

Recovery and Characterization of Fuel from Pyrolysis of Medical Wastes: An Alternative Source of Energy

by

Adnan Abedeen

A project report submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering in the Department of Energy Science and Engineering



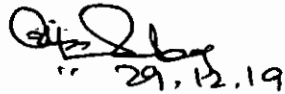
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December, 2019

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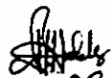
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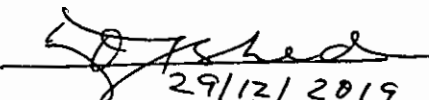
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Abstract

Bangladesh is a developing country and one of the most densely populated countries in the world. Energy consumption per capita of this country is also low compared to other developing nations. At present, the energy demands are becoming acute day by day. Environmental concerns and energy insufficiency led the government of the developing countries to think about innovative and nonconventional energy sources. Renewable energy sources may be a possible solution for meeting ever increasing energy demand as well as a way out of increasing environmental pollution. Various waste materials created from different sectors such as agricultural, industrial or medical sectors may also contribute to these matters. Inorganic materials like tyre waste are already contributing as a potential source of energy by deriving liquid and solid fuels through pyrolysis.

Appropriate and safe management of medical waste is acknowledged globally. Syringe/saline bottle wastes are mainly polyethelene and polypropelene plastic which are non-biodegradable and can create environmental pollution. Various typical problems are created to our surroundings by the disposal of such medical wastes. Sustainable management of such waste is important from various considerations. Lack of proper supervision of medical waste can cause some severe problems. The dumping of medical waste (syringe/saline bottle) into the drain is one of the main environmental issues in the municipal/city areas of Bangladesh. Blockage of drain and generation of mosquitoes and other bacteria are favoured by the disposal of such wastes in unplanned manner. The unmanaged recycling of infectious syringes and saline bottles represent a big threat to public health. Such circumstances are very likely to occur when medical waste is dumped in open space. Street children are chiefly at risk to come in contact with such wastes. Besides health-risk originated from direct contact, medical waste can harmfully affect the ecosystem by polluting water-bodies during waste treatment. Also, when such wastes are discarded in open areas close to water-bodies, they may become contaminated. So, deliberately this matters to the authority and researchers to manage these non-biodegradable waste materials. So, a way to manage waste as well as extraction of fuel may be a good solution to this problem.

Management of medical waste is the accurate constraint, storage, treatment and dumping of infectious waste produced at human and animal health-care facilities. Adequate treatment procedures of medical waste are processes or techniques specifically designed to change the biological nature and composition/structure of medical waste. If this is done effectively, the wastes will no longer be contagious or biologically hazardous. The safe discarding and treatment of medical wastes have been ignored in Bangladesh. Land filling is largely used to manage medical waste which is not an appropriate option as dumped plastic wastes can cause serious damage to environment.

It is a shocking situation that waste produced inside the health-care facilities are collected by untrained cleaners without any separation in almost every city of Bangladesh. Then the cleaners dumped them into a hole or city corporation dustbin. Waste collectors use open basket or plastic bowl. Medical wastes are discarded in some open places, whereas rest of the waste is taken at the city corporation burning area. Open burning of medical waste is causing serious air pollution. Therefore, pyrolysis process can be a promising way out of this crisis. It will indirectly help to manage such non-biodegradable wastes, also low grade liquid fuels can be obtained. When waste materials are pyrolyzed, they generate oil, char and gas, which are valuable. The oil and char has adequate calorific value and can be used to produce heat energy.

In the present research, waste syringe/saline bottle were collected from the local clinics and hospitals of Khulna city areas and were pyrolyzed in a batch type reactor. Experiments on pyrolysis of syringe/saline bottles were conducted by changing the temperature within the range of 150-250°C at an interval of 50°C. The batch type fixed-bed pyrolysis reactor was constructed and installed in the Heat Engine Laboratory of the Department of Mechanical Engineering, Khulna University of Engineering & Technology. The maximum yield of pyrolytic oil and pyrolytic char from syringe waste was 35.94% (by weight) at 250°C and 51.08% (by weight) at 150°C with the feed size of 2×2 cm with loading size of 1.5 kg. The maximum yield of pyrolytic oil and pyrolytic char from saline bottle waste was 36.14% (by weight) at 250°C and 51.15% (by weight) at 150°C with the feed size of 2×2 cm with loading size of 1.5 kg.

The properties of pyrolytic oil from waste syringe/saline bottle such as density, kinematic viscosity, pour point, boiling point and cloud point were measured and the respective values are in the range of 726 to 758kg/m³, 3.19 to 4.75cSt, -12 to -16°C, 86 to 95°C, -2 to -5°C and the gross calorific value (GCV) is around 42-44 MJ/kg which is comparable to diesel (42 to 46 MJ/kg). The GCV of pyrolytic char is around 42-43 MJ/kg which is comparable to anthracite coal (23 to 24 MJ/kg). The Gas chromatography-mass spectrometry (GC-MS) and Fourier Transform Infra-Red (FTIR) tests suggest presence of higher amount of aromatic compounds in pyrolytic oils evolved from the pyrolysis of syringe/saline bottle waste. The Thermogravimetric Analysis (TGA) shows that the experimental curve is higher from 150 to 300°C. The oil and char obtained from pyrolysis of syringe/saline bottle waste can be used as alternative fuel or chemical feedstock after some treatment. The results show that these properties are similar to that of the low grade liquid fuels and high grade solid fuels and thus pyrolysis of such waste (syringe/saline bottle) will reduce environmental contamination to a degree as well as be a substitute source of energy.

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Nomenclature

AFR	air-fuel ratio
API	American Petroleum Institute
BCSIR	Bangladesh Council of Scientific and Industrial Research
CARS	Centre for Advanced Research in Sciences
EPA	Environmental Protection Agency
FCI	Fixed Capital Investment
FCIPT	Facilitation Centre for Industrial Plasma Technologies
FTIR	Fourier Transform Infra-Red
GC-MS	Gas chromatography-mass spectrometry
GCV	Gross Calorific Value
GHG	Green House Gas
HCE	Health-care Establishment
HCW	Health-care Waste
HCWGR	Health-Care Waste Generation Rate
HDPE	High-Density Polyethylene
KCC	Khulna City Corporation
LDPE	Low-Density Polyethylene
MWM	Medical Waste Management
NTUH	National Taiwan University Hospital
PETE	Polyethylene Terephthalate
PMW	Plastic Medical Waste
PP	Polypropylene
PS	Polystyrene or Styrofoam
PVC	Polyvinyl Chloride
RCC	Rajshahi City Corporation
RT	Retention Time
TCR	Total Capital Requirement
TGA	Thermogravimetric Analysis

CHAPTER I

Introduction

1.1 General

Fossil fuel crisis has led mankind to focus on developing new and alternate energy sources. The focused alternative product and technologies are bio-fuel, bio-diesel, bio-ethanol, dimethyl-ether, biogas, pyrolysis, gasification etc. New and alternative energy sources are not always available. But a significant amount of diversified wastes are produced by human activities throughout the world. Sometimes waste generation becomes a problem of global concern. Therefore, proper waste management and strategic policy is thus an important feature for sustainable development [1]. Their harmful effects on public health and general environment have led to an increasing awareness to adopt scientific methods for safe and secure disposal of wastes. Thus, there is a crucial need to reduce waste generation and/or reuse or recycle them. The method for recovery of energy from various wastes can play an important role in mitigating these problems. Besides these, recovery of a considerable amount of energy, these technologies can show the way to a substantial diminution of overall waste requiring ultimate disposal. Then it could be better managed for safe disposal in a controlled mode whilst meeting the pollution control standards [2].

Waste from health-care facility that includes both potentially toxic and non-toxic materials is considered as medical waste. Even though medical wastes represent a comparatively small portion of the entire waste generated in a society, management of medical waste is considered to be an essential matter worldwide [3]. Health-care facilities are increasing at a rapid pace, which sequentially increases the quantity of medical waste production in developing countries, especially by clinics, hospitals and other health-care establishments. A wide range of factors are responsible for the production of health-care waste in a typical developing country. The rate of generation may range from 0.5 to 2.5 kg/bed/day [4]. Medical waste is proficient of causing diseases and disorder to citizens, either through straight contact or ultimately by contaminating air, soil, surface water and groundwater [5].

Medical waste possesses a threat to persons, communities and the surroundings if not carefully managed. Land filling is not an appropriate option for discarding plastic wastes because of their very slow degradation rates. Mechanical recycling can be an effective process, but it is limited to thermoplastics, contamination level, homogeneity of the types and colour similarity [6]. Chemical recycling of plastic wastes is one of the most remarkable plastic wastes management methods [7].

Pyrolysis is one of the most efficient and promising techniques to get liquid fuel from the plastic-based waste. It is a thermo-chemical process using very less or deficiency in oxygen supply. In this method, the organic constituents of the decomposable material yield gaseous and liquid products that can be used as fuels and chemicals [8]. Pyrolysis process produces a smaller amount of flue gas than incineration. This technique also produces a small content of heavy metals, dioxin and other pollutants, which is conducive to the refinement of flue gas and decreases the level of secondary pollutant emanations. Furthermore, pyrolysis is carried out in absence of oxygen, so there is less production of NO_x, SO_x and HCl.

The resulting pyrolysis oil or gas can be burned at a low air-fuel ratio with fewer exhaust gas and pollutants. Therefore, it is relatively a secure method of disposing medical waste. Incineration is a critical procedure, in which hydrocarbons are altered to their combustion products, whereas pyrolysis may change them to inferior hydrocarbons, which perhaps used as fuel and other different types of feed materials suitable for chemical industries [9]. An important magnitude of dangerous pollutants, for instance HCl, dioxins, furans and heavy metals including Hg, Cd and Pb have been produced from incineration of medical wastes [10].

1.2 Motivation of this Research Work

Various types of health-care establishments generate a huge amount of medical waste throughout the world each year. Medical waste is a variety of harmful waste materials with multi-components. Plastics of different types and textiles are the main constituents of medical waste. Medical waste also consists of needles, pathological wastes, surgical wastes

from surgery and autopsy and pharmaceutical wastes. Management and efficient disposal of medical waste is a massive task.

Traditionally, hospitals and clinics burn medical waste in incinerators and then dump the remaining into landfill sites. Sometimes they are deposited without incineration. Uncontrolled burning of medical waste releases toxic and harmful by-products including carbon dioxide, dioxins, mercury and ash that are released into the atmosphere. These contaminants endanger the environment. Furthermore, disposal of medical waste without proper handling can initiate spreading of diseases and pathogens that directly threatens human health.

Pyrolysis is an effective process of dangerous waste disposal and recovery of valuable products. Pyrolysis of decomposable medical waste can alter this type of waste into fuels in normal pressure. Pyrolytic oil from pyrolysis of medical waste can be used as fuel for diesel engines, burners, boilers and as heating oil. Additionally, evolved oil from pyrolysis can be refined through distillation column to obtain diesel, gasoline and machine oil.

As it is seen that researchers and scientists have found both oil composition and yield of oil through pyrolysis of various medical waste is comparable with diesel or gasoline. In the same guideline attempts will be carried out in this study to explore whether such kind of contents are present in medical waste like syringe and saline bottle.

1.3 Objectives of the Research Work

The main objective of this project is to produce and analyse pyrolytic oil from plastic oriented medical wastes through pyrolysis process in small scale at Khulna University of Engineering & Technology. Under the study, waste disposable plastic syringe and waste saline bottle will mainly be used as raw material.

The specific objectives of this project are:

- i. Construction of a fixed bed pilot scale plant for pyrolysis of medical wastes.
- ii. To study the temperature effect on specific types of raw materials.
- iii. To examine the rate of energy recovery of the products through pyrolysis.

- iv. Characterization of pyrolytic oil using different analysis such as calorific value and proximate analysis.
- v. Observation on GC-MS, FTIR and TGA of the pyrolytic oil.

1.4 Scope of Present Investigation

Nowadays, low-pollution processes and applications are in increasing demand by industry and governments to reduce environmental impacts as well as to obtain economic benefits. Medical waste disposal industry around the world has a significant influence on relevant industries and technological sectors as well as on the environment. In recent years, with technological advancement and improvement of medical services, medical waste generation is continuously increasing in most of the regions of the world. However, in developing countries, inappropriate treatment of medical waste is not an unusual case. Mixing of medical waste with other general waste and open-air burning of this type of waste is a common phenomenon.

Medical waste does not contain only plastics that has a challenge in treating through a simple method but also contains hazardous waste which is harmful to humans and other creatures. The pretty common and simple method adopted today is incineration due to its ability of decomposing different materials and destruction of organisms and pathogens. However, some pollution problems associated with incineration methods must be avoided or minimized. So, other methods are developed to supplement or replace traditional incineration method and the autoclave method prior to landfill. Searching for alternative fuel to meet the increasing energy demand, the present investigation will put emphasis on the followings:

- Proper disposal of medical wastes with potential material recovery.
- Emphasis on the production of liquid fuel.
- Study for the high quality oil production.
- Study the comparison of two different types of medical waste.
- Examine the feasibility of a small scale pyrolysis plant.

CHAPTER II

Theoretical Aspects

Plastic materials are usually made from synthetic or semi-synthetic organic compounds. Such materials always contain carbon and hydrogen, while other compounds might be present. Most industrial plastics are made from petrochemical compounds. There are two major types of plastics, viz., thermoplastics and thermosetting plastics. The term ‘plastic’ refers to the special property which is known as plasticity. It is the capability of a solid matter to undergo deformation without breaking. The compounds used to make plastic is most often mixed with additives, including plasticizers, colorants, fillers, stabilizers and reinforcements. These additives have an effect on the chemical properties, chemical composition and mechanical properties of plastic, along with its expenditure [11]. Plastic is an important constituent of many day-to-day commodities of our life, including plastic bags, plastic bottles, plastic containers etc. [12].

2.1 Various Types of Plastic

Different researchers classified plastic into various groups. The various groups of plastics are briefly discussed below:

Polyethylene Terephthalate (PETE or PET)

In 1940, J. R. Whinfield and J. T. Dickson first introduced this type of plastic. PETE or PET is one of the most frequently used plastic on earth. Interestingly, it took around thirty years before it was used for beverage bottles, like Coca-Cola and Pepsi. In USA, around 96% of all plastic containers and bottles are made of PETE plastics; however, only 25% of these plastic products are recycled [11].

PETE or PET plastics are generally known as polyester. This type of plastic is a lightweight plastic commonly used for groceries wrapping and beverage packaging. Furthermore, this plastic can entrap moisture and gaseous substances to keep product fresh.

Because of these attributes, this type of plastic is normally used for soft drink, mineral water, fruit-juice and cookery oil containers. It is also used in jar of peanut butter, jam, jelly and microwavable trays [13].

High-Density Polyethylene (HDPE)

Karl Ziegler and Erhard Holzkamp created high-density polyethylene in the laboratory by using catalysts and low pressure in the year of 1953. It was primarily used for pipes in storm drains, sewers and culverts. Nowadays, this type of plastic is used for a wide range of commodities. The most recycled plastic of the world is HDPE, because it will not destroy under contact with extreme heat or cold. According to United States Environmental Protection Agency (EPA), around 12% of all HDPE products produced in a year are recycled [11].

HDPE plastics are thick and durable one. They are stronger in comparison to PETE or PET plastics. As HDPEs are durable in nature, containers made from this type of plastics are used for containing shampoo, detergents and household cleaning products. Some other common stuff made from HDPEs are water, milk and juice containers. This type of plastic is also used for building construction materials for instance, injection moulding, plastic wood composites and wire or cable covering [13].

Polyvinyl Chloride (PVC)

In industrial and production history, polyvinyl chloride (PVC) is one of the oldest synthetic plastic materials. In fact, it was accidentally discovered two times; once by Henri Victor Regnault who was a French physicist in 1838 and then again in 1872 by Eugen Baumann who was a German chemist. On both incidents, they found it inside vinyl chloride flasks which were left out in open sunlight. This type of plastic is one of the least recycled plastic materials; in general not more than 1% of PVC plastic is recycled in every year. It has been named as ‘poison plastic’ since it contains several contaminants and is injurious to human health and the surroundings [11].

PVC is a multifarious plastic. Manufacturers of industrial materials use PVC plastic to make pipe and plumbing fittings. ‘Clamshell’ packaging, lunch/tiffin boxes, three-ring binders, toys, blood bags and tubes also contain this type of plastic [13].

Low-Density Polyethylene (LDPE)

LDPE is the grandfather of polyethylene material as it was the earliest type of polyethylene to be produced. It has lower density than HDPE so that it is considered as a different material for recycling. Packaging materials and containers produced from LDPE plastic make up about 56% of the total plastic waste, 75% of which comes from households. Nowadays, there are many recycling programs working to handle this type of wastes. As a result, a lesser amount of LDPE will end up in landfill sites and have an effect on the environment [11].

LDPE plastic is lightweight and flexible in nature. LDPEs are comparatively transparent and it can be used as heat sealer. Because of these unique properties, LDPEs are widely used in plastic wrapping/packaging. LDPEs are also used for shrink wrap, dry cleaning bags, coverings for paper milk cartons and coffee cups. These types of plastics are also used in plastic squeeze bottles for salt and sauces [13].

Polypropylene (PP)

In 1951, J. P. Hogan and R. L. Banks discovered polypropylene (PP). At that time, they were basically trying to convert propylene into gasoline, instead of that they have revealed a new catalytic method for making a new kind of plastic. In the United States of America just about 3% of polypropylene products are recycled. Interestingly, around 325 million pounds of non-bottle plastics are collected for recycling each year in USA. It is needless to say that a lot of polypropylene plastic is produced, but merely a small amount is actually recycled [11].

Melting point of this type of plastic is high. Based on this criterion, they are generally used in hot food packaging. Polypropylene plastic is also used for making bottle caps, yogurt containers, syrup bottles and deli wrappers. Moreover, because of their durability and heat resistivity polypropylene plastics are suitable for making automobile parts. These automobile parts include battery cases, signal lights, battery cables and ice scrapers [13].

Polystyrene or Styrofoam (PS)

In 1839, German apothecary Eduard Simon accidentally came across polystyrene (PS) while preparing medication. He isolated a substance from natural resin and did not realize

what he had invented. Later, German Nobel laureate organic chemist named Hermann Staudinger conducted research on this type of plastic material and expand its uses. PS is a lightweight substance which is easy to shape into plastic like materials. It also breaks naturally, making it more dangerous to our environment. Sea beaches around the globe are littered with pieces of PS plastic materials, which are putting the wellbeing of maritime creatures in danger. Polystyrene covers around 35% of United States landfill materials [11].

PS plastics are lightweight, flexible and versatile in nature. It is used in food packaging industry and making of plastic laboratory ware. Styrofoam often used for cushion packaging, packing peanuts and clamshell containers etc. [13].

Miscellaneous Plastics

The remaining types of plastics include: polylactide, polycarbonate, acrylic, acrylonitrile butadiene, fibreglass and nylon. There are many variations in these types of plastics, though they are classified as miscellaneous plastics by various recycling programs.

2.2 Types of Post-use Plastic Waste

Post-use plastic wastes usually falls into one of five major types [14]. These types are briefly discussed below.

Plastic Bottles

Plastic bottles, pots, buckets, tubs, jugs, mugs and trays are found mostly in the domestic waste stream. Plastic bottles are naturally used to store liquids for instance, water, soft drinks, cooking oil, motor oil, liquid medicine, shampoo, conditioner, milk and ink.

Plastic Film

Plastic film is a thin paper-like packaging material used for wrapping or as a bag. Examples of plastic film products contain plastic shopping bags, garbage bags, plastic wrap and bubble wrap. The main sources where huge amounts of recoverable plastic film are generated are those industrial areas where shipping and handling of products took

place. Wholesale marketing and distribution of various products generate large quantities of post-consumer commercial film wastes. These wastes are suitable for recovery.

Rigid Plastics

Rigid plastics cover up a big range of products for example, used pipes, plastic crates, mouldings, expanded-polystyrene packaging, bins and various types of containers. Different types of plastics are used to produce these products. Rigid plastics can come from any source, these sources include health-care facilities, household, industrial and agricultural sectors.

Plastic Foams

Plastic foams are commonly used in wrapping and packaging of various goods. The most familiar types of plastics being used for these purposes are polystyrene or Styrofoam (PS).

Flexible Plastics

Flexible plastics include cable sheeting, bundling, banding and some other products. These commodities are made from various types of plastics and can come from any sources.

2.3 Definition of Health-care Waste

The waste produced by health-care establishments can be defined as health-care waste. Hospitals, clinics, biological research institutes and laboratories all these are included in health-care establishments. Additionally, health-care waste contains the waste generating from 'minor' or 'scattered' sources such as waste produced during health care activities undertaken in household (e.g., different types of domestic first aid approaches, insulin injections, etc.).

