115]
Biochar selling price	300 US$/ton (less than others [116], [117])
Salvage price	3000 US$

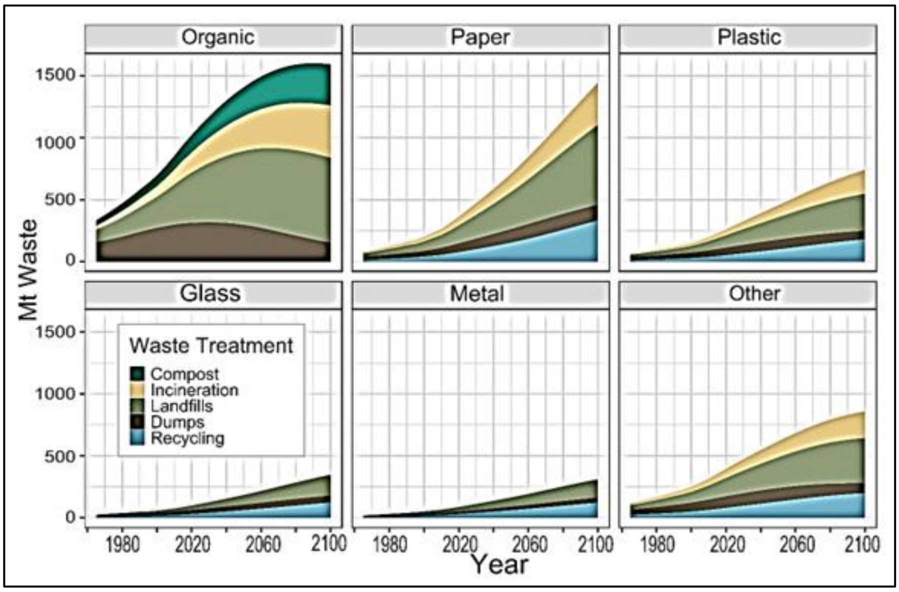
Note: M. I. Jahirul, M. G. Rasul, A. A. Chowdhury, and N. Ashwath, "Biofuels production through biomass pyrolysis- A technological review," *Energies*, vol. 5, no. 12, pp. 4952–5001, 2012, doi: 10.3390/en5124952.

Appendix B

Figures

Figure B.1

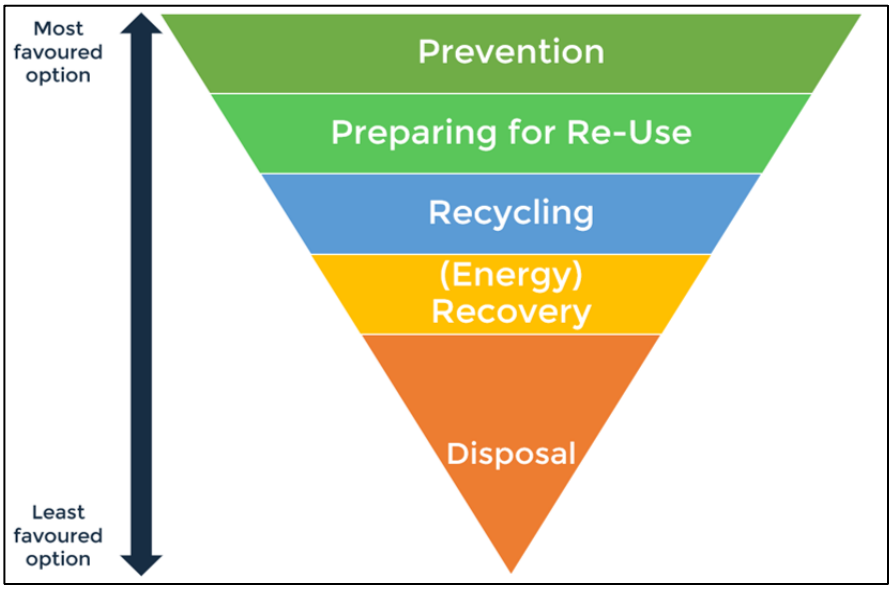
The global projection of expected waste generation by type and treatment from 1965 to 2100. Organic, paper, plastic, glass, metal, and other waste types



Note: D. M.-C. Chen, B. L. Bodirsky, T. Krueger, A. Mishra, and A. Popp, “The world’s growing municipal solid waste: trends and impacts,” *Environ. Res. Lett.*, vol. 15, no. 7, p. 74021, 2020, doi: 10.1088/1748-9326/ab8659.