Globally around 75- 90% of the waste generated by health-care establishments are non-toxic or non-risky health-care waste, comparable to household waste. This type of waste originates mainly from the maintenance and managerial functions of health-care organizations [15]. Other 10-25% of health-care waste is considered as toxic or dangerous and may cause multiple health risks. Types of wastes produced from health-care facilities are briefly described below:

2.3.1 Infectious Waste

Infectious waste is the type of waste which supposed to contain pathogens (viruses, bacteria, parasites or fungi) in sufficient amount or concentration to cause disease in vulnerable hosts. This group includes:

- Stocks and cultures of infectious agents (viruses, bacteria, parasites or fungi) from laboratory experiments;
- Waste from surgical treatments of patients and post-mortem examinations on dead bodies having infectious diseases (for example, tissues and equipment that have been in contact with the patients' or dead bodies' blood or other bodily fluids);
- Waste from isolation wards (e.g. dressings from unhygienic or surgical wounds, excreta, clothing in contact with infected patients);
- Waste produced from kidney dialysis of infected patients for instance dialysis apparatus such as bottle filters and tubes, disposable aprons, gowns, towels, gloves and lab coats);
- Waste from infected animals going through treatment in clinics or laboratories;
- Any other materials or apparatus that have been in touch with infected patients or animals.

Table 2.1 shows the groups of different health-care waste.

Table 2.1: Various Groups of Health-care Waste [15]

Waste Group	Illustration and Examples
Infectious Waste	Waste supposed to contain pathogens e.g. stocks and cultures of infectious agents; waste generated from isolation wards; swabs, apparatus or equipment that have been in touch with infected patients and animals
Pathological Waste	Human body parts or fluids e.g. fetuses, amputated body parts; blood and other bodily fluids
Sharps	Sharp waste e.g. needles; scalpels; blades; infusion sets; knives; broken glass
Pharmaceutical Waste	Waste contains medicines or drugs that are expired, unused or no longer required; bottles and boxes infected by or

	containing those type of drugs
Genotoxic Waste	Genotoxic wastes are those waste that may have teratogenic, mutagenic or carcinogenic properties e.g. residues of cytostatic drugs, urine, vomit and faces from victims under treatment with cytostatic drugs, radioactive materials and chemicals
Chemical Waste	Waste containing expired chemical substances e.g. solvents and reagents for laboratory experiments; film developing chemicals; sterilants and other disinfectants
Wastes with High Content of Heavy Metals	Waste containing heavy metals (e.g. mercury in broken thermometers); blood-pressure gauges and batteries
Pressurized Containers	Aerosol cans; any types of gas cylinders; gas canisters
Radioactive Waste	Waste containing radioactive materials e.g. medical apparatus polluted with trace amounts of radioisotope, clothing or an actual radiation source, unutilized liquids from radiation therapy or laboratory research; infected glassware, packages or blotting papers; body parts from patients treated with radiotherapy

2.3.2 Pathological Waste

Pathological waste contains tissues, human organs and body parts, fetuses and carcasses, blood and bodily fluids. In this group, anatomical waste which is a subdivision of pathological waste contains identifiable human or animal body parts. Anatomical waste should be defined as a subclass of infectious waste, although it may contain healthy human or animal body parts.

2.3.3 Sharps

Sharps are those types of objects that could cause laceration or puncture wounds. It includes scalpels, needles, hypodermic needles, knives, blades, saws, infusion sets, broken glass and intramedullary nails. Whether they are contaminated or not contaminated, such medical instruments are normally considered as extremely dangerous health-care waste.

2.3.4 Pharmaceutical Waste

This group of waste contains unused or expired and infected drugs, medicines and vaccines those are no longer needed and must be disposed of properly. The group also contains discarded products used in the handling of medicines and drugs for example bottles, containers or boxes with remnants, masks, gloves, connecting tubes and vials.

2.3.5 Genotoxic Waste

Genotoxic waste is exceedingly dangerous and might have teratogenic, mutagenic, or carcinogenic properties. This type of waste uplifts severe safety problems, both inside the hospitals and the surroundings after disposal so special attention should be given to genotoxic waste. It may include residues of cytostatic drugs, urine, vomit and faces from victims under treatment with cytostatic drugs, radioactive materials and chemicals.

2.3.6 Chemical Waste

Chemical waste includes redundant solid, liquid and gaseous chemicals. For example, chemical substances produced from medical diagnostic and experimental works and also from cleaning, maintenance and disinfection procedures. Chemical waste generated from health-care establishments may be risky or non-risky. In consideration of health protection, chemical waste is considered as hazardous waste if it has one of the following properties:

- Toxicity;
- Corrosive (e.g. acids having pH < 2 and bases having pH > 12);
- Inflammable;
- Explosive (water-reactive, shock-sensitive);
- Genotoxicity (e.g. cytotoxic drugs)

2.3.7 Wastes with High Content of Heavy Metals

Wastes with high percentage of heavy metals represent a subgroup of harmful chemical waste which is extremely toxic. Some medical apparatus e.g. blood pressure gauges or

sphygmomanometers and thermometers contain mercury which is a very toxic element. Usage of digital thermometer can be a possible solution of reducing mercury spillage.

2.3.8 Pressurized Containers

Many types of gases are used in various health-care activities and are commonly stored in pressurized containers e.g. cylinders, canisters and aerosol cans. When these pressurized containers are empty (but not fully) and no longer needed they must be disposed of very carefully to avoid environmental pollution.

2.3.9 Radioactive Waste

Radioactive waste contains solid, liquid and gaseous substances produced in health-care establishments polluted by radioisotopes. This type of waste produced as a result of radiotherapy treatments. In-vitro and in-vivo analysis and clinical treatments and procedures also produce radioactive waste. The storage and the dumping of these medical wastes should be appropriate and timely in order to prevent human health contamination as well as environmental pollution.

2.4 Composition of Medical Waste

The general medical waste consists of different types of plastics, paper, glass, metal and other waste. Figure 2.1 shows the medical waste composition in four different hospitals in different regions. It can be marked from the figures that different hospitals have different medical waste compositions. However, the main components of medical waste are very similar and the plastic account for around half or more in total mass.

2.5 Medical Waste Generation

There are lots of factor which is accountable for the variability of Health-care Waste Generation Rate (HCWGR). For example, different types of services in different types of hospitals, ambiguity on whether the non-hazardous medical waste proportion is included in the calculation of HCWGR, financial factors, units of expression of HCWGR, etc. [19]. It

might be tricky to evaluate the comparison of HCWGR between developed, developing and underdeveloped countries. Reasons behind this difficulty are different legal frameworks for different countries, dissimilarities in health-care services and Health-care Waste (HCW) management systems and illegal disposal of medical waste. The comparison could be more relatable among the developing countries, as there are similar kind of environmental problems and tight budgets [20]. HCWGRs are generally lesser in developing and poor countries than developed and rich countries [15]. However, it is noted that there is a stable increment of HCW generation worldwide. HCW generation is sharply escalating in developing countries because of improved access to medical services [21]. In rich countries, the augmentation of HCWGR is based on the rapid population ageing which plays a leading role to an increasing system usage [22]. Table 2.2 shows the waste generation rates in selected countries of the world.

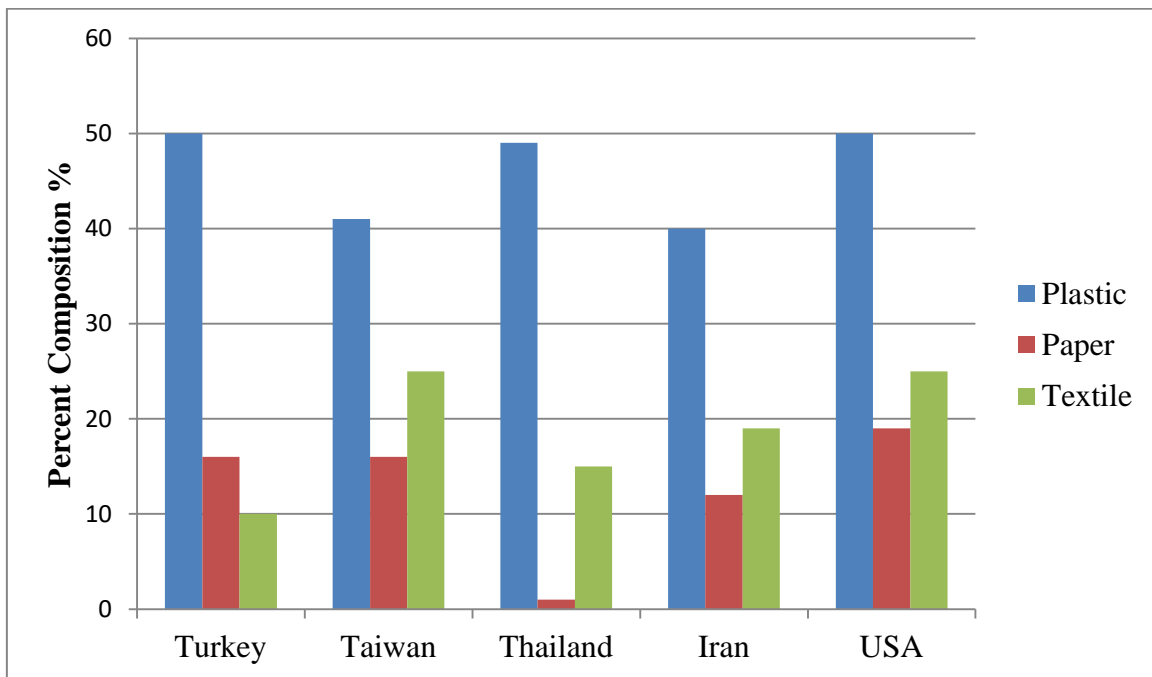


Figure 2.1: Medical Waste Composition of Different Countries [16, 17, 18]

As it is seen from Table 2.2 that health-care waste production rate is lesser in developing countries. It is much higher in developed countries.

Table 2.2: Health-care Waste Generation Rates in Selected Countries

Country	HCWGR (kg/Bed/Day)	References
Bangladesh	1.24	[20, 23, 24]
India	1.55	[24, 25]
Pakistan	2.07	[26]
Nepal	0.5	[24]
Indonesia	0.75	[27]
Malaysia	1.9	[24]
Thailand	2.05	[28]
Iran	3.04	[24, 29]
France	3.3	[26]
United Kingdom	3.3	[26]
Germany	3.6	[30]
China	4.03	[31, 32]
Canada	8.2	[33]
United States of America	8.4	[26, 33, 34]

A case study in Khulna City Corporation (KCC) shows an average health-care waste production of about 1.29 kg/bed/day [35]. Similar study on Jashore municipality shows an average health-care waste generation rate of 1.59 kg/bed/day [36]. Another study on Rajshahi City Corporation (RCC) shows an average health-care waste production of 1.54 kg/bed/day [37]. From these case studies it is found that average production of health-care waste in different big cities of Bangladesh is approximately 1.5 kg/bed/day. As it is evident from Table 2.2 that average HCWGR of Bangladesh is 1.24 kg/bed/day; it is because of lower production of health-care waste in small cities of Bangladesh.

2.6 Medical Waste Treatment

The escalating trend of medical waste generation indicates the importance of developing medical waste treatment technologies, especially for those countries which have fewer pollution control and abatement challenges. Various methods and processes have been used for medical waste treatment. They are briefly discussed below:

2.6.1 Incineration Method

Incineration is always considered as a typical method of medical waste treatment due to a large mass and volume reduction of waste and various types of medical waste can be treated as well. Generally, hospital incinerators deal with the medical waste generated from hospitals and the final products are deposited at landfill sites.

Incineration means the burning of medical waste. This process can be grouped into low temperature incineration (300-400°C), middle temperature incineration (800-900°C) and high temperature incineration (>1000°C) according to the heating temperature. Middle and high temperature-range incinerations are always favored because of its reliable destructive effects on various organisms. However, some pathogenic organisms could still survive if the incineration process is incomplete and that could cause those pathogens to spread. Moreover, toxic pollutants are produced during the incineration process such as dioxins and furans when airflow is insufficient or temperature is not high enough.

High temperature incineration could handle most of the types of medical waste and destroy them completely. However, this needs more energy, thereby more fuels are required and high quality of the incinerator is also needed. The ash generated is also potentially hazardous which may cause water and soil pollution under improper treatment situation. The possible environmental challenges associated with traditional incineration methods have prompted further research into non-incineration methods. With the improvement of health-care services, more and more health-care wastes are produced. If a suitable and timely management of health-care waste is adapted in the hospitals, clinics and research centers, the efficiency and the safety will be improved. With the aim of increasing the effectiveness and flexibility, other non-incineration methods are developed which are smaller in capacity and much easier to handle.

2.6.2 Non-incineration Method

Non-incineration means no combustion process exists during the treatment of medical waste. Non-incineration methods are applied because the control of harmful gas emission and solid residue are better than incinerator. Non-incineration methods can be sorted into a

thermal process, irradiative process, chemical process and biological process according to the differences of their fundamental behaviors. Some pre-treatments are applied such as mixing, compaction, shredding etc. This helps to reduce the volume and increase bulk density and make the waste more even in terms of composition for the follow-up treatment.

2.6.3 Thermal Process

Thermal process is based on heat application to treat the medical waste. They also could be divided into low-heat process, mid-heat process and high-heat process according to the energy supplied.

Low-heat Thermal Process

Generally, the temperature range of low-heat thermal process is between 93°C and 177°C. Due to lower temperature, the combustion or pyrolysis process would not take place and the chemical properties of waste would be stable. Both steam and dry air can be used in low-thermal process and the typical technologies are autoclaves and hot air ovens respectively.

The temperature range is low in this process so the main components of medical waste i.e., plastic will not be melted completely by applying this process. As the melting points of Polypropylene (PP) and High Density Polyethylene (HDPE) are 166.01°C and 132.39°C respectively [38]. More importantly the toxic materials associated with medical waste will not be destroyed and thus it will create a harmful effect on environment.

Medium-heat Thermal Process

Medium-heat thermal process operates between the temperature range of 177°C and 371°C [39]. The range of medical waste can be treated in a medium-heat process is wider than low-heat thermal process such as sharps, plastic, glass and biological wastes.

During the medium-heat thermal process, microwaves supply the energy to break down the organic material. The process is called depolymerization, that means, large molecules break down to small molecules. As the microwave energy is first absorbed by the inside part of medical waste and then spread out. The inside temperature of medical waste reach a

high temperature but the outside of the waste keeps a lower temperature level. When the temperature is high enough, the combustion or pyrolysis process could happen. So, N₂ gas is introduced into the system to prohibit the combustion throughout the thermal process.

During the medium-heat thermal process, there are some chemical reactions with the organic waste, but some wastes are chemically stable such as metal and glass. The off-gas of the medium-heat process may contain some light hydrocarbons and hydrogen chloride (HCl) that, in turn, can be eliminated through combustion and the use of an alkaline filter or solution.

High-heat Thermal Process

The temperature range of the high-heat thermal process is above 371 °C and the temperature could go up to 8300 °C or even higher [39]. During the high-heat thermal process, the medical wastes are destroyed completely due to some chemical and physical reactions involved.

Pyrolysis process is considered as one of the non-incineration methods although the heating temperature of it is quite high. Pyrolysis method can be defined as the breakdown of organic materials at elevated temperature and this process occurs when the oxygen is depleted. Some chemical reactions are involved during the pyrolysis and it is an irreversible process. The products may vary such as glassy material, hydrocarbon and carbon residue. Except the products are different from incinerator, the final pollutants are at a lower level comparing to the incineration methods.

Plasma Pyrolysis

Through breaking down atoms into electrons and ions, the plasma state is obtained. By means of plasma method, the temperature can reach to 10000 °C easily and quickly [39]. This technology can treat both liquid and solid medical waste due to the supply of high energy. The basic part of this technology is the plasma torch that includes a water-cooled anode and a cathode surrounded by magnetic field produced by a coil. The DC or microwave power source provide the energy and the nitrogen gas flow is introduced into the torch for stabilizing the plasma arc. Because of the high resistance of conductive ionized gas, the electrical energy is transformed to heat and the temperature range is above

1650°C. Figure 2.2 indicates a schematic of commercial plasma system. The medical waste enters the system through the feeder and then reaches the primary chamber. The primary products enter the secondary chamber to finish the pyrolysis process.

After plasma pyrolysis, most of the medical wastes are completely destroyed. Hydrogen and carbon monoxide are produced as byproduct and heat from the combustion of these gases can be recycled. Other toxic gases produced are under the limit. Another benefit of plasma pyrolysis is the complete destruction of the pathogenic bacteria under the elevated temperature and radiation condition.

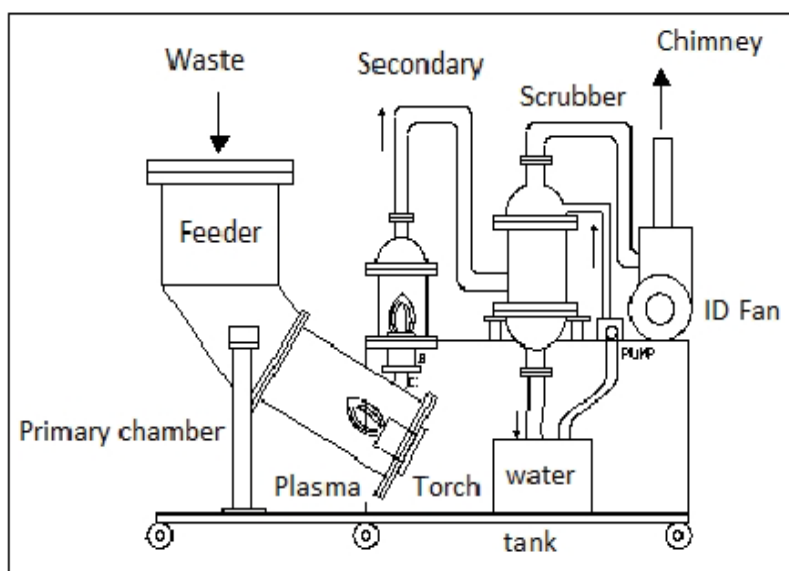


Figure 2.2: Schematic of Plasma Pyrolysis System

According to the plasma pyrolysis system developed by Facilitation Centre for Industrial Plasma Technologies (FCIPT) of the Institute for Plasma Research, the electricity required per kg of charge is approximately less than 1kWh with other co-system addition; the cost is still quite low comparing to other conventional waste treatment system in the market nowadays.

There is no doubt that plasma pyrolysis has a large potential to take the place of conventional incineration method. However, the extreme high temperature, complex chemistry and corrosion problem increase the difficulty of commercialization. There is no

sufficient information of the small-scale plasma pyrolysis equipment for medical waste treatment in the market.

Pyrolysis-Oxidation

This technology contains two steps. The medical waste is treated in the pyrolysis chamber first and then transported to the combustion chamber to complete the combustion process. During the oxidation process, some oxygen is added into the chamber as oxidizer. Post treatment of the off-gas is necessary so that pollution can be effectively controlled. Because of the effective treatment and the control of waste gas, this technology is used commercially e.g., Bio-Oxidizer. Although the cost is pretty high, still the potential of this technology cannot be ignored.

Induction Based Pyrolysis

When the properties of medical waste are evident or there is only one kind of waste, the heating process can be adopted according to the medical waste properties. However, the medical waste always contains different types of wastes and this is the reason why pyrolysis method is always adopted. Comparing to other heating processes, the induction heating is always considered as the most optimal method due to its flexibility and high efficiency.

The current could be induced in a conductor when there is a coil carrying alternative current couple with it. As a result, magnetic field is created and the heat is generated with every drop of voltage. A schematic in Figure 2.3 illustrates the induction heating principle. A larger amount of heat can be generated when the current is high enough. The benefit of this technology is the heating process which is pretty fast and the temperature control is precise and flexible. Decreasing the heating time to low temperature range (200-300°C) is beneficial to the control of dioxin. This technology has a high efficiency so it can be used to manage large amount of medical waste and work continuously.

The operating mode of commercial pyrolysis system can be designed as batch or continuous. The batch mode is always adopted in smaller system i.e. lower capacity. The initial investment of batch pyrolysis system is quite low comparing to the continuous pyrolysis system. Only a small fraction of manufacturer provides batch pyrolysis system to

the market nowadays, but it would be capable of treating the medical waste from hospitals, clinics and research centers.

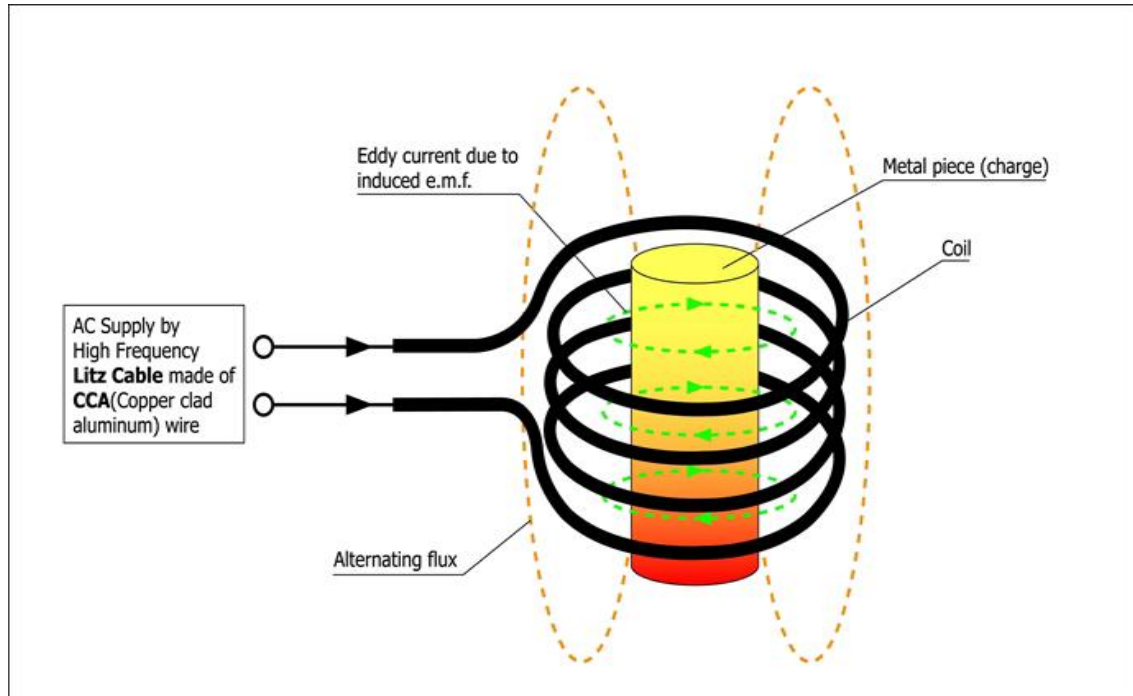


Figure 2.3: Schematic of Induction Heating

Figure 2.4 shows a schematic of machine based on induction heating principle that mainly consists of input unit, feeding unit and heating unit.

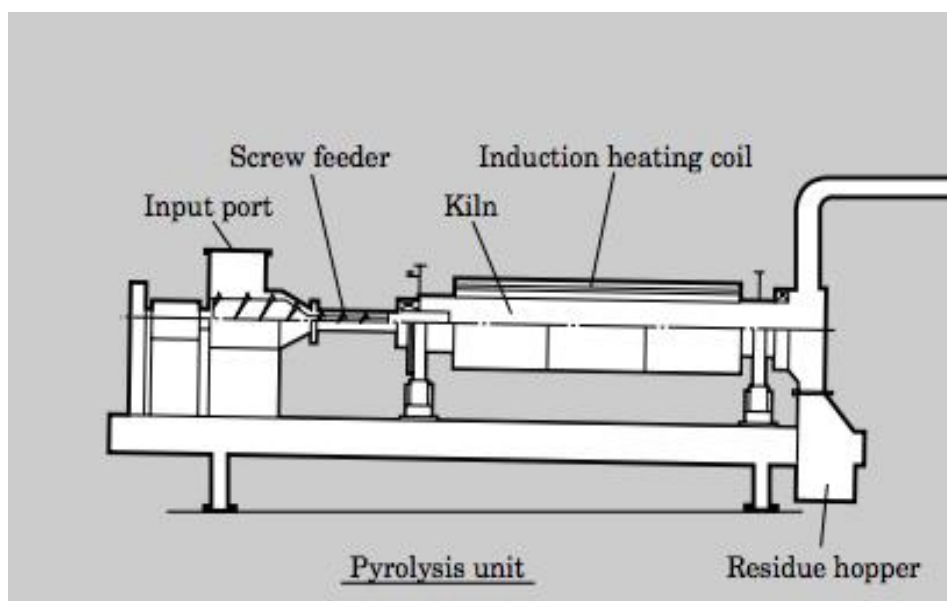


Figure 2.4: Schematic of Induction-based Pyrolysis Technology

The research from P. T. Williams et. al. [40] states that the gas yield shows an increasing trend when the pyrolysis temperature and heat rate increases. Some other research shows similar effects of temperature on pyro-gas generation e.g., when the temperature increases from 500°C to 800°C, pyro-gas composition in end products goes up to 96.5% from 5.7% [41].

2.7 Equipment Used for Medical Waste Treatment

Several equipments are used for the treatment of medical waste. Some of them are briefly described below:

2.7.1 Controlled Air Incinerator

Controlled air incineration is widely used in hospitals and research facilities nowadays to deal with various medical wastes such as injector, injection bag and general medical waste. The combustion process in the controlled air incinerator is a two-stage procedure. In the first stage, the amount of air injected into the primary combustion chamber is under the required level. Therefore, the air-fuel ratio (AFR) is low in the first combustion chamber and most of the carbon burns. In the second stage, extra air is injected into the secondary combustion chamber with the volatile gases from the primary chamber. The combustion is completed in the secondary chamber and the resultant gas stream mainly contains carbon dioxide and water vapor. The gas temperature range in first chamber is approximately from 760°C to 980°C and the secondary chamber gas temperature is higher from 980°C to 1095°C. The feed capacity of the incinerator is adjustable (e.g. from 25kg/hr up to 1000kg/hr intermittently or continuously according to various companies).

2.7.2 Autoclave

The autoclave is widely used nowadays in hospitals and research centers to disinfect the instrument or medical waste. Figure 2.5 shows an autoclave for disinfection. The water is heated to its boiling point and turned into steam. The saturation temperature of water depends on the pressure (e.g. the saturation temperature is 100°C, at atmospheric pressure).

The autoclave comprise an inside metal chamber and an outside steam jacket. Steam exists in both metal chamber and steam jacket in order to balance the high pressure.

After the collection of medical waste, the metal chamber is pre-heated to the required temperature and then waste is loaded into the chamber. Checking the sealing before introducing the steam is necessary. The air should be removed with the intention of developing effectiveness of heat conduction and the removal of air could be ensured by using a vacuum pump. After steam sterilization, more time is needed to cool down the medical waste. Furthermore, some mechanical shredding may be needed in order to facilitate the follow-up treatment. To prevent the harmful emissions, some hazardous waste should be separated (e.g. waste containing Hg). The post-process of emissions from some hazardous waste should be evaluated prior to the steam disinfection.

The advantages of autoclave are cost-effective comparing to other non-incineration method and capability is also high and well established. Although there are various types of autoclaves, it is quite easy to handle. Because there is a little change of the mass and the volume, the transportation and the storage of waste would still be a problem. The properties of waste would affect the efficiency of disinfection (e.g. materials with low thermal conductivity may need longer time to complete the disinfection process).



Figure 2.5: Autoclave for Disinfection of HCW

2.7.3 Hot Air Oven

The temperature control device of a hot air oven is a thermostat and the typical temperature range is between 50°C and 300°C. The inner layer and outer layer are made of different materials. The air between the layers facilitates the heat isolation. There is a fan inside the oven helping the circulation of hot air. The hot air oven is much safer and stable than autoclave due to the absence of water and low pressure inside. Although its' size is smaller but the efficiency is quite high. The drawback of hot air oven is the incomplete destruction of some organisms because of the absence of moisture sterilization.

2.8 Analysis of the Properties of Raw Materials

To study the behaviour of the raw materials used for pyrolysis some of its properties are need to be examined. Proximate analysis and gross calorific values of raw syringe and raw saline bottles are some of them.

Proximate Analysis

Proximate analysis is the process of determining the percent distribution of products when the samples are heated under specific circumstances [42]. The determination of percent distribution of volatile matter, fixed carbon, moisture and ash is found by prescribed methods.

Gross Calorific Value (GCV)

The gross calorific value of a substance is the amount of heat generated during the combustion of a specific amount of that substance [43]. It is also defined as energy value or heating value of a substance which is one of the most significant property of any fuel. Gross calorific value (GCV) of raw syringe and saline bottle waste can be measured by Bomb Calorimeter.

2.9 Analysis of the Properties of Pyrolytic Products

To study the behaviour of any chemical substance it is important to determine its properties. Normally there are two types of properties of a substance such as physical and

chemical properties. The analyses of the properties of pyrolytic products are briefly described below:

2.9.1 Physical Properties

The physical properties of pyrolytic products are determined by following the standard test methods for density, kinematic viscosity, pour point, boiling point, cloud point etc. these are briefly described below:

Density

The density of a substance is its mass per unit volume. The symbol often used for denoting density is ρ . It is mathematically defined as mass divided by volume [44]. It is an extremely vital feature for oil analysis and predictive maintenance. It plays an important role in calculating the performance of lubricants as well as calculating the performance of the machinery. Density of pyrolytic oils has been measured according to ASTM D4052 test methods [44].

Kinematic Viscosity

Kinematic viscosity of a fluid is the measure of the intrinsic resistance of that particular fluid to flow at the same time no external force is applied, apart from gravity. It is a quantity which is force independent. Kinematic viscosity can be acquired by dividing the absolute viscosity of a fluid with the fluid mass density [45]. Kinematic viscosity value of a liquid fuel is used to measure the stability of the fuel during storage. Glass Capillary Tube Kinematic Viscometer is used to measure the kinematic viscosity of pyrolytic oil, according to ASTM-D445 test methods.

Pour Point

Pour point of a liquid substance is that temperature under which the liquid substance loses its flowability. Pour point is an indication of that minimum temperature at which the liquid substance has the capability to fall down from a container [46]. The standard test method for the determination of the pour point is ASTM D97.

Boiling point

The boiling point of a material refers that temperature at which the vapour pressure of the liquid material is equivalent with the external pressure surrounding the liquid material and the liquid material converts into vapour. This temperature of the liquid varies with the environmental pressure exerted by the surroundings of the liquid [47]. The standard test method for the measurement of the boiling point is ASTM D1120.

Cloud Point

Cloud point of a fluid refers to that temperature at which dissolved solid substances are no longer entirely dissoluble; precipitation of undissolved solid substances then forms a cloudy appearance [48]. It shows the tendency of a fluid to clog pipelines at cold operating conditions. ASTM D5773 is the standard test method for measuring cloud point.

2.9.2 Chemical Properties

Gross Calorific Value (GCV)

The gross calorific value of a substance is the amount of heat generated during the combustion of a specific amount of that substance [43]. It is also defined as energy value or heating value of a substance which is one of the most significant property of any fuel. Gross calorific value (GCV) of pyrolytic oils can be measured by Bomb Calorimeter.

Gas chromatography–mass spectrometry (GC-MS)

Gas chromatography–mass spectrometry (GC-MS) is an analytic process which combines the characteristics of gas-chromatography and mass spectrometry to categorize different components within a test sample [49]. Pyrolytic oils from syringe and saline bottle waste can be analysed by GC-MS.

Fourier Transform Infra-Red (FTIR) Spectroscopy

Fourier-transform infrared spectroscopy (FTIR) is a method used to achieve an infrared spectrum of emission or absorption of a solid, liquid or gaseous substance [50]. Functional groups and class of compounds of the pyrolytic oils could be analysed by Fourier Transform Infra-Red (FTIR) spectroscopy.

Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is a process of thermal testing wherein the thermal stability of a substance and its fraction of volatile materials are measured by analysing the weight change of a sample when the temperature increases at a constant rate [51]. Thermal stability of pyrolytic oils from syringe and saline bottle waste can be measured by TGA.

2.10 Cost Analysis

Cost analysis is the procedure of preparing and assessing cost data from different business elements and calculating additional and total capital needed to maintain present and future business policies. It is a decision making mechanism used to analyse and prioritize financial needs based on cost estimation and their predicted return on investment. The cost analysis of a pyrolysis plant is described in the following section:

2.10.1 Cost Analysis of Pilot Plant

Techno-economic analysis showed the production cost for crude pyrolytic oil from syringe and saline bottle waste feedstock for three cases namely, medium commercial scale, small commercial scale and pilot scale plants. Production cost of pyrolysis plant can be measured by calculating the capital cost and the operating costs for collecting and chopping of syringe or saline bottle wastes.

2.10.2 Capital Costs

The capital cost of a plant is calculated by totalling the costs involved with the main parts of key equipment. Capital cost was calculated as a Total Capital Requirement (TCR) by adding to the Fixed Capital Investment (FCI). The capital charges were determined by the formula given by Eq. (1),

$$ACC = \frac{TCR}{\{1-(1+i)^N\}} \times i \dots\dots\dots(1)$$

Where, ACC is the annual capital cost, i is the interest rate and N is the plant life time.

2.10.3 Operating Costs

The major sectors of the fixed operating costs (e.g., maintenance, over-heads, taxes and insurance) were on the basis of percentages of the Fixed Capital Investment (FCI). There are different parameters used in cost estimation. These are given in Table 2.3. The analysis of unit production cost of oil is the basis for assumptions.

Table 2.3: Parameters used in Annual Cost Estimation of a Syringe/Saline Bottle Waste Pyrolysis Plant

Plant Capacity	4.5kg/day, Syringe/saline bottle waste
Location, time, currency	Bangladesh, 2019, Tk
Annual operating time	2240h@ 8 h/day& 280 days
Maintenance charge [52]	5% of FCI
Overheads [52]	0.15% of FCI
Taxes and Insurance [52]	2% of FCI
Other fixed operating costs	1% of FCI
Feed stock cost	20 Tk./kg
Heater cost	1,500 Tk./pc
Labor cost	450 Tk./day
Total labor	01 (working 280 days/yr)
Electricity price	5 (Tk./kWh)
General overheads	40% of total salaries
Interest rate	10%
Plant life	5 years

N.B: Costs of electrical heaters are included in capital cost.

CHAPTER III

Literature Review

Production of liquid fuel through pyrolysis is a promising technology nowadays. In general, all non-biodegradable and biodegradable inorganic and organic materials can be transformed into liquid substances by pyrolysis. Organic materials like biomass can be thermo-chemically converted to crude oil like substance known as bio-oil or bio-crude oil. Inorganic materials like plastics, waste tyres and tubes, shoe/sandal soles also produce pyrolytic liquid when they are treated by pyrolysis process. Liquid fuel from pyrolysis is termed as pyrolysis oil, pyrolytic oil or pyrolytic liquid.

Like plastics, tyres etc. many scientists and researchers have worked with medical waste pyrolysis. Some of their works are summarized below:

Rutala et al. (1992) reviewed the disposal of health-care waste and the danger of washing hospital wastes in the beaches of United States. They revealed that about 65% of the wastes were syringe related which came from home health-care and illegal intravenous drug use [53]. Compositional analysis is normally deemed to be the baseline information for choosing the most effective processing method of medical waste. *Li et al.* (1993) investigated the physical composition as well as the qualitative and quantitative elemental composition of the waste generated from the National Taiwan University Hospital (NTUH). They have measured that 4,600 kg waste was generated per day at NTUH. In which around 400 kg waste was infectious and 4,200 kg was non-infectious waste [54].

Lee et al. (2002) examined the recycling opportunity of plastic wastes produced from health-care facilities. They had also explored the sources, dumping costs and plastic content of health-care wastes. The sources, types, components and volume of health-care plastic wastes were also analysed by them [55]. *Deng et al.* (2008) studied thermogravimetric analysis and various kinetic parameters on pyrolysis of some typical medical waste compositions [56].

Zhu et al. (2008) analysed the pyrolysis of some known medical wastes using thermogravimetric analyser combined with Fourier transform infrared spectroscopy (TG-FTIR). The study also paved a way for designing medical waste pyrolysis model. For predictive pyrolysis modelling, TG-FTIR method is useful to give valuable inputs [57]. *Cheng et al.* (2009) evaluated the amount of medical waste produced and the factors related with the production rate at health-care organizations in Taiwan. Health-care waste production records of 150 health-care organizations were assembled for evaluation [3].

Marcilla et al. (2009) studied the thermal as well as catalytic pyrolysis of low density polyethylene and high density polyethylene with HUSY and HZSM5 under dynamic circumstances. Batch reactor has been used in this study for pyrolysis process. They have analysed the evolved products and compared the results with other commercial fuels [58]. *Syed et al.* (2012) reviewed the medical waste management (MWM) condition and exercises in Dhaka city. They have also examined some promising solutions for further research [59].

Rahman et al. (2013) demonstrated the health-care waste management system prevailing at Khulna city. They have also studied the categorization of various types of health-care waste, their rate of production and contributions of public organization (KCC) and private organizations involved in health-care waste management of Khulna city [35]. *Rahman et al.* (2013) investigated the production rate, existed medical waste management system and problems of medical waste disposal in Jashore municipality [36].

Alam et al. (2013) revealed that the current practices of inappropriate management of produced health-care wastes in various Health-care Establishment (HCEs) of Rajshahi City Corporation (RCC) is playing an important role to develop a fragile situation in spreading out Diarrhoea, Hepatitis, Allergies and different skin diseases. They have identified various types of health-care wastes, their rate of production and assessed the present waste management system in different HCEs of Rajshahi city [37].

Subramani et al. (2014) investigated the practices and compliances of health-care waste management system. They have showed that most developing countries around the globe are facing a depressing condition of environmental degradation due to increasing

generation of health-care waste. Generally higher growth of population causes more and more expansion of hospital units [60].

Dash et al. (2015) studied the thermolysis of syringe waste and the prospect of hydrocarbon production. A semi-batch reactor was used for this study. They have also investigated the FTIR spectroscopy of the pyrolytic oil, the result of the analysis confirmed the existence of certain aliphatic, and aromatic compounds. They have found through GC-MS analysis that pyrolytic oil from syringe waste contains about twenty five types of hydrocarbons. Carbon chain length of these hydrocarbons is in the range of C₁₀-C₂₀. The study also revealed that the physical properties of pyrolytic oil from syringe waste were closer to the mixture of diesel and petrol [61].

Minoglou et al. (2017) examined the dependency of health-care waste generation rate (HCWGR) on numerous socio-economic and environmental standards [62]. *Pramanik et al.* (2018) studied the production of pyrolytic oil from waste polyethylene using a specially designed semi-batch reactor. The pyrolytic oil produced was investigated and characterized for some valuable properties like American Petroleum Institute (API) gravity, fire point, carbon residue, flash point, heating value and proximate analysis [63].

Som et al. (2018) investigated the potentiality of beneficial products recovery from plastic medical waste (PMW) through pyrolysis process. Polypropylene (PP) and High density polyethylene are the main components of several PMW. These types of plastics have higher potentiality as hydrocarbon sources for various types of chemical industries [6].

3.1 Pyrolysis Process

Pyrolysis process is the thermal breakdown of both organic and inorganic materials at increased temperature in an inert condition. It includes an alteration of chemical composition and the process is chemically irreversible. Pyrolysis process occurs between the temperature ranges of 100 to 800 °C for different types of materials which is relatively low in temperature in comparison to 800 to 1000 °C employed for gasification [64, 65].

Pyrolysis process can be classified into slow pyrolysis process and fast pyrolysis process. Among them fast pyrolysis process is presently the most commonly applied pyrolysis process. Slow pyrolysis process requires a few hours to complete pyrolysis. Pyrolytic char is the main evolved product of slow pyrolysis. In contrary, products of fast pyrolysis contain around 60% of pyrolytic oil, 20% of pyrolytic char and 20% of synthesis gas. Moreover fast pyrolysis requires a few seconds to complete pyrolysis [66]. Flash pyrolysis which is often titled as very fast pyrolysis is used to increase either gas yields or liquid yields in proportion to the temperature applied [65].

The mechanism of pyrolysis is the heating of the sample in complete absence of O₂ where the organic portions of the sample are decomposed and generates gaseous and liquid substances. Alternatively, the inorganic portion of the sample, which is free from organic compounds, remains basically unaltered in the form of solid substances. These solid products of pyrolysis can be separated and recovered for further recycling. For that reason, pyrolysis process is considered as a promising alternative method for reusing waste plastics [67-71].

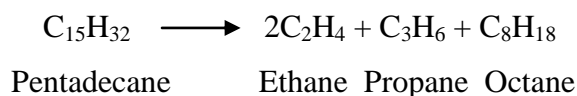
Products evolved from pyrolysis could be utilized as a substitute fuel and also as a source of chemicals for industrial uses [71]. Chemical composition of pyrolytic products depends on the types and concentration of the catalysts. Lower pyrolysis temperature favours the generation of gaseous products, while higher pyrolysis temperature decreases the production of methane, hydrogen, acetylene and various types of aromatic compounds [72].