Figure B.2

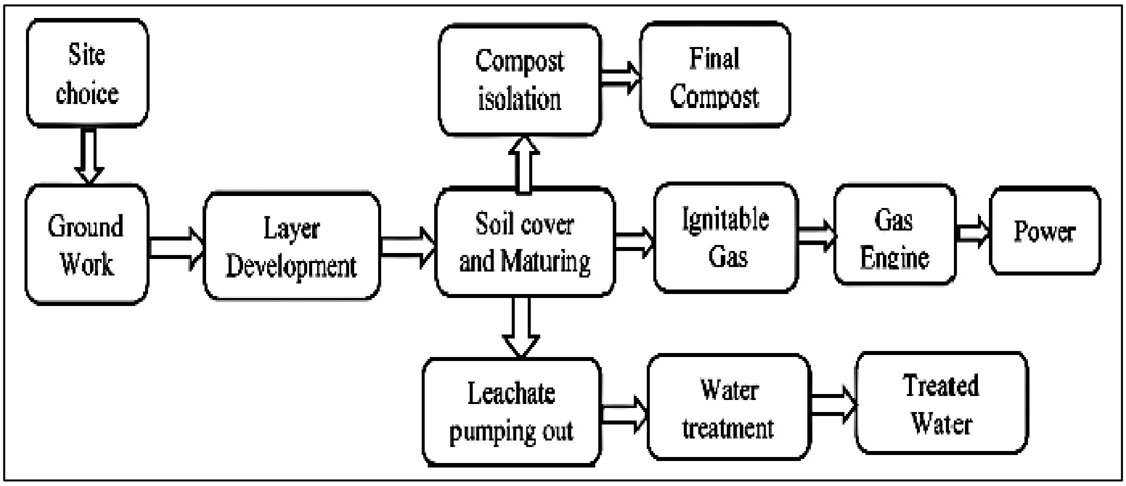
Waste Treatment Hierarchy in Preference Order



Note: T. Jamasb and R. Nepal, “Issues and options in waste management: A social cost–benefit analysis of waste-to-energy in the UK,” Resour. Conserv. Recycl., vol. 54, no. 12, pp. 1341–1352, 2010.

Figure B.3

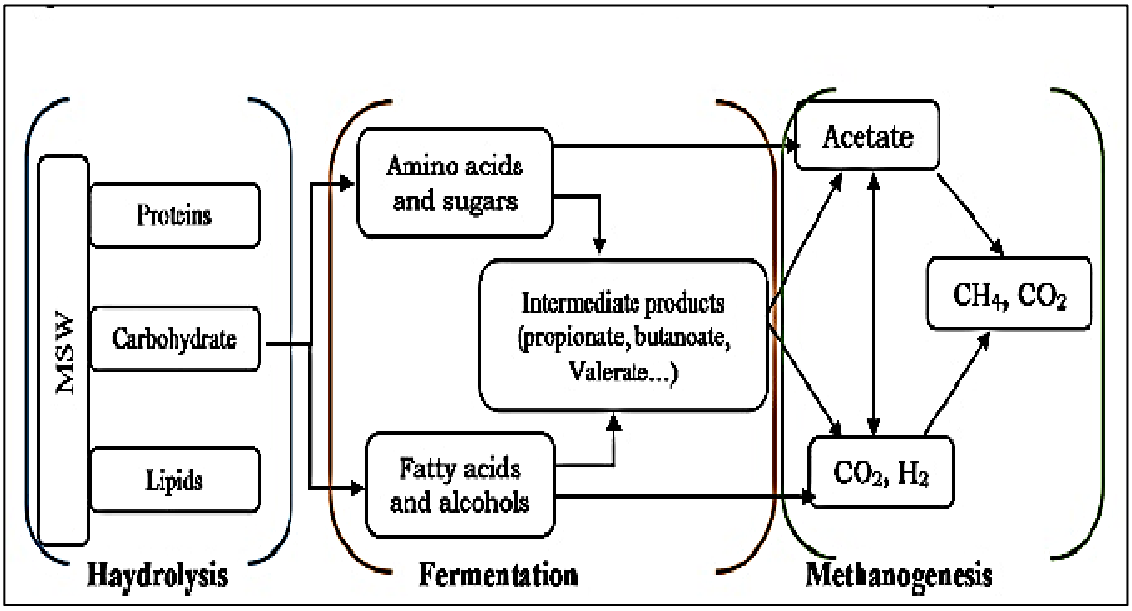
Schematic of the landfill process



Note: A. Fazeli, F. Bakhtvar, L. Jahanshaloo, N. A. C. Sidik, and A. E. Bayat, “Malaysia's stand on municipal solid waste conversion to energy: A review,” Renew. Sustain. Energy Rev., vol. 58, pp. 1007–1016, 2016.