3.2 Chemical Cracking

Cracking is a chemical process in which long-chain hydrocarbons or complex organic molecules are broken into short-chain hydrocarbons or simple organic molecules. During the process break down of carbon-carbon bonds took place [73]. Cracking of long-chain hydrocarbons can be obtained by applying high pressure and temperature in absence of catalyst or low temperature and pressure in presence of catalyst. The source of long-chain hydrocarbons is normally naphtha (C₆ to C₁₀) and diesel (C₁₆ to C₂₀) from fractional

distillation column of crude oil. The hydrocarbon products achieved from fractional distillation are in liquid form but they are gasified before cracking.

There is no single reaction that occurs during the cracking process. Long-chain hydrocarbons are broken down in a moderately random way to generate mixtures of short-chain hydrocarbons, some of which contain carbon-carbon double bonds. One possible chemical reaction involving long-chain hydrocarbon, Pentadecane ($C_{15}H_{32}$) is given below [74].



3.3 Catalytic Cracking

In petroleum refining industries catalytic cracking is a very significant conversion process. It is extensively applied for converting long-chain hydrocarbon fractions of petroleum crude oils into more useful olefins, gasoline and other petrochemical products [75]. A common group of minerals used as catalyst for petroleum refining industries are zeolites. They are hydrated aluminosilicate minerals prepared from interconnected tetrahedral of alumina (AlO_4) and silica (SiO_4). They are very stable substances and can resist tough environmental conditions in which many other substances cannot exist. Melting points of zeolites are relatively high with $1000^\circ C$ and they cannot be destroyed by fire. Zeolites can also resist elevated pressures. They are also not soluble in water or inorganic solvents [76].

3.4 Catalytic Reforming

Catalytic reforming is a chemical procedure in which low-octane naphtha fraction from fractional distillation of petroleum crude oil is converted into high-octane petrochemical products. These high-octane petrochemical products are called reformates [77]. Reformates are the finest gasoline blending stocks. In this process the reduction of carbon number is not significant. In catalytic reforming typical chemical reactions occur are dehydrogenation, dehydrocyclization and isomerisation [78]. Catalytic reforming process transforms low-octane saturated hydrocarbons (paraffins) into branched chain hydrocarbons (isoparaffins) and cyclic aliphatic hydrocarbons (naphthenes), which are then

partly dehydrogenated to produce aromatic hydrocarbons having high octane ratings. The dehydrogenation process also generates a significant amount of hydrogen gas as by-product, which is supplied into other petroleum refining processes for instance hydrocracking.

3.5 Catalytic Pyrolysis

Catalytic pyrolysis process is a promising technology using renewable biomass, plastic materials and other wastes to generate petrochemical products [79]. It has been conducted to improve the concentration of valuable chemicals in the pyrolytic oil. This oil could be used as chemical feedstock in various industries [80]. Sodium hydroxide (NaOH) catalyst can enhance the fast cracking of high molecular weight organic compounds into low molecular weight organic compounds, even when the operating temperature is low [81]. For waste plastic pyrolysis the most frequently used catalysts includes amorphous silica-alumina, zeolites (ZSM-5, beta, USY, REY, etc.), and MCM-4 [82].

Williams and Brindle [83, 84] used Ultra stable Y-zeolite catalysts with varying Si/Al ratios and different pore sizes to analyse the effect on product yields and also the compositions of evolved pyrolytic oils. In these studies catalyst Y-zeolite had a lesser silica/alumina ($\text{SiO}_2/\text{AlO}_2$) ratio and because of that the surface acidity was high. Y-zeolite had also possessed larger pore size than ZSM-5 catalyst. Y-zeolite catalyst generated considerably better concentrations of toluene, benzene, xylene, naphthalene and alkylated naphthalene in comparison with ZSM-5 catalyst. The importance of different shape-selectivity of Hydrogen ion-exchanged zeolites (HY and HZSM-5) is evident in the transformation reaction of primary products of thermal pyrolysis. Both catalysts increase the yield of aromatic portion (with a higher fraction of xylene) in comparison with thermal pyrolysis.

3.6 Pyrolysis Products and Their Possible Applications

Pyrolysis of various wastes is commonly conducted for energy recovery, as the products from pyrolysis usually have high-quality properties of fuels. Furthermore, energy (specially electricity) is for all time a very useful product, which is quite effortless to put

up for sale. Moreover, some pyrolytic products can be burned with the aim of meeting the energy requirement of pyrolysis process. Small scale pyrolysis plants can convert waste into a promising source of energy for households and energy from large scale pyrolysis plants can be used for other greater purposes, which increase the effectiveness of this method [85]. Some valuable properties of pyrolytic oil and char possibly make them favorable as raw material for a number of industrial sectors. Some possible applications of pyrolytic products are stated below.

3.6.1 Pyrolytic Gas

Generally, it could be mentioned that the composition of pyrolytic gas has high dependency on the operating temperature and the raw materials for pyrolysis. Slow pyrolysis of biomass for instance, waste from wood and forest, food crop residues and human wastes at temperatures lower than 400°C generates a small amount of gas. Produced gas has a higher concentration of carbon dioxide (CO₂), carbon monoxide (CO) and hydrocarbons with lower molecular weight. The percentage of gas production at these circumstances normally does not exceed 30% by weight. Elevation of temperature initiates secondary cracking reactions and incomplete char decomposition as a result of production of gaseous substances. The heating value of the pyrolytic gas generated from slow pyrolysis is about 10-15 MJ/m³ and the heating value varies with different temperatures and heating rate [86].

Heating value of pyrolytic gas produced from fast pyrolysis of biomass is approximately 14 MJ/m³. Conversely, when the temperature is more than 700°C especially when pyrolysis process is combined with gasification process it generates synthesis gas. The major constituents of syngas are hydrogen (H₂), carbon dioxide (CO₂) and carbon monoxide (CO). Gaseous substances are the major product of fast pyrolysis process. Pyrolytic gas can be generated from the pyrolysis of various types of plastic waste. The key constituents of this gas are hydrogen (H₂) and low molecular weight hydrocarbons namely methane (CH₄), ethane (C₂H₆), propane (C₃H₈) and butane (C₄H₁₀). The heating value of the pyrolytic gas derived from Polypropylene (PP) and Polyethylene (PE) varied from 42 to 50 MJ/kg [87]. Comparable properties have been found in the pyrolytic gas from plastic wastes like other pyrolytic gas produced from tyres or other synthetic products.

It is observed that co-pyrolysis of more than one raw materials increases oil production, heating value and content of aromatic hydrocarbons as a result the production cost decreases [88]. Co-pyrolysis of polymer waste and biomass at low temperature results in increased generation of carbon monoxide (CO) and carbon dioxide (CO₂). The pyrolytic gas from municipal solid waste contains carbon dioxide (CO₂), carbon monoxide (CO), hydrogen (H₂), methane (CH₄) and light hydrocarbons. The heating value of the pyrolytic gas is approximately 15 MJ/m³, which elevates with higher temperature [89]. The most desired thing from pyrolytic gas is its utilization as a potential source of required energy for the pyrolysis process. However, the proper management of non-condensable gases generated from pyrolysis process should be maintained.

Pyrolytic gas produced from waste tyres contains a comparatively higher percentage of hydrogen sulfide (H₂S). Oxidation of hydrogen sulfide (H₂S) can create sulfur and a lower amount of sulfur dioxide (SO₂) [90]. Pyrolysis of Polyvinyl chloride (PVC) generates a huge amount of hydrochloric acid (HCl) [91]. Food waste pyrolysis generally produces various types of nitrogen compounds which are very harmful for the environment [92]. As the composition of the waste cannot be identified precisely so some undesirable compounds may appear in the pyrolytic gas. As a result, gas cleaning equipment and emission control facilities should be applied.

3.6.2 Pyrolytic Oil

Pyrolytic oil provides more possible applications than pyrolytic gas. Depending on the process parameters and composition of the raw materials, the composition of the pyrolytic oil from pyrolysis process can change drastically. Pyrolytic oil derived from biomass contains mainly sugars, acids, alcohols, aldehydes, ketones, phenolic compounds, furans and some other hydrocarbons containing one or more oxygen atoms. Higher concentration of phenolic compounds is usually present in the pyrolytic oil. These types of compounds can be half of the total amount of produced oil, composed of comparatively lower amount of phenols, cresols, eugenol, xylenols and a larger amount of polyphenols [93].

Pyrolytic oil can be utilized for the generation of thermal energy, electricity, synthesis gas or valuable chemicals. For biomass pyrolysis temperatures between 500 and 600 °C yields

the maximum production of oil. The heating value of this oil is about 15-20 MJ/kg. On the contrary, pyrolytic oil derived from waste plastic materials has a better heating value of around 30-45 MJ/kg, depending on the composition of various plastics. *Ahmad et al.* [94] compared the characteristics of the oil produced from pyrolysis of Polypropylene (PP) and High-density polyethylene (HDPE) with Diesel and Gasoline. Quality of pyrolytic oil as a fuel can be identified by measuring its physical properties such as density, viscosity, boiling point, pour point, cloud point and flash point [94, 95]. The average heating value of pyrolytic oils generated from mixed plastics waste is around 40 MJ/kg [70, 96].

Pyrolytic oil produced from polyethylene (PE) at a temperature of 425°C contains about 30% (wt.) of aliphatic compounds. These compounds have carbon number range from C₁₂ to C₁₈ and α -olefins. They are very much desirable in detergent industries as chemical feedstock for the manufacturing of various raw materials for example, alkylbenzene sulphonic acid and sodiumlauryl ether sulphate [97]. Both of them are high quality surfactants. A unique concept of feedstock recovery from polyolefin waste is proposed by *Donaj et al.* [72]. Extraction of waste polyolefins from municipal solid waste can be done and then it is used as raw materials for the pyrolysis process. The size of the waste plastics used as feed materials should be 1-5 mm.

When the pyrolysis process is carried out at a temperature range from 600-700°C, fluidized bed reactor is used for completing the process. The products generated from the pyrolysis of waste plastics provide around 15-30% of gaseous olefins, which can be directly utilized in a polymerization plant. Petroleum naphtha-like portion of the pyrolytic liquid should be improved to olefins or other valuable chemicals by using accessible petrochemical techniques. Hydrocarbons having less importance can be utilized as a source of energy for operating the pyrolysis process. Scientists come to the conclusion that refining waste polyolefins through pyrolysis process with approximately 25% efficiency can cover around 20% of the total feedstock. It increases not only the rate of waste recovery but also reduces the usage of fossil fuels.

The utilization of pyrolytic oil from polyethylene terephthalate (PET) is less evident, because of the highly acidic nature of the pyrolytic oil [98]. On the other hand, pyrolysis of other plastic waste containing polyethylene (PE), polypropylene (PP), polystyrene (PS) and

polyvinyl chloride (PVC) produces a liquid fraction which is valuable. The heating value of pyrolytic oils from waste plastics is around 37 MJ/kg therefore they can be utilized as an alternative source of energy reducing consumption of fossil fuels. A significant amount of toluene, styrene and ethylbenzene is present in this oil; so that it can be used as chemical feedstock in various chemical industries [96].

These aromatic compounds can be used as solvents and they are extremely valuable as precursors for a wide range of useful day to day life compounds including detergents, drugs, lubricants, plastics (e.g., polycarbonate, polystyrene,) and explosives. The likelihood of getting precious aromatic hydrocarbons makes plastic waste pyrolysis process very attractive, although a well-organized extraction of aforementioned chemicals is difficult to obtain.

3.6.3 Pyrolytic Char

Pyrolysis process parameters are generally optimized with the intention of maximizing the production of liquid and gas. Although, a solid portion called pyrolytic char is also generated. It mostly made-up of carbon-rich matrices that include nearly every single inorganic compounds present in the pyrolysis raw materials. Also, a large amount of condensed secondary products are formed during the pyrolysis process and they have dispersed through the solid porous formation [99].

Pyrolytic char produced from the pyrolysis of waste materials has a heating value of about 34 MJ/kg [100], which is similar to bituminous coal. However, a number of heavy metals and harmful elements such as sulfur, chlorine and nitrogen can also be found in the solid yields. For that reason, it is vital to characterize pyrolytic chars completely to evaluate their effect on the environment and mankind. Generally, this solid product can be burned to get energy for operating the pyrolysis process or other applications. Moreover, pyrolytic char produced from pyrolysis can be processed into activated carbon.

Possibility of this application was studied by *Zeng et al.* [101]. Char reactivity was measured with the intention of finding a correlation between the char reactivity and temperature as well as relationship with heating rate. Theoretically, any unprocessed

material with high carbon content can be utilized to generate activated carbon. Generally, coal, peat, wood, coconut shells and fruit stones are used to produce activated carbon [102]. On the other hand, in scientific laboratories a wide range of various unprocessed materials has been used to manufacture activated carbons. Using waste materials to generate activated carbon is preferred since it reduces the production cost. Pyrolytic char can be used as an absorbent of air pollutants which is an attractive application. Normally, pyrolytic chars have porous formations which are very suitable for adsorption.

Bernardo et al. [103] examined the physicochemical characteristics of pyrolytic chars produced from the co-pyrolysis of biomass and waste plastics. The common metals in pyrolytic chars obtained from the co-pyrolysis of biomass and waste plastics are calcium (Ca), magnesium (Mg), potassium (K) and iron (Fe). Some other metals such as chromium (Cr), nickel (Ni), zinc (Zn), aluminum (Al), molybdenum (Mo) and manganese (Mn) are also present.

Scientists applied sequential solvent extraction method with highly polar solvents with an intention of removing the non-condensable products of liquid-phase pyrolysis from pyrolytic char. This application has increased the removal efficiencies, mainly for calcium (Ca), magnesium (Mg), and potassium (K). Meanwhile, a huge amount of pyrolytic oil was also recovered, which improved the percentage of oil production.

Another implementation of pyrolytic char from biomass pyrolysis is its utilization as an organic fertilizer, which provides numerous benefits. Bio-char enhances the ability of the soil for holding both nutrient and water and it offers habitations for symbiotic bacteria as a result crop production increases. Furthermore, bio-char can sequester carbon for a very long time in the soil because of the high stability and resistance properties of its aromatic compounds to biological decomposition [104]. Most beneficial product is the bio-char slurry which can be conveyed by truck from the pyrolysis plant to the agricultural field and spread like fertilizer. Researchers stated that co-production of bio-char and thermal energy by slow pyrolysis process shows significant reduction in Green House Gas (GHG) emission.

CHAPTER IV

Methodology and Design of Pyrolysis System

4.1 Introduction

Various types of equipment, chemicals and materials were used for the transformation of medical waste into pyrolytic oil, char and gas. Description of materials and equipment used for the transformation work and methodology applied in the whole experiment are illustrated in details in the following sections.

4.2 Design of Pyrolysis System

A fixed bed pyrolysis reactor has been designed and constructed for the pyrolysis of syringe and saline bottle waste. The key components of this pyrolysis system were: fixed bed reactor chamber, electric heater, condenser and liquid collector. These components are briefly described below:

Fixed Bed Reactor Chamber

The fixed bed reactor chamber was made from stainless steel. The top cover of the reactor chamber was flanged with the main reactor body so that it could be opened easily for feeding the raw material from the top. The reactor chamber was fixed to a convenient height and supported by three supporting stands. A pipe was fitted at the bottom of the reactor chamber for injecting nitrogen gas. A temperature sensor was connected at the middle part of the reactor chamber to show the temperature inside the reactor. The top cover of the reactor chamber was connected with a stainless steel pipe with which the condenser pipe is connected. Figure 4.1 shows the schematic diagram of the pyrolysis system of the present study.

Electric Heater

Three U-shaped stainless steel electric heaters were used for heating the raw materials. Heaters were designed to fixed with the top cover of the reactor chamber. To maintain uniform temperature distribution within the reactor chamber, they were placed at uniform distance from one another. The choice of using electric heater was to control the heating rate easily as desired. Switching off the heaters may slow down the heating rate.

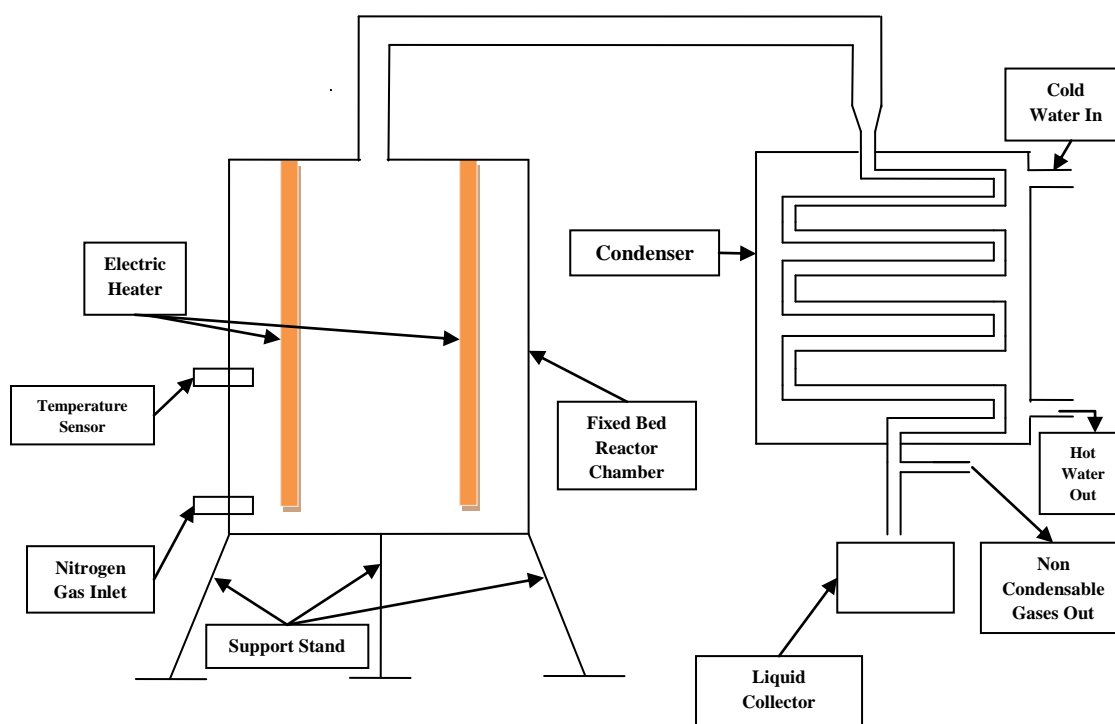


Figure 4.1: Schematic Diagram of Pyrolysis System

Condenser

Condenser chamber was also made with stainless steel. A ½-inch diameter copper tube was connected with the pipe came from reactor chamber. A copper pipe was spirally bended to avoid clogging of liquid pyrolytic product. A provision of cold water supply and warm water out was also provided with the top and bottom of the condenser. An extra copper pipe was connected at the bottom part of the condenser pipe to allow condensate to be collected at the liquid collector and also to flare the non-condensable gases to open air.

Liquid Collector

At the end of the condenser pipe there was a liquid collector to collect the condensed pyrolytic oil.

4.3 Raw Materials and Methodology

The raw materials used in this study for pyrolysis were disposable syringe and saline bottles collected as medical waste. These waste syringes and saline bottles were collected from the local clinics and hospitals of Khulna city of Bangladesh. The seal of the syringes, which are black in colour, were removed from the raw samples assuming that the evolved pyrolytic oil would not be blackish in colour. The needles of the syringe waste and the caps of the saline bottles were removed as they were metal and will not participate in the pyrolysis process. The wastes were then washed thoroughly by water and detergent to get rid of blood, mud and other containments adhered to them. The washed raw materials were then sun-dried and after that the sun-dried raw materials were chopped with a scissor or knife into small pieces as desired so that they could be easily put into the reactor chamber. Figure 4.2 and 4.3 shows the photographic view of washed and sun-dried syringe waste materials and prepared feed materials of syringe waste for pyrolysis. The size of the feed material was approximately 2.0 cm in length.



Figure 4.2: Photographic View of Washed and Sun-dried Syringe Waste Materials



Figure 4.3: Photographic View of Prepared Feed Materials of Syringe Waste for Pyrolysis

Figure 4.4 and 4.5 shows photographic view of washed and sun-dried saline bottle wastes and prepared feed materials of saline bottle waste for pyrolysis. The size of the feed material was approximately 2.0 by 2.0 cm.



Figure 4.4: Photographic View of Washed and Sun-dried Saline Bottle Waste Materials



Figure 4.5: Photographic View of Prepared Feed Materials of Saline Bottle Waste for Pyrolysis

A weighed sample was charged into the reactor by opening the top cover and was heated by switching on the heaters. The heating of raw materials took place in an oxygen free atmosphere. To ensure complete non-existence of oxygen, inert gas (nitrogen) was purged through the system; even the flow of N_2 might be continued all through the experiment. As the temperature increased, the raw materials were decomposed and converted to gaseous substance. The evolved gas was then cooled by passing through a water-cooled condenser where the condensable gases were condensed and converted into liquid oil (commonly known as pyrolysis oil or pyrolytic oil). The non-condensable gases were flared into open air. The heating was continued until all the gases came out.

After completion of the process the heater was turned off and the reactor was cooled down. The remaining solid part was pyrolytic char mixed with a very little amount of ash and was collected before next charging by opening the top cover of the reactor. Even after finishing the total experiment, the nitrogen gas supply was continued a bit so as to restrict the creation of any harmful gas within the reactor.

4.4 Construction of Experimental Set-up

Various Researchers used different types of reactors for performing pyrolysis process. The methodology is to some extent similar. As the amount of feed materials was fixed for research purpose only and feed size changes with different experiments in this study, a batch type fixed-bed reactor was selected. A prominent characteristic of batch type pyrolysis reactor is the potentiality of carrying the experiment directly in the laboratory which leads to the scale-up process. The main reactor chamber was cylindrical and was constructed from stainless steel having a length of 27.0 cm; the external diameter of the chamber was 22.7 cm and the internal diameter was 22.0 cm. One end of the reactor chamber was closed and the other end was used as feeding end. The reactor chamber was wrapped with asbestos rope for thermal insulation so that the heat could not come out the chamber. The inside temperature of the reactor chamber was recorded by K-type thermocouple sensors with display facility. Figure 4.6 shows the photographic view of the experimental set-up which contains the reactor chamber in which the pyrolysis process took place. Reactor chamber and condenser was supported by support stands. The condenser was filled with cold icy water to condense pyrolytic vapours came from the reactor chamber. Under the condenser there was a liquid collection pot to collect pyrolytic oil which drops out from the outlet of the condenser. Non-condensable gases were flared into open air with the substitute outlet of the condenser. Nitrogen gas cylinder and thermostat was also alongside with the experimental unit.

The key components of the experimental setup were:

- (i) fixed-bed reactor chamber
- (ii) heating elements (heater)
- (iii) water-cooled condenser for condensing the pyrolytic vapour;
- (iv) liquid collecting pot;
- (v) N₂ gas cylinder with flow control valve and pressure regulator;
- (vi) K-type thermocouples with temperature indicator;
- (vii) thermostat for controlling the temperature

Three U-shaped electric heaters each having a length of 10 mm and a combined capacity of 1500W were fixed with the top cover at an equal distance from one another inside the reactor.

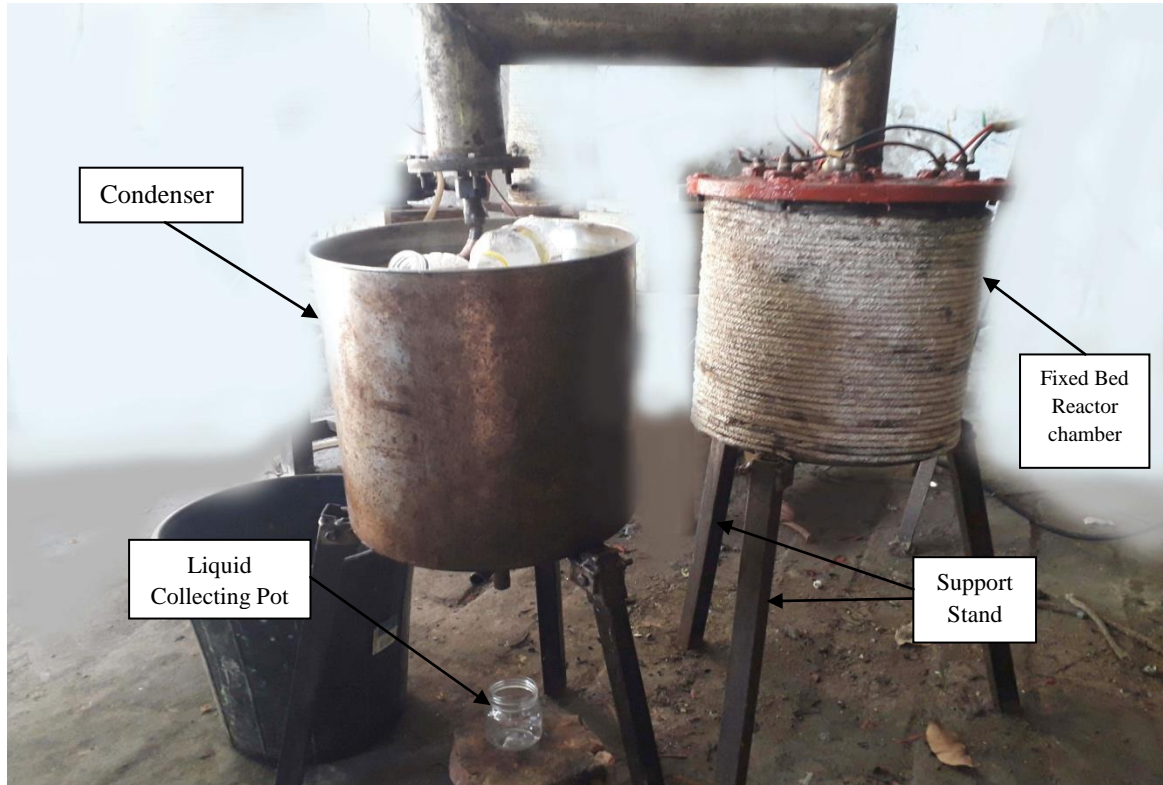


Figure 4.6: Photographic View of the Experimental Set-up for Pyrolysis

4.5 Experimental Procedure

The batch type fixed-bed pyrolysis system as described before was constructed and installed in the Heat Engine Laboratory of the Department of Mechanical Engineering, Khulna University of Engineering & Technology.

The experiments were conducted at different temperatures and feed volumes (size of raw material) and they were performed for syringe waste and saline bottle waste. 1.5 kg waste sample were taken in the reactor for each operation. The pre-treated samples were weighed and were put into the reactor chamber from top by the action of gravity. The top cover was then closed and sealed carefully with sealing materials. Passing of nitrogen gas was

maintained for 2-3 minutes from a cylinder to achieve oxygen free environment inside the reactor.

After completion of setting up the reactor, the heater was switched ON and the operation was started. At about 140°C temperature, pyrolytic yields were produced which were passed through the condenser pipe. Average heating rate maintained in this study were approximately 2°C/min. It was maintained at 150°C for 1st experiment. Condensed pyrolytic vapour was collected in the liquid collector. The non-condensable gases were flared to open air.

After completion of the experiment the reactor was turned OFF. After cooling down the reactor chamber, remaining char was taken out and collected. Then the collected char was taken into a sample bag and weighed. The liquid product was also weighed. Weight of pyrolytic gas was determined by subtracting the summation of the liquid and char weight from the original weight of the feed materials. After that, the arrangement was prepared for the next operation.

The experiments were conducted for three different temperatures of 150°C, 200°C and 250°C. Because of the heterogeneity in the raw sample, for each temperature 2-3 samples were used to run the experiment and the average value was taken as representative value. The various characteristic properties such as density, kinematic viscosity, pour point, boiling point, cloud point and GCV of the pyrolytic products were measured in the laboratory.

4.6 Experimental Data

As mentioned before, the experiments were performed at temperatures of 150°C, 200°C and 250°C for syringe waste and saline bottle waste. The data collected during pyrolytic conversion of medical wastes are shown in Table 4.1 to 4.6.

Table 4.1: Pyrolysis Data of Syringe Waste at 150°C

Feed Materials: 1.5 kg						
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)	
		Oil	Char	Gas		
01	150	320	747	433	118	
02	150	328	766	406	122	
03	150	373	704	423	125	
Average	150	340	739	421	122	

Table 4.2: Pyrolysis Data of Syringe Waste at 200°C

Feed Materials: 1.5 kg						
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)	
		Oil	Char	Gas		
04	200	399	675	426	113	
05	200	431	638	431	128	
06	200	488	583	429	129	
Average	200	439	632	429	123	

Table 4.3: Pyrolysis Data of Syringe Waste at 250°C

Feed Materials: 1.5 kg						
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)	
		Oil	Char	Gas		
07	250	453	613	434	134	
08	250	527	536	437	117	
09	250	539	526	435	124	
Average	250	506	558	435	125	

Table 4.4: Pyrolysis Data of Saline Bottle Waste at 150°C

Feed Materials: 1.5 kg					
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)
		Oil	Char	Gas	
10	150	311	767	422	133
11	150	340	739	421	127
12	150	350	728	422	118
Average	150	334	745	422	378

Table 4.5: Pyrolysis Data of Saline Bottle Waste at 200°C

Feed Materials: 1.5 kg					
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)
		Oil	Char	Gas	
13	200	404	672	424	122
14	200	417	656	427	137
15	200	467	608	425	141
Average	200	429	645	425	133

Table 4.6: Pyrolysis Data of Saline Bottle Waste at 250°C

Feed Materials: 1.5 kg					
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)
		Oil	Char	Gas	
16	250	458	614	428	129
17	250	524	546	430	136
18	250	542	525	433	143
Average	250	508	562	430	136

CHAPTER V

Result and Discussion

5.1 General

As mentioned before, pyrolysis is a thermo-chemical conversion process where a chemically irreversible transformation occurs by the action of thermal energy in complete absence of oxygen. It converts organic or inorganic materials into a variety of compounds that have fuel values [64]. Medical wastes are made from a variety of different materials which includes polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), thermoplastic polymers and copolymers, and some cotton and textile materials.

The pyrolytic oil produced from medical wastes pyrolysis is a brownish liquid with pervasive smell. It has no particles suspended in the liquid in an unrefined state.

5.2 Production of Pyrolytic Products

Under the study of pyrolytic conversion of medical wastes in a fixed-bed pyrolysis reactor, the experiments were conducted in the temperature range of 150 to 250°C. Three different types of products were obtained namely pyrolytic oil, gas and solid char. At similar conditions the weight of the pyrolytic yields were varied for medical wastes. The experimental results are shown in Table 4.1 to 4.6. They are discussed in the following sections:

Pyrolytic Oil

The liquid produced after condensation from pyrolysis of medical wastes is an oily organic compound and appears as brownish colour with a strong unpleasant smell. Figure 5.1 and 5.2 shows the photographic view of the physical colour of pyrolytic oils derived from syringe waste and saline bottle waste respectively. The physical appearance of the

pyrolytic oils is very similar to petrol and diesel. It is different from pyrolytic oil obtained from tyre waste which is blackish in colour.



Figure 5.1: Photographic View of Pyrolytic Oil Derived from Syringe Waste



Figure 5.2: Photographic View of Pyrolytic Oil Derived from Saline Bottle Waste

Pyrolytic Solid/Char

The yield and application of pyrolytic solid is influenced by the composition of feed materials and the conditions prevailed during the pyrolysis process. Figure 5.3 and 5.4 depicts the photographic view of pyrolytic chars derived from syringe and saline bottle waste respectively.



Figure 5.3: Photographic View of Pyrolytic Char Derived from Syringe Waste



Figure 5.4: Photographic View of Pyrolytic Char Derived from Saline Bottle Waste

Pyrolytic Gas

During the pyrolysis process, some gases are produced such as CO, H₂, CH₄, CO₂ and other hydrocarbons. These gases were flared into atmosphere in this study. A proper treatment of these gases could have energy recycling benefits, as well as helping to prevent air pollution. Combustion is a promising method of treating pyrolytic gas. Some gases are combustible such as CO, CH₄, H₂ and other hydrocarbons. Therefore, these gases could be used for supplying necessary heat for pyrolysis by combusting them in the reactor

chamber. The heat generated could be supplement as a partial energy source for operating the pyrolysis process and thus decreasing the cost.

5.3 Temperature Effect on Product Yield

The effects of temperature on pyrolytic products of syringe waste are shown in Table 5.1 and Figure 5.5, 5.6 and 5.7. The effect of temperature on pyrolytic products of saline bottle waste is shown in Table 5.2 and Figure 5.8, 5.9 and 5.10. As mentioned before, the tests were performed at temperatures of 150°C, 200°C and 250°C. In these cases, three types of products were produced which are liquid oil, solid char and gas.

Table 5.1: Temperature Effect on Pyrolytic Yields of Syringe Waste

Serial No.	Set No.	Weight of Syringe Waste (kg)	Temperature (°C)	% of Product Yield (w/w)		
				Oil	Char	Gas
01	01	1.5	150	21.36	49.78	28.89
02			200	26.60	45.02	28.38
03			250	30.17	40.86	28.97
04	02		150	21.86	51.08	27.06
05			200	28.75	42.56	28.69
06			250	35.12	35.73	29.15
07	03		150	24.89	46.90	28.21
08			200	32.56	38.87	28.57
09			250	35.94	35.08	28.98

In Table 5.1 the Set No. 01, 02 and 03 indicates the temperature range from 150 to 250°C along with the percentage of product yield in different experiments of pyrolysis of syringe waste. Similarly in Table 5.2 the Set No. 01, 02 and 03 indicates the temperature range from 150 to 250°C along with the percentage of product yield in different experiments of pyrolysis of saline bottle waste. In each case, the mass of sample taken was 1.5 kg.

Table 5.2: Temperature Effect on Pyrolytic Yields of Saline Bottle Waste

Serial No.	Set No.	Weight of Saline Bottle Waste (kg)	Temperature (°C)	% of Product Yield (w/w)		
				Oil	Char	Gas
01	01	1.5	150	20.73	51.15	28.12
02			200	26.94	44.77	28.29
03			250	30.53	40.90	28.57
04	02		150	22.64	49.29	28.07
05			200	27.81	43.76	28.43
06			250	34.92	36.41	28.67
07	03		150	23.32	48.53	28.15
08			200	31.11	40.54	28.35
09			250	36.14	34.99	28.87