Figure B.4

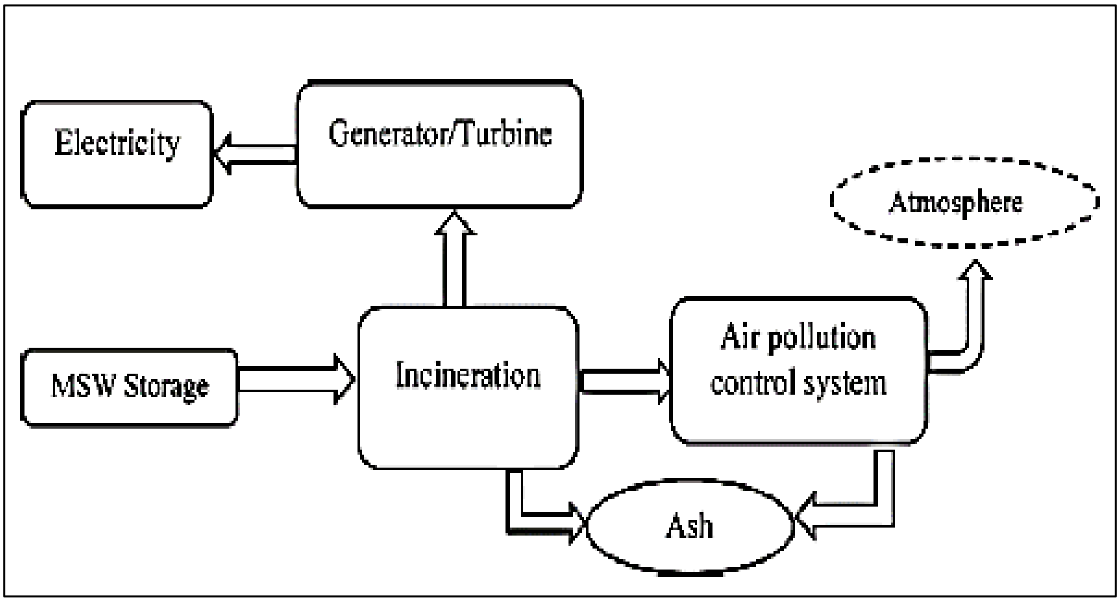
Schematic reactions of AD of complex organic matter



Note: J. C. Akunna, “19 - Anaerobic treatment of brewery wastes,” in Brewing Microbiology, A. E. Hill, Ed. Oxford: Woodhead Publishing, 2015, pp. 407–424.