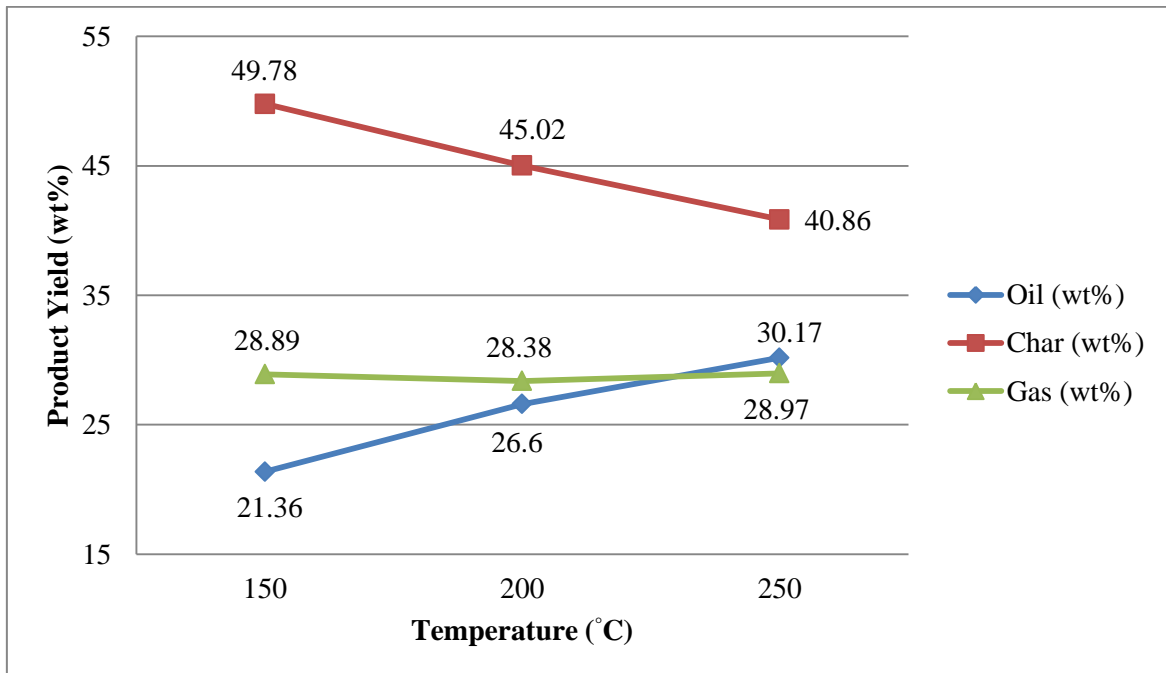


Figure 5.5: Temperature effect on Product Yield for Syringe Waste Set No. 01

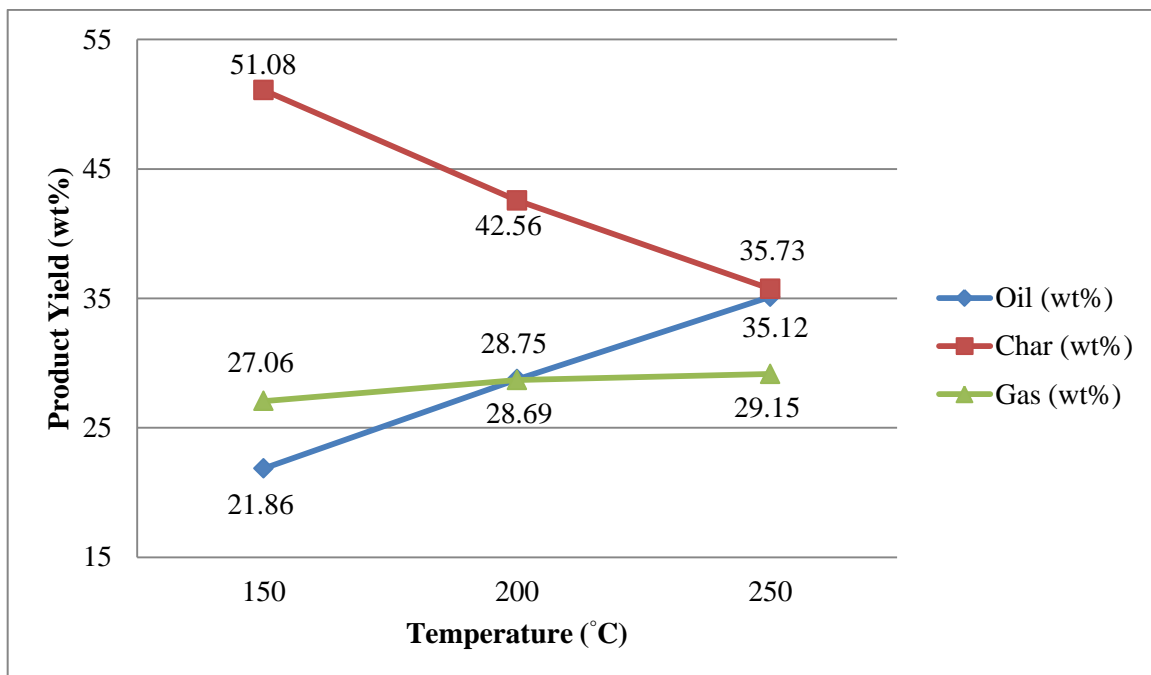


Figure 5.6: Temperature effect on Product Yield for Syringe Waste Set No. 02

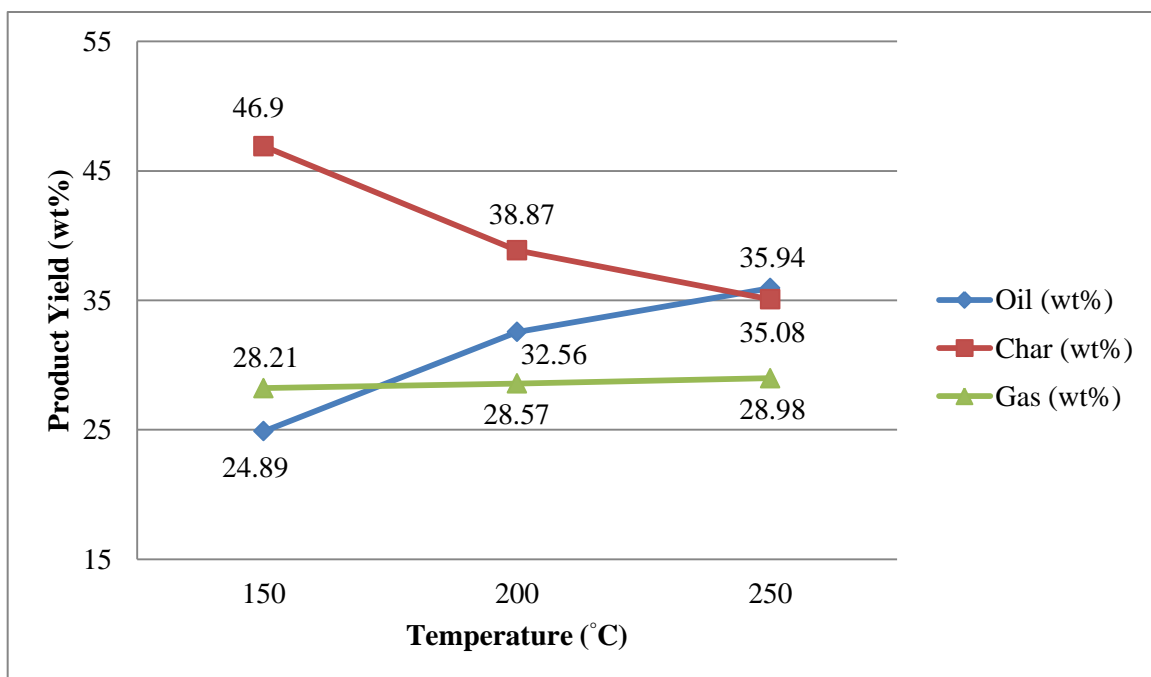


Figure 5.7: Temperature effect on Product Yield for Syringe Waste Set No. 03

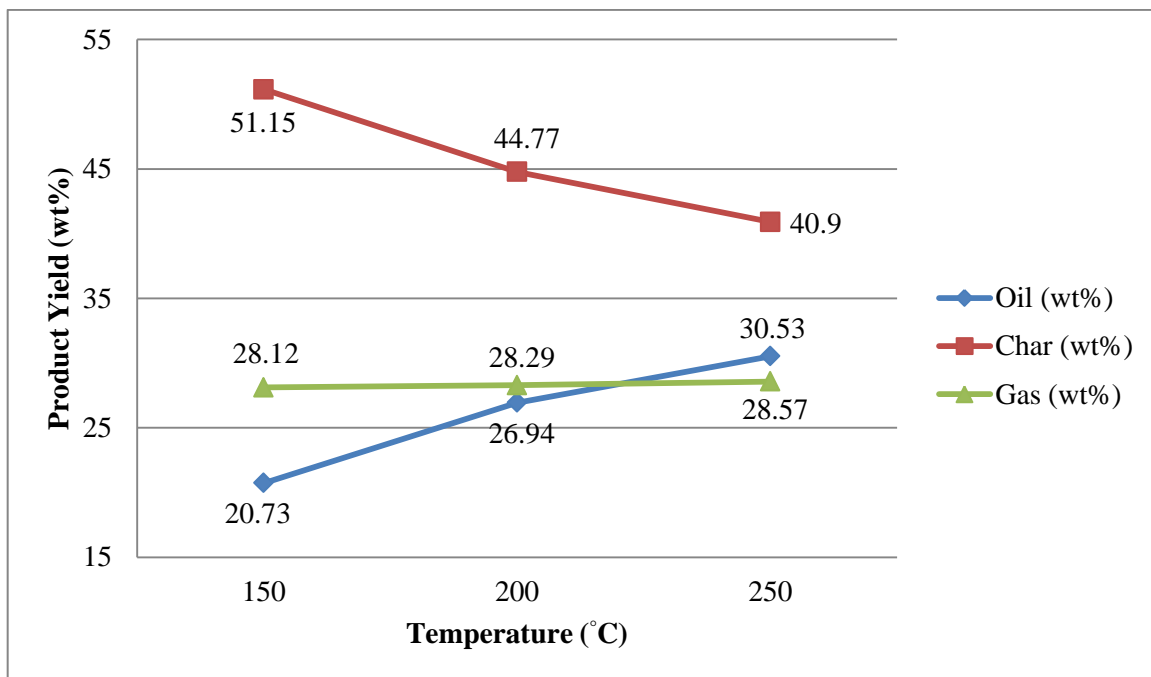


Figure 5.8: Temperature effect on Product Yield for Saline Bottle Waste Set No. 01

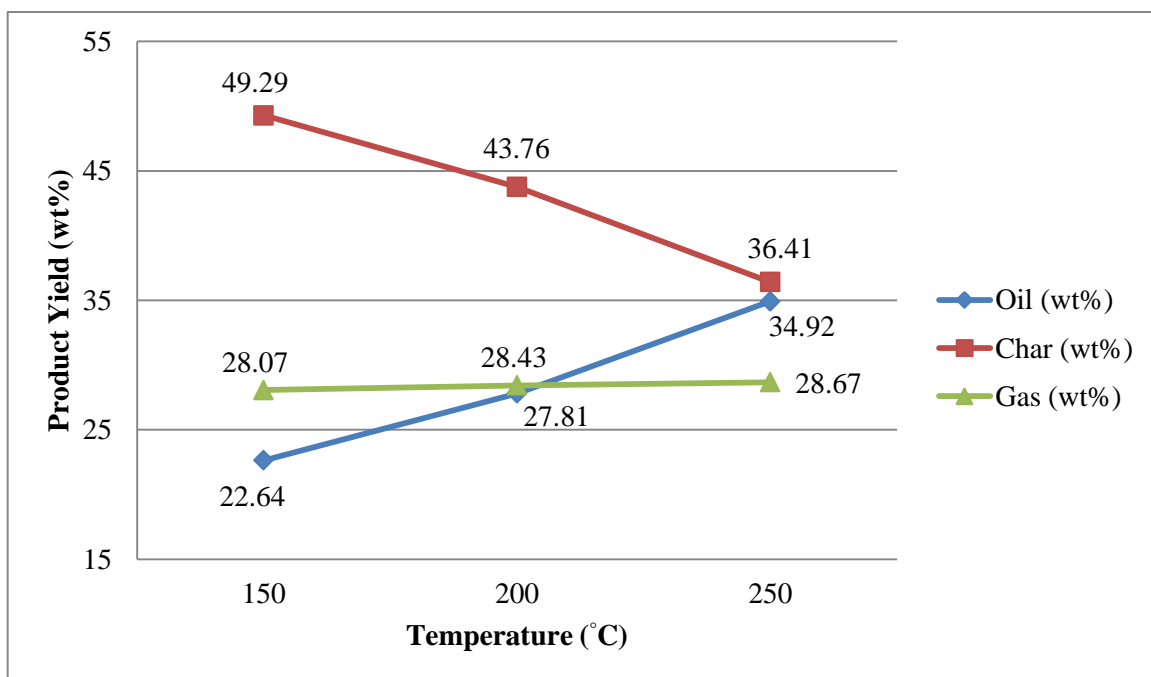


Figure 5.9: Temperature effect on Product Yield for Saline Bottle Waste Set No. 02

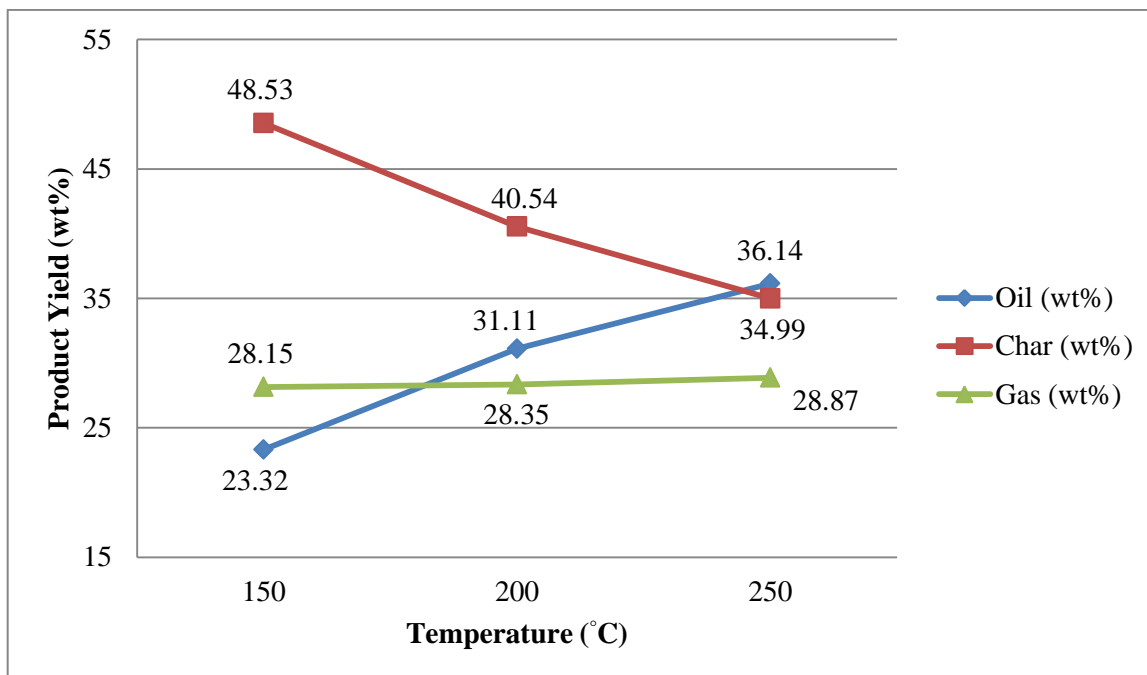


Figure 5.10: Temperature effect on Product Yield for Saline Bottle Waste Set No. 03

It is observed from Table 5.1 and 5.2 that as the temperature increases the generation rate of liquid product also increases; but for solid the trend is reverse. All the graphs from Figure 5.5 to 5.10 shows similar pattern. The increasing trend of oil production and decreasing trend of char production has been seen for both raw materials. The trend is to some extent constant for gas production in all the graphs. Since three sets of experiments were conducted and an increasing trend has been found for liquid production so the actual maximum liquid yields may be beyond 250°C.

The maximum yield (by weight) of pyrolytic oil from these experiments with syringe waste was 35.94% at a temperature of 250°C and the maximum yield (by weight) of pyrolytic char from syringe waste was 51.08% at a temperature of 150°C.

The maximum yield (by weight) of pyrolytic oil from these experiments with saline bottle waste was 36.14% at a temperature of 250°C and the maximum yield (by weight) of pyrolytic char from saline bottle waste was 51.15% at a temperature of 150°C.

5.4 Comparison of Properties of Evolved Pyrolytic Oil with other Commercial Fuels

The characteristic properties of the evolved pyrolytic oil from two different types of medical waste are important for understanding the qualitative value of the pyrolytic liquid. Some of the characteristics properties were measured in the Heat Engine laboratory of Mechanical Engineering Department of KUET. These properties are presented in tabular form in Table 5.3.

Table 5.3: Property Comparison between Pyrolytic Oils Derived from Syringe Waste, Saline Bottle Waste, Gasoline and Diesel

Physical Properties	Syringe Waste	Saline Bottle Waste	Reference with [61, 105, 106]	
			Gasoline	Diesel
Density (kg/m ³), 30 °C	758	726	720	840
Kinematic Viscosity at 40°C (centistokes)	4.75	3.19	0.6	2-5.5
Pour Point, °C	-12	-16	-40	-40 to -1
Boiling Point, °C	95	86	27 to 225	172 to 355
Cloud Point, °C	-2	-5	-	-9
Gross Calorific Value (MJ/kg)	41.519	43.578	42 to 46	42 to 45

It is noted from Table 5.3 that the density of pyrolytic oil derived from syringe and saline bottle waste is quite similar to gasoline. Kinematic viscosity is little bit higher than gasoline and diesel oil. Pour point, boiling point and cloud point is also comparable with gasoline and diesel. GCV of syringe and saline bottle waste is also alike the GCV of gasoline and diesel. Similar property comparison has been made between pyrolytic oils derived from syringe waste, saline bottle waste, tyre waste and sandal/shoe waste which is presented in Table 5.4.

Table 5.4: Property Comparison between Pyrolytic Oils Derived from Syringe Waste, Saline Bottle Waste, Tyre Waste and Sandal/Shoe Waste

Physical Properties	Syringe Waste	Saline Bottle Waste	Reference with [107, 108]	
			Tyre Waste	Sandal/Shoe Waste
Density (kg/m ³), 30°C	758	726	935.1	877-934
Kinematic Viscosity(cSt), 30°C	4.75	3.19	6.59	-
Pour Point (°C)	-12	-16	-7	-11 to -12.5
Boiling Point(°C)	95	86	-	153-158
Cloud Point(°C)	-2	-5	-	-
Gross Calorific Value (MJ/kg)	41.519	43.578	37.98	35-38

It is observed from Table 5.4 that the density of pyrolytic oil derived from syringe and saline bottle waste is lower than pyrolytic oils obtained from tyre waste and shoe/sandal waste. Kinematic viscosity of pyrolytic oil derived from syringe and saline bottle waste is also lesser than that of pyrolytic oil produced from tyre waste. Pour point of pyrolytic oil derived from syringe and saline bottle waste is comparable with tyre waste and shoe/sandal waste pyrolytic oil. GCV of syringe and saline bottle waste is much higher than other pyrolytic oils. So, the pyrolytic oil from syringe and saline bottle waste is better in quality.

5.5 Proximate Analysis and GCV of Raw Materials

Proximate analysis gives the exact percentages of fixed carbon, volatile matter, moisture content and ash content of a fuel. When fuel samples are burnt under given conditions, certain percentage of the fuel that burns in a gaseous state (volatile matter), in the solid state (fixed carbon) and the percentage of inorganic waste material which is almost inert (ash), moisture content is the amount of water particle in the sample given as a percentage of the sample's original (wet) weight and is therefore of fundamental importance for biomass fuel particularly [42]. Thus, they are important criteria for understanding fuel properties precisely. Table 5.5 illustrates the proximate analysis and GCV of raw syringe and saline bottle waste.

Table 5.5: Proximate Analysis and GCV of Raw Syringe and Saline Bottle Waste

Parameters	Syringe Waste	Saline Bottle Waste
Fixed Carbon (%)	34.06	36.13
Volatile Matter (%)	61.78	60.56
Moisture Content (%)	1.25	0.97
Ash Content (%)	2.91	2.34
GCV (MJ/kg)	41.06	43.31

From Table 5.5, it is evident that the fixed carbon percentage is slightly higher in saline bottle waste than syringe waste. But the volatile matter percentage is little lower in saline bottle waste. Moisture content is quite low in both waste and also there is a tiny percentage of ash after burning. The gross calorific value of raw syringe is less than that of saline bottle waste which is supported by fixed carbon percentage but both values are similar to petrol or diesel oil.

5.6 Gas Chromatography-mass spectrometry (GC-MS)

The major products of syringe and saline bottle waste are condensable liquids. It is very difficult to determine the different compounds numerically of these liquids. GC-MS analysis is a very resourceful process as it quantifies the components effectively. GC-MS analysis was carried out for pyrolytic oil obtained from this study. The purpose of the test was to get an idea about the characteristics and categories of the compounds of evolved pyrolytic oils and also to find out some promising method of treating and recycling those oils [109]. The analysis was conducted at the laboratory of Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka.

For GC-MS analysis, Shimadzu GCMS- TQ8040 with inbuilt database library was used in this study. The carrier gas was Helium of 99.9999% purity and 5% diphenyl 95% dimethyl polysiloxane (Rxi-5ms) of 0.25 μ m with dimension of 30m and 0.25mm was used as column. Pyrolytic oil produced in this study was filtered through 0.45 μ m membrane syringe filter and then 1 μ l was injected into the apparatus. The following program was adopted for the GC-MS experiment. Table 5.6 shows the various conditions under which GC analysis was carried out. During the gas chromatography analysis column oven

temperature and injection temperature was 75°C and 250°C respectively. Injection mode was split less. Pressure during the experiment was 79 kPa. Total flow, column flow and purge flow was 12.2 ml/min, 1.2 ml/min and 5.0 ml/min respectively.

Table 5.6: Various Conditions of GC Analysis

GC Condition	
Column Oven Temperature	75°C
Injection Temperature	250°C
Injection Mode	Split less
Pressure	79kPa
Total Flow	12.2 ml/min
Column Flow	1.2 ml/min
Purge Flow	5.0 ml/min

Table 5.7 shows the oven temperature and retention time of GC-MS analysis. Two oven program rates were maintained during the experiment. Average oven temperature was within the range of 150 to 240°C and retention time was 1 minute.

Table 5.7: Oven Temperature Program

Rate (°C/min)	Average Oven Temperature (°C)	Retention time (min)
5.00	150.0	1.0
10.0	240.0	1.0

Table 5.8 shows the various conditions under which MS analysis was carried out. During the mass spectrometry analysis ion source temperature and interface temperature was 230°C and 250°C respectively. End time of the experiment was 35 minutes. Event time was 0.5 second and the mass divided by charge number i.e., m/z range was within the range of 50-1000. Figure 5.11 shows the Chromatography Analysis of pyrolytic oil derived from syringe waste.

Table 5.8: Various Conditions of MS Analysis

MS Condition	
Ion Source Temperature	230°C
Interface Temperature	250°C
Detector Gain	1.13 kV + 0.2 kV
End Time	35 min
Acq. Mode	Q3 Scan
Event Time	0.5 sec
Scan Speed	2000
m/z Range	50-1000

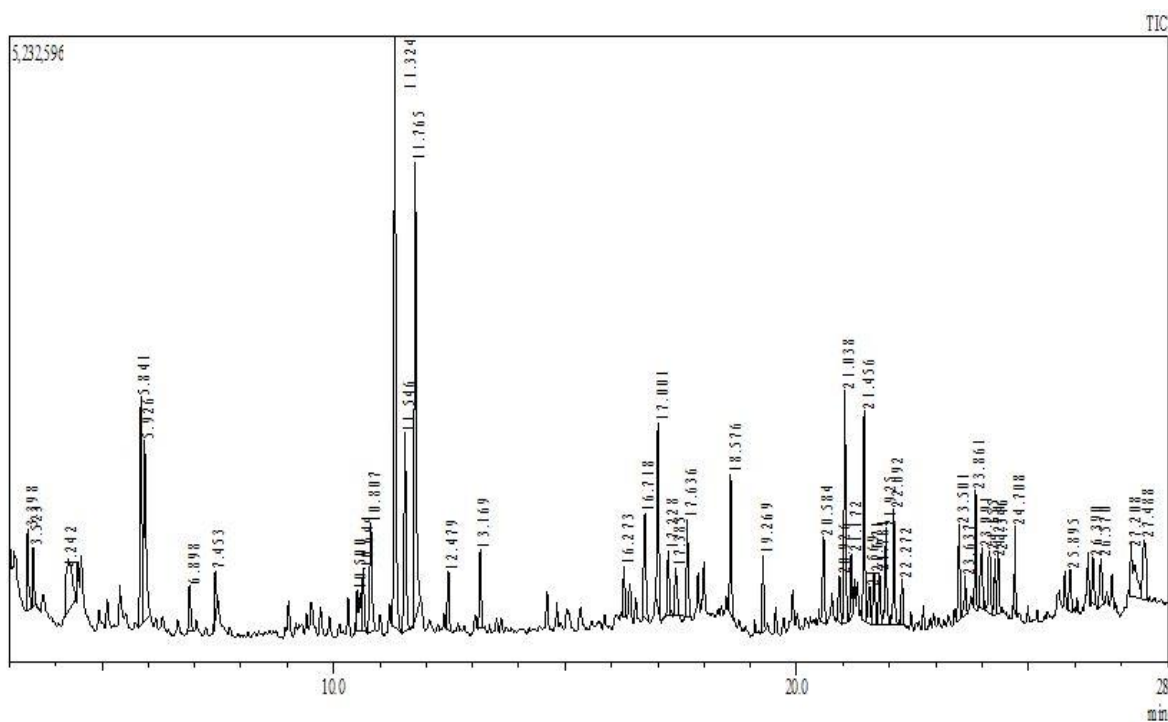


Figure 5.11: Chromatography Analysis of Pyrolytic Oil Derived from Syringe Waste

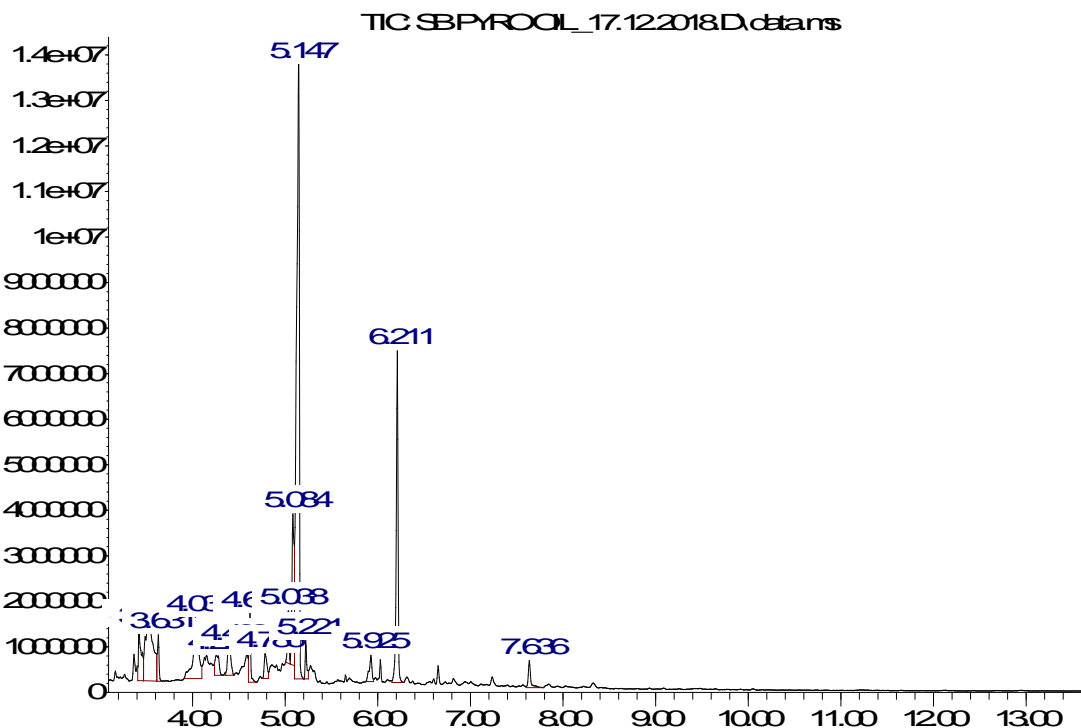
Table 5.9: Composition of Pyrolytic Oil Derived from Syringe Waste