Figure B.5

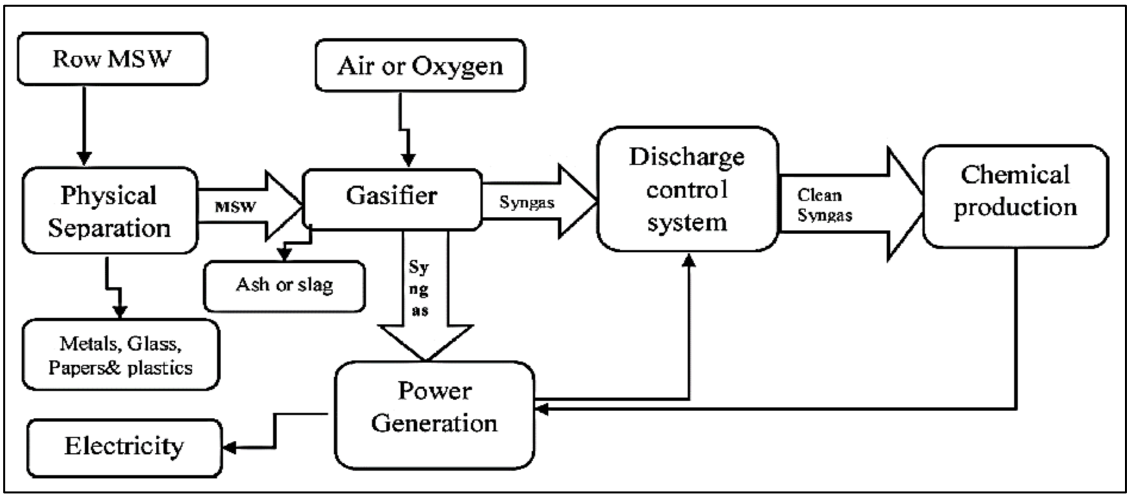
The schematic of incineration process



Note: E. Anderson, M. Addy, H. Ma, P. Chen, and R. Ruan, “Economic screening of renewable energy technologies: Incineration, anaerobic digestion, and biodiesel as applied to waste water scum,” Bioresour. Technol., vol. 222, pp. 202–209, 2016.

Figure B.6

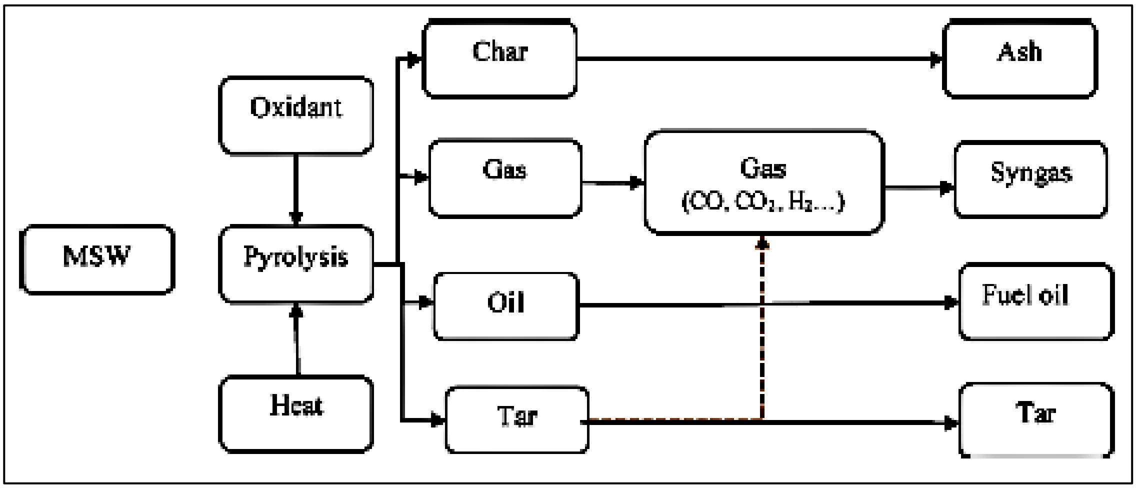
The schematic of gasification



Note: M. J. Rogoff and F. Screve, Waste-to-energy: technologies and project implementation. Academic Press, 2019.

Figure B.7

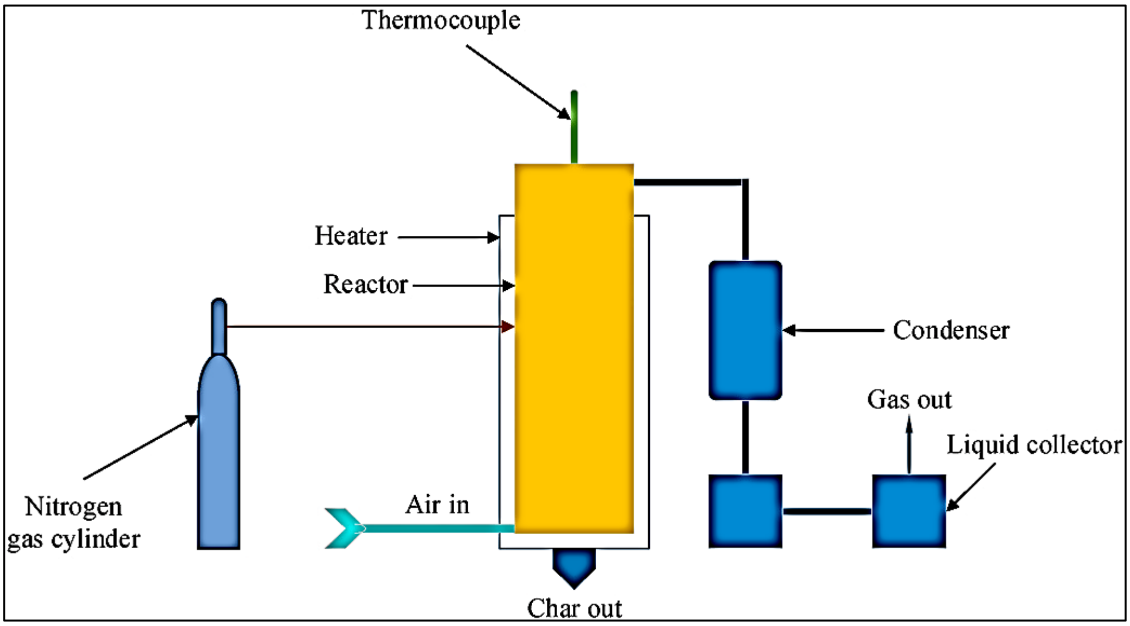
The schematic diagram of pyrolysis



Note: H. D. Beyene, A. A. Werkneh, and T. G. Ambaye, "Current updates on waste to energy (WtE) technologies: a review," Renew. Energy Focus, vol. 24, pp. 1–11, 2018.

Figure B.8

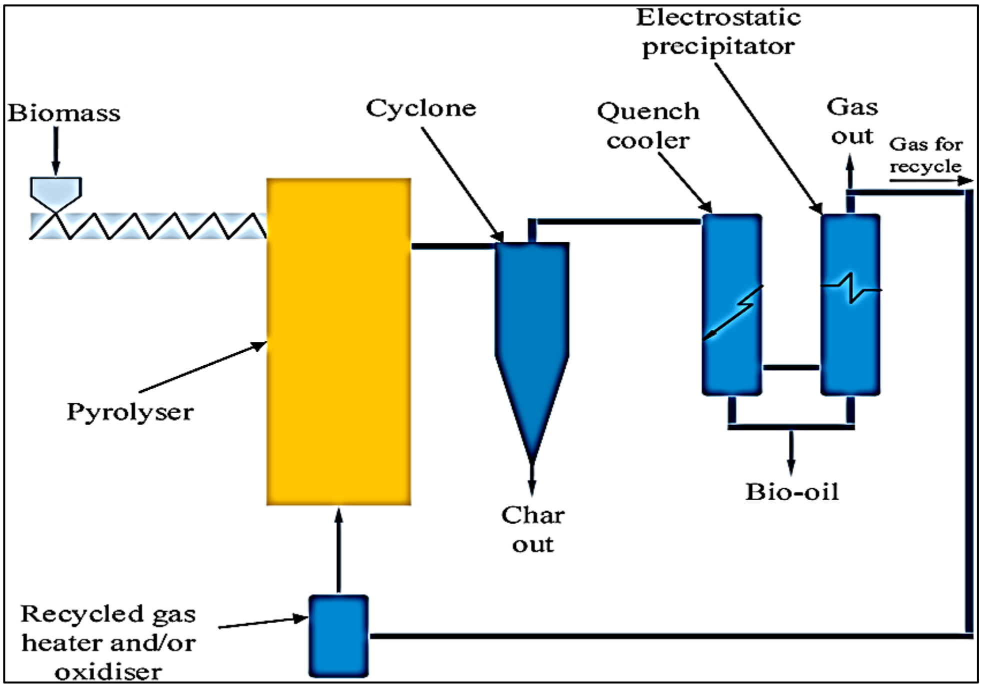
A typical fixed-bed pyrolysis reactor diagram



Note: M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, "Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments," Renew. Sustain. Energy Rev., vol. 145, no. April, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