Peak	Retention Time (RT), min	Area (%)	Name of Components
3	4.242	2.84	2-Decene, 4-methyl-, (Z)-
4	5.842	4.86	Isodecyl methacrylate
5	5.925	4.33	2-Undecene, 4,5-dimethyl-, [R*,S*-(Z)]-
6	6.9	0.86	n-Tridecan-1-ol
7	7.45	0.77	(2,4,6-Trimethylcyclohexyl) methanol
8	10.5	1.61	Butyric acid, 2-phenyl-, dec-2-yl ester
9	10.642	1.06	Dodecane, 4,6-dimethyl-
10	10.808	2.44	9-Eicosene, (E)-
11	11.325	10.92	11-Methyldodecanol
12	11.55	4.44	11-Methyldodecanol
13	11.767	8.72	11-Methyldodecanol
14	12.483	1.01	1-Heptanol, 2,4-diethyl-
15	13.167	1.32	Bicyclo[2.2.1]heptane-2,5-dione, 1,7,7-trimethyl-
16	16.273	0.80	Decane, 1-iodo
17	16.718	2.27	2,4 -Di-tert-butylphenol
18	17.001	2.95	1-Decanol, 2-hexyl-
19	17.228	1.11	1-Decanol, 2-hexyl-
20	17.383	0.94	Eicosane
21	17.636	1.84	1-Decanol, 2-hexyl-
22	18.576	2.42	n-Nonenylsuccinic anhydride
23	19.269	1.16	2,5-Cyclohexadien-1-one, 2,6-bis(1,1-dimethyl-)
24	20.584	1.68	Eicosane
25	20.925	1.03	1-Cyclopentyleicosane
26	21.042	3.70	Hexa-triacontyl-trifluoroacetate
27	21.175	1.00	Heptacos-1-ene
28	21.458	3.27	1-Decanol, 2-hexyl-
29	21.567	0.81	Nonadecylpentafluoropropionate
30	21.675	1.08	1-Cyclopentyleicosane

31	21.781	1.02	1-Nonadecene
32	21.925	1.66	1-Decanol, 2-hexyl-
33	22.092	1.77	10-Dodecen-1-ol, 7,11-dimethyl-
34	22.272	0.74	Cyclononasiloxane, octadecamethyl-
35	23.501	1.65	Tetrapentacontane
36	23.633	0.74	Cyclohexane, 1,2,3,5-tetraisopropyl-
37	23.858	1.63	Triacontylheptafluorobutyrate
38	23.991	1.31	11-Methyltricosane
39	24.158	1.52	Octatriacontylpentafluoropropionate
40	24.275	1.02	Ethyl 14-methyl-hexadecanoate
41	24.35	1.11	Cyclohexane, 1,2,3,5-tetraisopropyl-
42	24.708	1.02	Cyclohexane, 1,2,3,5-tetraisopropyl-
43	25.892	0.82	Hexacosylnonyl ether
44	26.392	0.81	Tetrapentacontane, 1,54-dibromo-
45	26.567	1.19	tert-Hexadecanethiol
46	27.208	2.43	Cyclohexane, 1,2,3,5-tetraisopropyl-
47	27.488	1.93	Cyclononasiloxane, octadecamethyl-
48	29.330	1.52	Cyclodecasiloxane, eicosamethyl-
49	31.194	1.40	Cyclodecasiloxane, eicosamethyl-
50	33.140	1.46	Tetracosamethyl-Cyclodecasiloxane

Table 5.9 shows the composition of pyrolytic oil derived from syringe waste. It also shows the most probable compounds allocated and their area percentage compared to the total area of the chromatogram, which gives an idea of their relative concentration in the pyrolytic oil of syringe waste. It is seen from the table that evolved pyrolytic oil have a higher concentrations of some valuable compounds namely Isodecyl methacrylate, 11-Methyldodecanol, Hexa-triacontyl-trifluoroacetate etc. These compounds often used in various industrial applications. Figure 5.12 depicts the Chromatography Analysis of pyrolytic oil derived from saline bottle waste.

Abundance



Time->

Figure 5.12: Chromatography Analysis of Pyrolytic Oil Derived from Saline Bottle Waste

Table 5.10: Composition of Pyrolytic Oil Derived from Saline Bottle Waste

Peak	Retention Time (min)	Area (%)	Name of Components
1	3.419	3.66	.alpha.-Bisabolol oxide B
2	3.51	10.64	1,1,3,3,5,5-HEXAMETHYL-CYCLOHEXASILOXANE
3	3.631	1.68	2-Methyl-5H-dibenz[b,f]azepine
4	4.031	7.29	Oxime-, methoxy-phenyl-
5	4.26	1.81	2-(Dimethylamino)-1,3-dimethyltetrahydro-1,3,2-diazaphosphole 2-oxide
6	4.403	2.32	2-OCTANONE
7	4.62	2.37	Octamethylcyclotetrasiloxane
8	4.786	1.61	Ethylhexanol
9	5.038	1.98	BENZENE, 1,4-BIS(TRIMETHYLSILYL)-
10	5.084	8.21	6 METHYL-2 PHENYLINDOLE

11	5.147	40.11	3,3-Diisopropoxy-1,1,1,5,5,5-hexamethyltrisiloxane
12	5.221	1.39	2,5-Hexanediol, 2,5-dimethyl-
13	5.925	1.62	Benzoic acid
14	6.211	13.81	Perhydro-htx-2-one, 2-depentyl-, acetate ester
15	7.636	1.48	3,4-Dihydroxybenzyl alcohol, tris(trimethylsilyl)-

Table 5.10 shows the composition of pyrolytic oil produced from saline bottle waste. It also shows the most probable compounds allocated and their area percentage compared to the total area of the chromatography, which gives an idea of their relative concentration in the pyrolytic oil of saline bottle waste. It is seen from the table that evolved pyrolytic oil have a higher concentrations of hexamethyl-cyclohexasiloxane, Oxime-, methoxy-phenyl-, 6 methyl-2 phenylindole, 3,3-Diisopropoxy-1,1,1,5,5,5-hexamethyltrisiloxane, Perhydro-htx-2-one, 2-depentyl-, acetate ester etc. These compounds are valuable for various industrial purposes.

5.7 Fourier Transform Infra-Red (FTIR) Spectroscopy

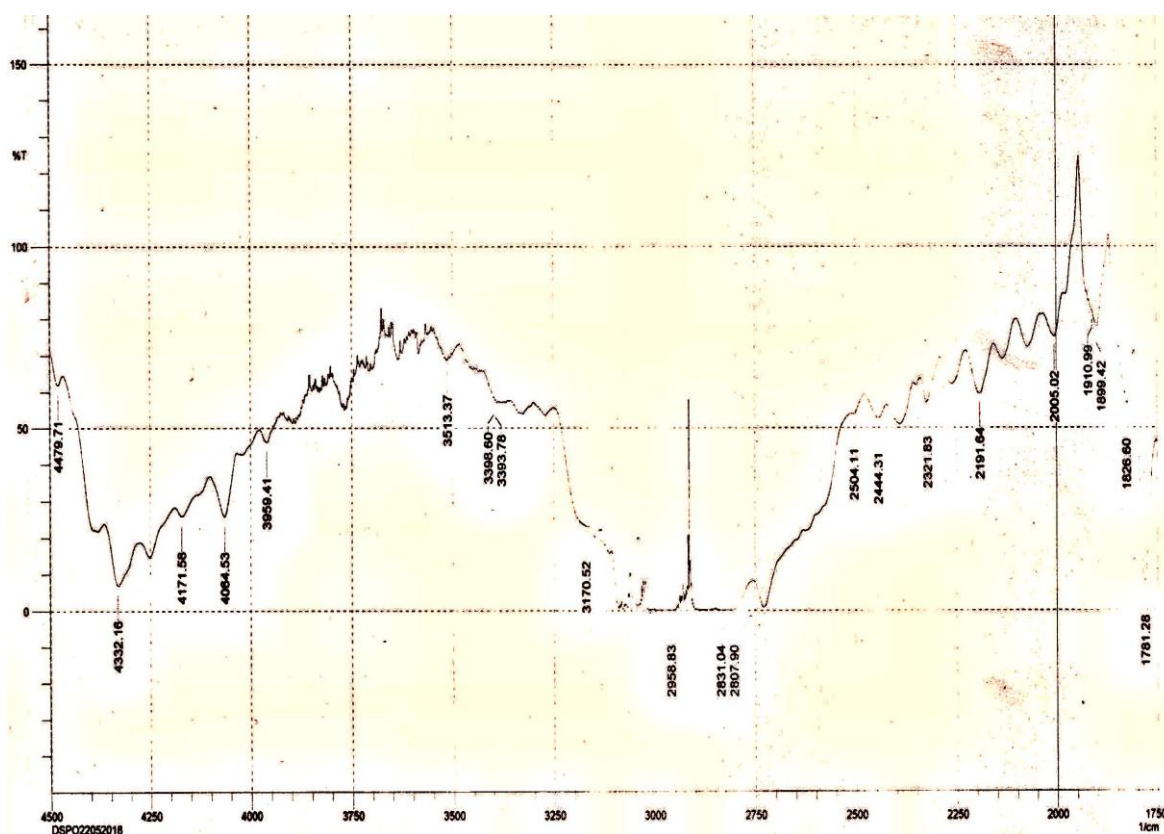
The Fourier transform infra-red spectroscopy (FTIR) provides not only qualitative but also quantitative information about organic and inorganic samples. It determines the class of chemical compounds and associated functional groups. The analysis was conducted at the laboratory of Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka.

For FTIR analysis, Shimadzu IRPrestige-21 ranging from 400- 4500 nm equipped with liquid sample holder having cell thickness of 0.5 mm with NaCl window was used. The sample was injected into the cell and analyzed in the instrument.

The absorption frequency spectra representing the functional group composition analysis of the syringe waste pyrolytic oil is summarized in Table 5.11 and also presented in Figure 5.13.

Table 5.11: FTIR Functional Groups and Indicated Compounds of Pyrolytic Oil Derived from Syringe Waste

Absorbance Range (cm ⁻¹)	Functional Group	Class of Compound	Pyrolytic Oil
4300-4500	C-H	Aliphatic	4332-4479
4050-4200	C-H	Aromatic	4064-4171
3500-3960	O-H	Alcohol, Phenol, Carboxylic acid	3513-3959
3150-3400	N-H	Amines	3170-3398
2850-2960	C-H	Aldehydes	2807-2958
2190-2510	C≡C	Alkynes	2191-2504
1750-2000	C=C	Alkenes	1781-2005



	Peak	Intensity	Corr. Intensity	Base (H)	Base (L)	Area	Corr. Area
1	1781.28	8	50.21	1807.8	1756.2	29	16.47
2	1826.6	56.4	1.69	1829.98	1825.16	1.16	0.04
3	1899.42	77.9	9.95	1910.03	1869.04	2.45	1.01
4	1910.99	82.3	0.58	1918.22	1910.03	0.65	0.02
5	2005.02	75.22	5.97	2017.08	1983.32	3.47	0.63
6	2191.64	59.51	0.35	2226.35	2190.67	6.7	0.06
7	2321.83	57.01	0.48	2322.8	2320.87	0.47	0
8	2444.31	52.72	4.75	2478.07	2423.09	14.16	1.07
9	2504.11	53.83	0.91	2508.45	2478.07	7.6	0.08
10	2807.9	0.01	0.04	2808.86	2805.97	10.31	0.83
11	2831.04	0	0.05	2832.01	2830.56	5.81	1
12	2958.83	0.01	0.07	2959.31	2957.86	4.96	0.55
13	3170.52	23.09	0.42	3245.26	3169.55	35.58	1.77
14	3393.78	57.76	0.1	3397.64	3393.3	1.02	0
15	3398.6	58.41	0.38	3422.71	3397.64	5.19	-0.01
16	3513.37	68.81	0.57	3516.26	3509.51	1.08	0.02
17	3959.41	46.05	0.34	3962.3	3957.48	1.62	0.01
18	4064.53	25.7	14.53	4101.18	4034.15	32.82	6
19	4171.58	25.8	0.2	4186.05	4170.62	8.81	0.03
20	4332.16	6.99	0.25	4365.43	4331.67	27.93	-2.09
21	4479.71	61.77	5.24	4500.45	4469.1	5.82	0.6

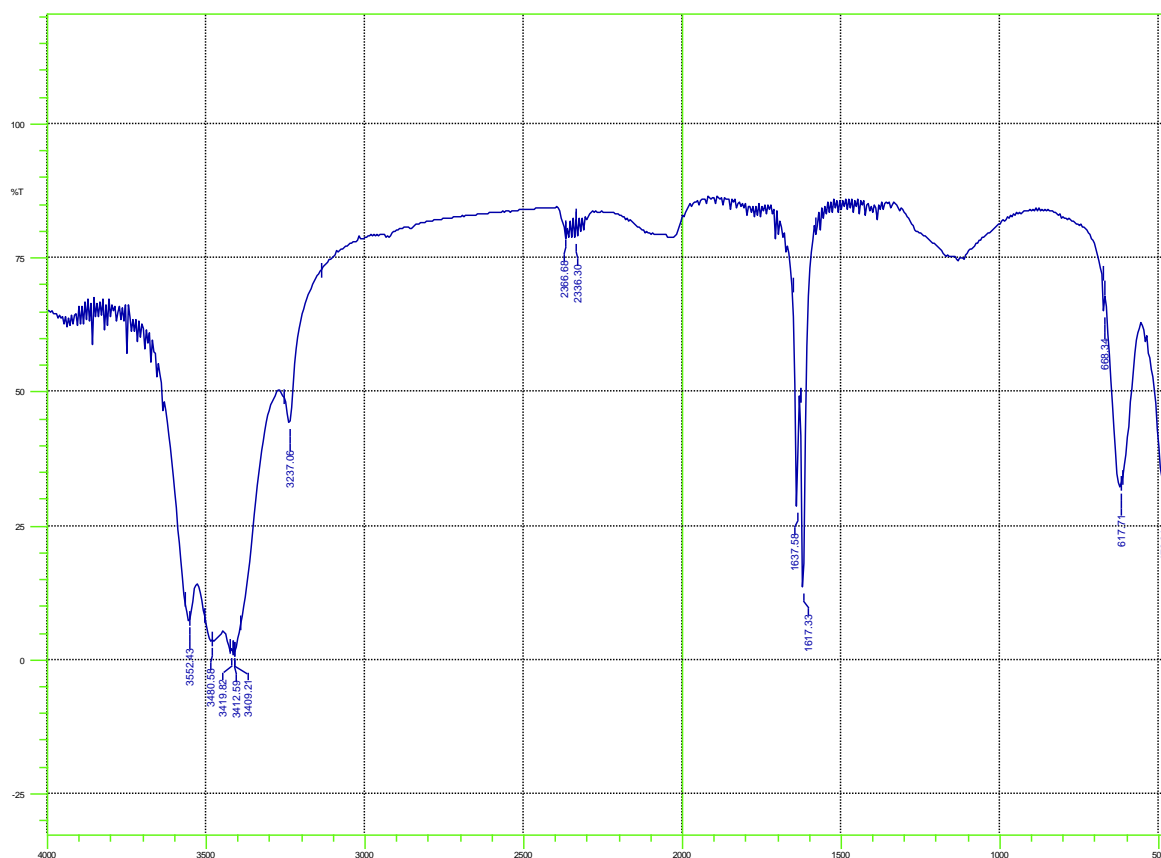
Figure 5.13: FTIR spectra of Pyrolytic Oil Derived from Syringe Waste

The absorbance peak of C=C stretching vibration is between 1781-2005 cm^{-1} and 2191-2504 cm^{-1} indicates the presence of alkenes and alkynes. The absorbance peak for C-H stretching vibration is between 2807-2958 cm^{-1} indicates the presence of aldehydes. N-H stretching vibration is between 3170-3398 cm^{-1} indicates the presence of amines. Absorbance range between 3513-3959 cm^{-1} indicates the presence of primary, secondary and tertiary alcohols, phenol and carboxylic acid. The possible presence of aromatic and aliphatic compounds is indicated by the absorbance peak between 4064-4171 cm^{-1} and 4332-4479 cm^{-1} , presenting C-H aromatic stretching and C-H aliphatic stretching vibration respectively.

The absorption frequency spectra representing the functional group composition analysis of the saline bottle waste pyrolytic oil is summarized in Table 5.12 and also presented in Figure 5.14.

Table 5.12: FTIR Functional Groups and Indicated Compounds of Pyrolytic Oil Derived from Saline Bottle Waste

Absorbance Range (cm ⁻¹)	Functional Group	Class of Compound	Pyrolytic Oil
3450-3550	O-H	Alcohol, Phenol, Carboxylic acid	3480-3552
3200-3420	N-H	Amines	3237-3419
2330-2370	C-H	Aliphatic Nitrites	2336-2366
1600-1650	C=C	Aromatic	1617-1637
450-700	C-H	Alkynes	479-668



No.	Peak	Intensity	Corr. Intensity	Base (H)	Base (L)	Area	Corr. Area
1	479.31	29.641	0.760	482.21	477.87	2.258	0.022
2	617.71	32.344	0.545	618.67	611.44	3.475	0.026
3	668.34	65.072	4.260	675.57	667.86	1.208	0.042
4	1617.33	13.564	43.131	1629.38	1578.27	15.405	5.192
5	1637.58	28.730	27.740	1652.53	1629.38	7.856	2.479
6	2336.30	78.848	3.501	2337.26	2335.33	0.178	0.015
7	2366.68	79.608	0.755	2367.64	2366.19	0.141	0.003
8	3237.06	44.238	8.128	3253.46	3139.17	25.119	-0.524
9	3409.21	1.648	0.242	3409.69	3390.40	28.070	0.231
10	3412.59	1.361	0.538	3416.93	3410.17	12.015	0.425
11	3419.82	1.706	0.435	3424.16	3417.41	11.440	0.205
12	3480.58	3.444	0.492	3502.76	3479.13	31.145	1.294
13	3552.43	7.298	0.769	3565.93	3550.98	15.843	0.428

Figure 5.14: FTIR Spectra of Pyrolytic Oil Derived from Saline Bottle Waste

The absorbance peak of C-H stretching vibration is between 479-668 cm^{-1} indicates the presence of alkynes. The absorbance peak for C-H stretching vibration is between 2336-2366 cm^{-1} , indicates the presence of Aliphatic Nitrites. N-H stretching vibration is between 3237-3419 cm^{-1} indicates the presence of amines. Absorbance range between 3480-3552 cm^{-1} indicates the presence of primary, secondary and tertiary alcohols, phenol and carboxylic acid. The possible presence of aromatic compounds is indicated by the absorbance peak between 1617-1637 cm^{-1} .

5.8 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) is a technique in which the temperature increases at a constant rate and the mass of the heated sample is measured over a period of time. This analysis gives information about both physical and chemical phenomena, for example, phase transitions, adsorption, absorption, chemisorptions, solid-gas reactions and thermal decomposition [110]. The analysis was conducted at the laboratory of Centre for Advanced Research in Sciences (CARS), University of Dhaka. The TGA spectra of the syringe waste pyrolytic oil are summarized in Table 5.13 and presented in Figure 5.15.