Figure B.9

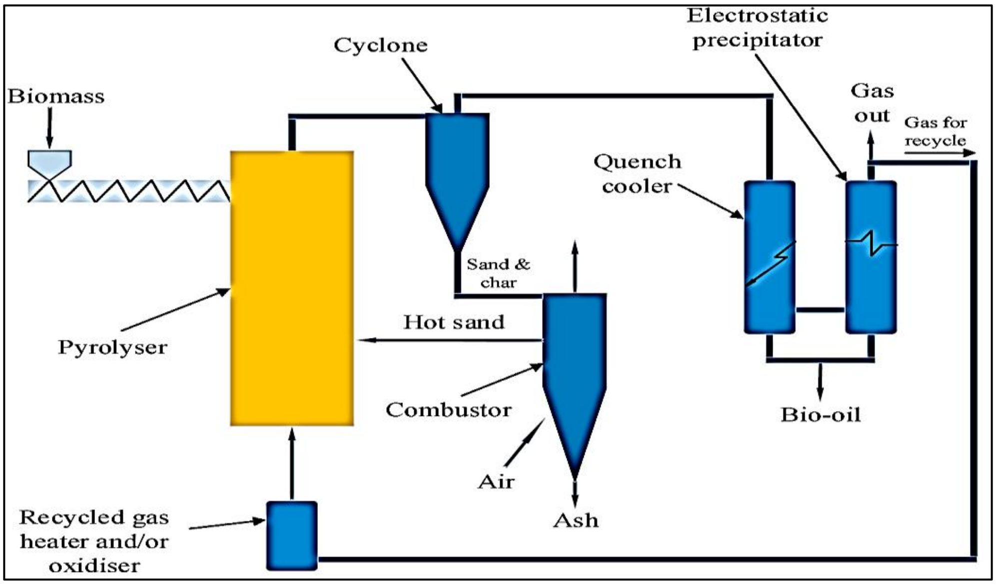
A typical bubbling fluidized-bed pyrolysis reactor diagram



Note: M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, "Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments," Renew. Sustain. Energy Rev., vol. 145, no. April, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

Figure B.10

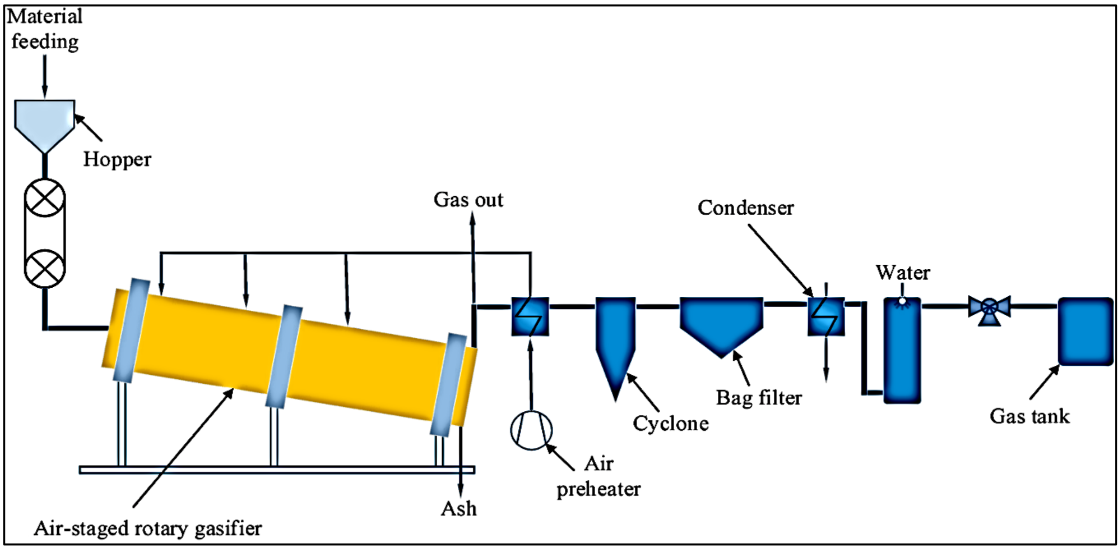
A typical circulating fluidized-bed pyrolysis reactor diagram



Note: M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, "Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments," Renew. Sustain. Energy Rev., vol. 145, no. April, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

Figure B.11

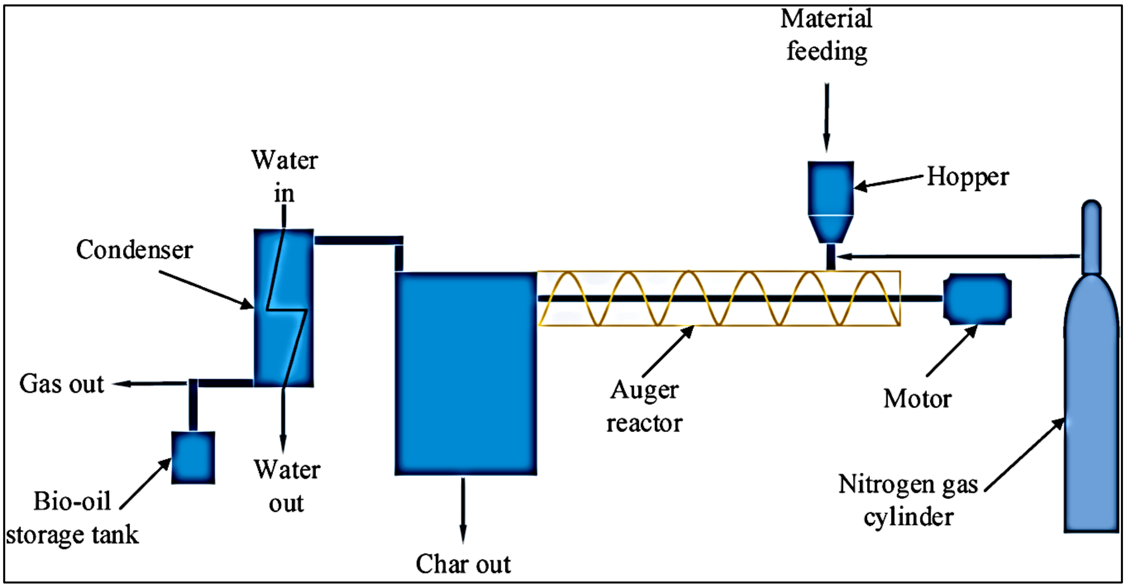
A typical rotary kiln pyrolysis reactor diagram



Note: M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, “Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments,” Renew. Sustain. Energy Rev., vol. 145, no. April, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

Figure B.12

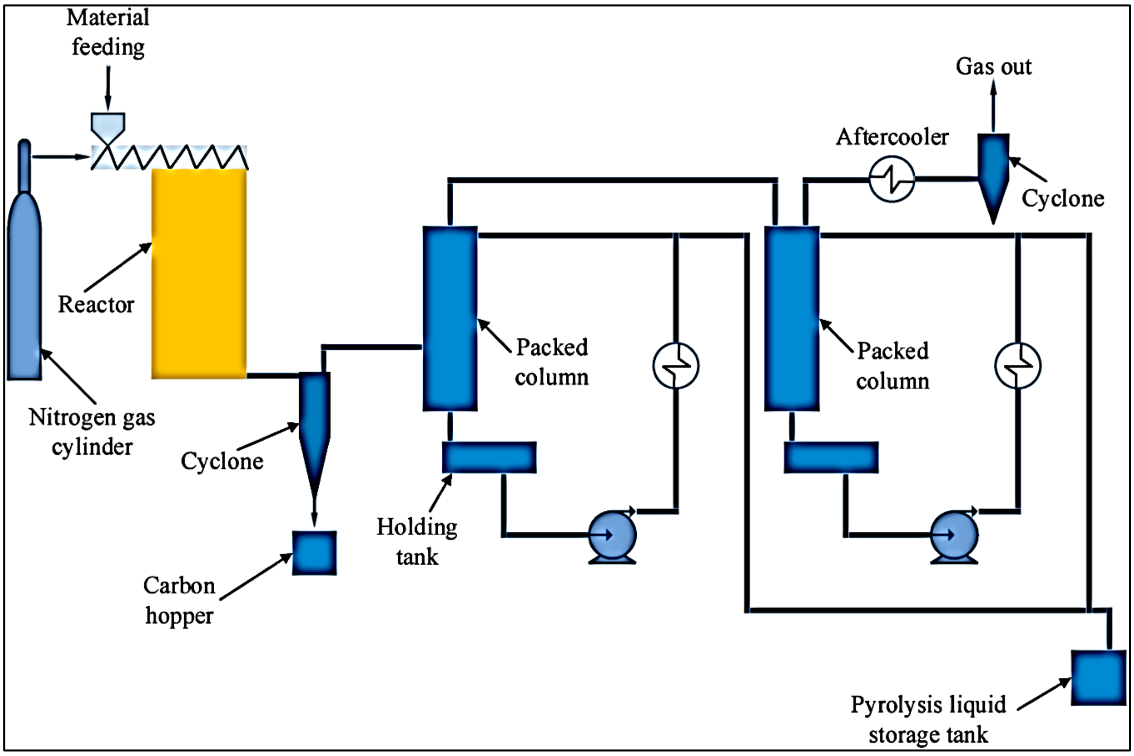
Atypical Auger reactor pyrolysis reactor diagram



Note: M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, “Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments,” Renew. Sustain. Energy Rev., vol. 145, no. April, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

Figure B.13

A typical ablative reactor pyrolysis reactor diagram



Note: M. M. Hasan, M. G. Rasul, M. M. K. Khan, N. Ashwath, and M. I. Jahirul, “Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments,” Renew. Sustain. Energy Rev., vol. 145, no. April, p. 111073, 2021, doi: 10.1016/j.rser.2021.111073.

جامعة النجاح الوطنية
كلية الدراسات العليا

تحويل النفايات الصلبة البلدية إلى وقود ومواد كيميائية عن طريق الانحلال الحراري: محطة تحويل طولكرم كحالة دراسية

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د. عبد الرحيم ابو صفا

قدمت هذه الرسالة استكمالا لمتطلبات الحصول على درجه الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس– فلسطين.

2023

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الملخص

إن تداعيات تراكم النفايات الصلبة البلدية واستمرار استهلاك الوقود الأحفوري على البيئة وصحة الإنسان قد زاد من أهمية مصادر الطاقة البديلة في جميع أنحاء العالم. يعتبر الانحلال الحراري للنفايات الصلبة طريقة مبتكرة لإنتاج الوقود الحيوي الذي يمكن استخدامه في العديد من التطبيقات، ليس فقط لإنتاج الكهرباء، حيث ان توليد الكهرباء في فلسطين مقيدًا بالوضع السياسي. كما أنه حل للارتفاع العالمي في أسعار النفط ونقص احتياطيات الوقود الأحفوري في الأراضي الفلسطينية. في بحثنا هذا تم اتخاذ محطة تحويل طولكرم كحالة دراسية، والتي استقبلت في عام 2021 أكثر من 200 طن من النفايات الصلبة البلدية يوميًا.

تم استخدام برنامج المحاكاة Aspen Plus للحصول على النتائج ، وتم تطوير المعادلات التي استخدمت في تطبيق المحاكاة بناءً على العديد من التجارب العملية التي تم توثيقها في الأبحاث العلمية. تم تقديم أربعة سيناريوهات في هذه الدراسة من أجل إيجاد أفضل طريقة لإنتاج الوقود الحيوي من النفايات الصلبة البلدية ، وفهم تأثير الانحلال الحراري المشترك على إنتاجية العملية.

أظهرت نتائج محاكاة عملية الانحلال الحراري للنفايات الصلبة المقصودة دون أي تعديل عليها أن أقصى إنتاج للزيت الحيوي يبلغ 21.3% بالوزن. في السيناريو الثاني، تم تطبيق المحاكاة فقط لجزء الكتلة الحيوية للنفايات الصلبة المقصودة ، والذي أنتج 60.5% بالوزن من الزيت الحيوي. كان الحد الأقصى لإنتاج الزيت

الحيوي 67.82 و 82.32% بالوزن، على التوالي، للسيناريو الثالث (50% بلاستيك مع 50% كتلة حيوية) والسيناريو الرابع (100% مواد بلاستيكية).

أظهرت هذه النتائج، جنبًا إلى جنب مع التقييم الاقتصادي والبيئي الذي تم إجراؤه، أن الانحلال الحراري قد يكون الخيار الأفضل لحل مشاكل النفايات الصلبة المحلية و نقص الطاقة. من الناحية الاقتصادية، يتمتع هذا المشروع بفترة استرداد مدتها 3 سنوات ومعدل عائد داخلي بنسبة 31% بيئيًا، يمكن أن يؤدي استخدام الوقود الحيوي إلى تقليل انبعاثات ثاني اكسيد الكربون بشكل كبير, يطلق الوقود الأحفوري 95.5 جرامًا من مكافئ ثاني أكسيد الكربون لكل ميجا جول في قطاع النقل، في حين ان الزيت الحيوي يوفر 9.5 جرام من مكافئ ثاني أكسيد الكربون لكل ميجا جول في ذات القطاع. من ناحية أخرى، يمكن للتقنية المشتركة ما بين التحلل اللاهوائي والانحلال الحراري أن تقلل من متوسط كمية انبعاثات غازات الدفيئة في البيئة عند إنتاج 1 ميجاوات ساعة من الكهرباء بمقدار 237.42 جرامًا من مكافئ ثاني أكسيد الكربون لكل ميجا جول، مقارنة بالوقود الأحفوري، الذي ينتج 182.8 جرامًا من مكافئ ثاني أكسيد الكربون لكل ميجا جول لإنتاج ذات الكمية من الكهرباء.

الكلمات المفتاحية: الانحلال الحراري، الزيت الحيوي، النفايات الصلبة البلدية، الانبعاثات.