Table 5.13: TGA Spectra of Pyrolytic Oil Derived from Syringe Waste

Observation No.	Heating Rate (°C/min)	Flow Rate (mL/min)	Sample Weight (mg)	Time (min)	Yield of Volatile (%)	Range of Degredation (°C)	Temperature (T _{max}) (°C)
1	10	10	3.348	0.01	99.99	24.44	600
2				5.56	70.29	85.50	600
3				11.48	37.47	144.01	600
4				19.87	14.15	227.17	600
5				57.06	9.42	599.41	600

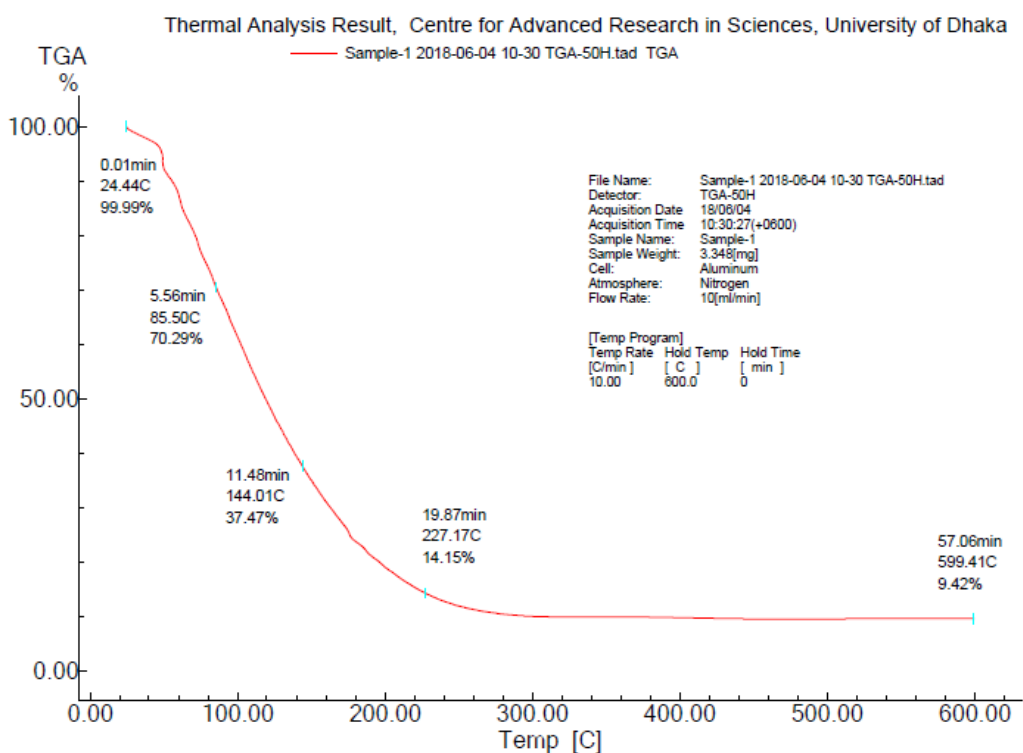


Figure 5.15: TGA of Pyrolytic Oil Derived from Syringe Waste

The experiment with nitrogen flow rate of 10 mL/min has been conducted within the heating range (24°C – 600°C) while the heating rate was 10°C/min. The weight of the sample was 3.348 mg. The pyrolysis had taken place in the temperature range from ≈25°C to ≈550°C. This method was used to measure the weight loss of the sample and kinetic parameters. Thermogravimetric analysis of syringe waste pyrolysis involves the thermal degradation of the pyrolytic oil in an inert atmosphere measuring the weight loss values of the pyrolytic oils with increasing temperature at a constant heating rate simultaneously.

The purpose of this experiment was to evaluate the thermal behavior of pyrolytic oil produced from syringe waste under certain pyrolysis conditions. The temperature ranges for pyrolysis of syringe waste pyrolytic oil overlap at temperatures from 150 to 200°C. From this temperature the experimental curve of weight loss lays over the theoretical one, decreasing abruptly the difference up to 250°C and slightly decreasing at higher temperatures. The facts described above are more accurately observed in the rate of weight loss. The experimental curve is higher from 150°C to 250°C, when the rate of weight loss of syringe waste pyrolytic oil is higher.

The TGA spectra of the saline bottle waste pyrolytic oil are summerized in Table 5.14 and presented in Figure 5.16.

Table 5.14: TGA Spectra of Pyrolytic Oil Derived from Saline Bottle Waste

Observation No.	Heating Rate (°C/min)	Flow Rate (mL/min)	Sample Weight (mg)	Time (min)	Yield of Volatile (%)	Range of Degredation (°C)	Temperature (T _{max}) (°C)
1	10	10	3.348	0.01	100	28.19	600
2				5.58	91.57	81.73	600
3				14.55	46.09	171.51	600
4				25.69	8.75	282.38	600
5				44.36	1.91	469.64	600
6				57.42	0.80	599.61	600

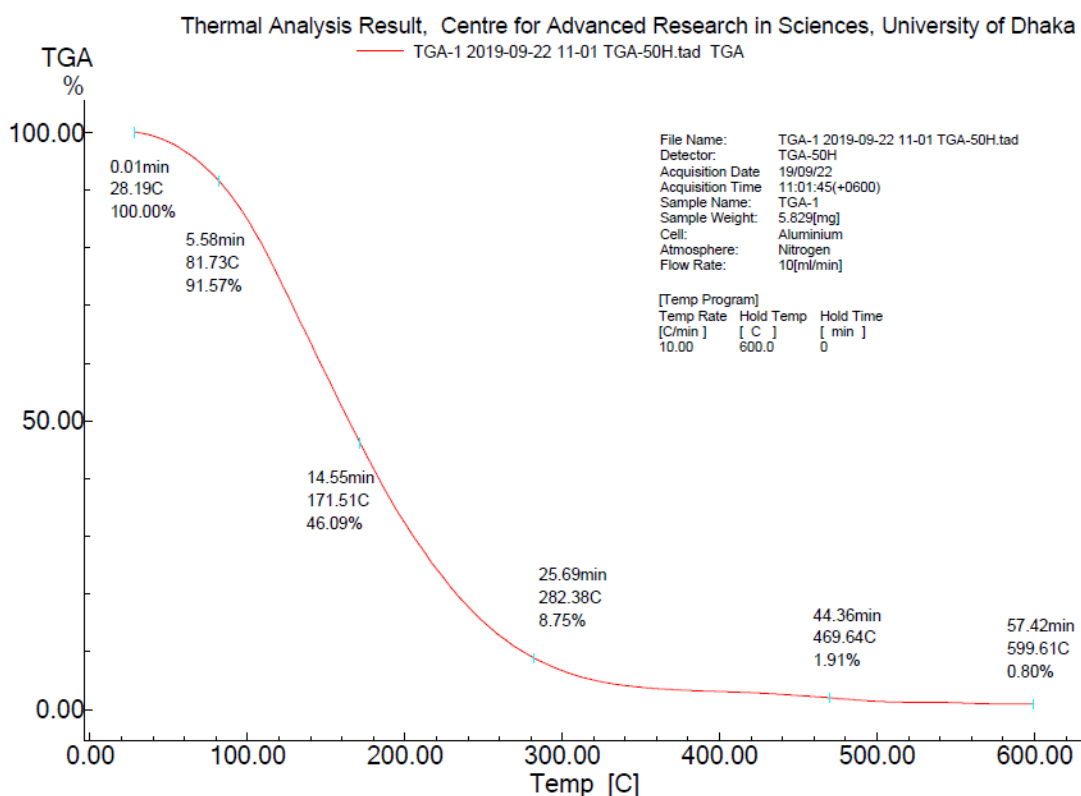


Figure 5.16: TGA of Pyrolytic Oil Derived from Saline Bottle Waste

The experiment i.e., TGA has been conducted within the heating range ($28^{\circ}\text{C} - 600^{\circ}\text{C}$) while the heating rate was $10^{\circ}\text{C}/\text{min}$. Nitrogen flow rate was $10\text{mL}/\text{min}$ and the weight of the sample was 5.829 mg . The pyrolysis had taken place in the range from $\approx 25^{\circ}\text{C}$ to $\approx 550^{\circ}\text{C}$. The temperature ranges for pyrolysis of saline bottle waste pyrolytic oil overlap at temperatures from 200 to 250°C . From this temperature the experimental curve of weight loss lays over the theoretical one, decreasing abruptly the difference up to 300°C and slightly decreasing at higher temperatures. The facts described above are more accurately observed in the rate of weight loss. The experimental curve shows a very sharp decrease within the range of 150°C to 250°C , when the rate of weight loss of saline bottle waste pyrolytic oil is higher.

The boiling point distribution of pyrolytic oils derived from syringe and saline bottle waste is presented in Figure 5.17 and comparison with diesel fuel [111] is also presented in the same figure.

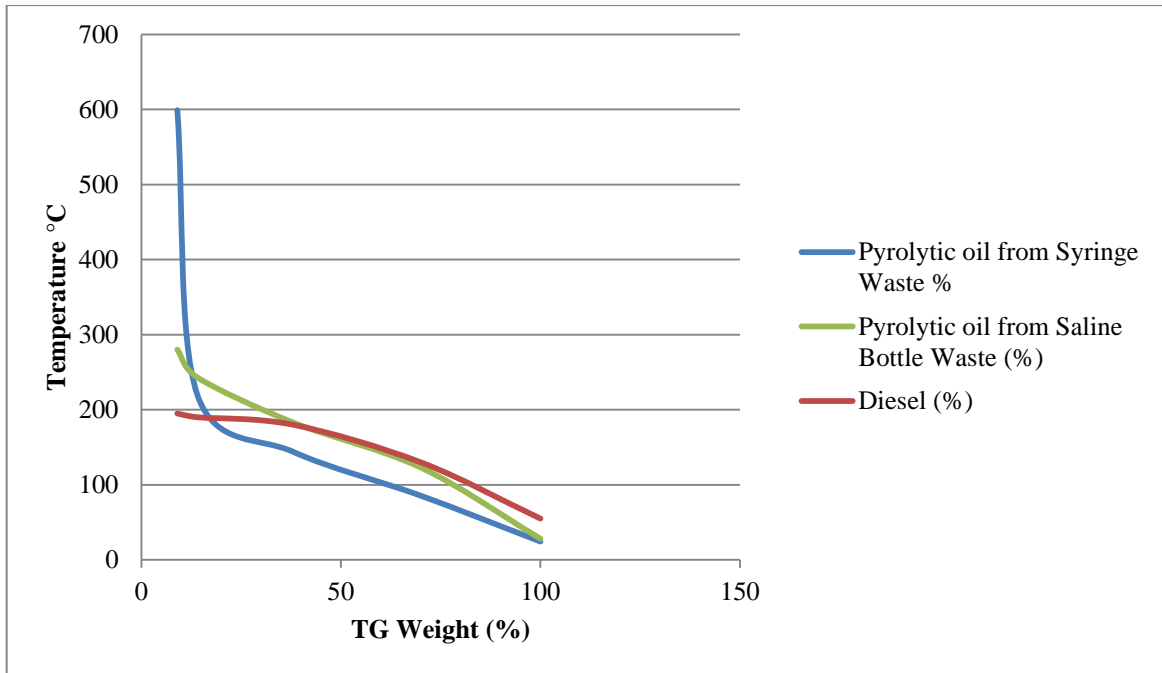


Figure 5.17: Boiling Point Distribution of Pyrolytic Oils Compared to Diesel Fuel

It is seen from Figure 5.17 that the boiling point of pyrolytic oil derived from syringe waste is higher than that of diesel fuel up to 16% by weight. For the rest 84%, it has lower boiling point than that of diesel fuel. However, the boiling point of pyrolytic oil derived from saline bottle waste is higher than that of diesel fuel up to 35% by weight. For the rest 65%, it has lower boiling point than that of diesel fuel.

5.9 Rate of Energy Recovery

Recovery of energy from waste means the transformation of non-recyclable waste into utilizable thermal energy, electricity or fuel by applying various types of methods such as combustion, gasification, pyrolysis, etc. [112]. The rate of energy recovery indicates how much energy can be extracted from any particular waste after the energy recovery process applied.

GCV of syringe waste and saline bottle waste in different states (i.e., raw waste, pyrolytic oil and char) were measured. The following section describes the rate of energy recovery from pyrolysis of syringe and saline bottle waste.

Syringe Waste

Gross Calorific Value of raw syringe waste, pyrolytic oil derived from syringe waste and pyrolytic char derived from syringe waste is presented in Table 5.15

Table 5.15: Heating Value of Raw Syringe Waste, Pyrolytic Oil from Syringe Waste and Pyrolytic Char

	Raw Syringe Waste	Pyrolytic Oil Derived from Syringe Waste	Pyrolytic Char Derived from Syringe Waste
Gross Calorific Value (GCV) in MJ/kg	41.06	41.519	42.737

From Table 5.15 it is found that the calorific value of evolved pyrolytic oil and char is slightly higher than the calorific value of raw syringe waste. The reason may be loss of some volatiles from raw waste.

Saline Bottle Waste

Gross Calorific Value of raw saline bottle waste, pyrolytic oil derived from saline bottle waste and pyrolytic char derived from saline waste is presented in Table 5.16

Table 5.16: Heating Value of Raw Saline Bottle Waste, Pyrolytic Oil from Saline Bottle Waste and Pyrolytic Char

	Raw Saline Bottle Waste	Pyrolytic oil derived from Saline Bottle Waste	Pyrolytic char derived from Saline bottle Waste
Gross Calorific Value (GCV) in MJ/kg	43.31	43.578	43.319

From Table 5.16 it is found that the calorific value of evolved pyrolytic oil is slightly higher than the calorific value of raw saline bottle waste but the GCV of raw waste and char is comparable.

5.10 Cost Analysis for Present Project

The total cost such as capital cost, operating cost and payback period for present project as pyrolysis of syringe and saline bottle waste are given below:

5.10.1 Capital Costs

Capital costs are one-time expenditures spend for purchasing land, establishments, infrastructures and equipment used in the manufacturing of any goods or services. The cost analysis is based on the assumptions of equipment expected life of 5 years and 3 (three) runs per day and 280 working days per year. The details of capital cost are summarized in Table 5.17.

Table 5.17: Components of Capital Costs

Name of material	Amount taken	Unit Price Tk.	Total Cost (Tk.)
Reactor construction cost	1 pc	10,000/=	10,000/=
Electrical heater	20 pcs	1,500/=	30,000/=
Thermocouple wire with Temperature Indicator	3 pcs	1,200/=	3,600/=
Asbestos ropes and Blanket	1.5 kg	200/=	300/=
MS angle	Lump Sum	---	1,000/=
Condenser coil (copper tube)	1 Coil	3,200/=	3,200/=
Condenser Arrangement	1 pc	1,500/=	1,500/=
Fabrication cost	Lump Sum	---	500/=
Total Capital Cost for 5 years=			50,100/=
Total Capital Cost (per year) = $(50,100 \div 5)$ =			10,020/=

5.10.2 Operating Costs

Operating costs are the expenditures spend for running a business or buying and operating a device, component or facility. Operating cost per day is given below:

Waste Syringe/saline bottle: 4.5kg @ Tk.20 = Tk. (4.5×20) = Tk.90

Total Electricity required for pyrolysis of 4.5 kg syringe/saline bottle waste: 9.0 kWh

Charge for electricity @ Tk. 5 per kWh: Tk. (5×9) = Tk. 45

Labor cost: 6 hrs. @ Tk. 75 per hr. = Tk. (6×75) = Tk. 450

Charge for Nitrogen Gas for each run @ Tk.10 per day cost: Tk. (3×10) = Tk. 30

Miscellaneous lump sum = Tk. 60

Total operating cost per day: Tk. (90+45+450+30+60) = Tk. 675

Total annual operating cost: Tk. (280×675) = Tk.1,89,000

Total Cost (per year): Total Annual Capital Cost + Total Annual operating cost
= Tk. (10,020+1, 89,000) = Tk. 1,99,020

Total Cost for 5 Years = Tk. (1, 99,020×5) = Tk. 9,95,100

5.10.3 Payback Period

Payback period is the amount of time in which the initial cost of an investment is expected to be recovered. Thus,

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Cash Inflow per Period}}$$

Calculation:

Operation time: 2 hrs. per batch and 3 batches per day

Yield of oil per batches = 0.539 kg (syringe waste) (sample size 2×2 cm at 250°C)

Yield of oil per batches = 0.542 kg (saline bottle waste) (sample size 2×2 cm at 250°C)

Annual product yield for syringe waste = 0.539 kg/run × 3 run /day × 280 days/ yr
= 452.76 kg/yr

Annual product yield for saline bottle waste = 0.542 kg/run × 3 run /day × 280 days/ yr
= 455.28 kg/yr

Price of diesel oil = Tk. 65/litre (0.832 kg), as of December, 2019 (assuming that the price of pyrolytic oils derived from syringe and saline bottle waste is similar to diesel oil)

Total annual value of product (syringe waste) = Tk. (452.76 × 78.13) = Tk. 35,374.14

Total annual value of product (saline bottle waste) = Tk. (455.28 × 78.13) = Tk. 35,571.03

Payback period for syringe waste = (1, 99,020) / (35,374.14) = 5.63 yrs.

Payback period for saline bottle waste = (1, 99,020) / (35, 571.03) = 5.59 yrs.

Based on present calculation, the payback period is more than that of plant life. If the capacity of the plant is in large scale then it may be possible to operate. On the other hand some environmental issues are vital factors for the consideration of operating cost. Syringe/saline bottle waste is increasing day by day and it has been dumped in open places. Dumped waste syringe/saline bottle is one of the suitable places for the reproduction of disease carrying mosquitoes and other insects as rain water can easily deposited into the syringe/saline bottle. So, if the environmental issues are considered for operating cost, it could be possible.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Pyrolysis of syringe and saline bottle waste has been conducted to convert these wastes into solid, liquid and gaseous products. From this study within the range of experimental limitations and also from the analysis of pyrolytic oil and char the following conclusions could be made.

- i. The maximum production of pyrolytic oil from waste syringe was 35.94% (by weight) at a temperature of 250°C and the maximum production of pyrolytic char from waste syringe was 51.08% (by weight) at a temperature of 150°C for loading of 1.5 kg raw materials.
- ii. The maximum production of pyrolytic oil from saline bottle waste was 36.14% (by weight) at a temperature of 250°C and the maximum production of pyrolytic char from saline bottle waste was 51.15% (by weight) at a temperature of 150°C for loading of 1.5 kg raw materials.
- iii. Pyrolysis could reduce the difficulty of disposing waste syringes and saline bottles. At the same time, it could be a source of alternative energy and chemicals. The pyrolytic oil, thus obtained, may be a supplement to depleting fossil fuels.
- iv. The calorific value of pyrolytic oil derived from syringe and saline bottle waste is about 41.5 MJ/kg and 43.6 MJ/kg respectively.
- v. The calorific value of pyrolytic char derived from syringe and saline bottle waste is about 42.7 MJ/kg and 43.3 MJ/kg respectively.
- vi. The GC-MS analysis of pyrolytic oil from both syringe and saline bottle waste shows the presence of useful chemical compounds.
- vii. The FTIR test indicates noticeable amount of aromatic compounds in both syringe and saline bottle waste pyrolytic oil.
- viii. The liquid pyrolytic oil derived from both syringe and saline bottle waste could be used as low grade fuel and could be a supplement to diesel oil.

- ix. Solid char obtained from syringe and saline bottle waste could also be used as fuel after making them solid lump by mixing with some kind of binder or can be utilized as activated carbon.

Taking into consideration for all these findings, it could be concluded that pyrolytic oil and char obtained from pyrolysis of syringe and saline bottle wastes can be utilized as substitute fuel or chemical feedstock after some treatment. Pyrolysis of syringe and saline bottle waste also decreases the environmental vulnerabilities resulting from the unmanaged disposal of such waste.

6.2 Recommendations for Future work

A better experimental setup could be constructed to get improved quality and greater amount of products. Some recommendations for further studies are pointed below.

- i. The best possible temperature for pyrolysis could be found by conducting experiments with some higher temperatures and smaller intervals.
- ii. Catalysts could be used to achieve better performance and products.
- iii. More efficient fractionating columns could be added for the separation of pyrolysis oil into different fractionates.
- iv. Optimization of the process to accomplish a cost-effective and eco-friendly method could be achieved.
- v. Sustainable management system for health-care waste could be established.

REFERENCES

1. Panda, A. K., Singh, R. K. and Mishra, D. K., 2010, "Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products-A world prospective", *Journal of Renewable and Sustainable Energy Reviews*, Vol. 14(1), pp. 233-248.
2. [Online]. Available at: <https://www.alternative-energy-news.info/waste-renewable-energy-source/>
3. Cheng, Y. W., Sung, F. C., Yang, Y., Lo, Y. H., Chung, Y. T. and Li, K. C., 2009, "Medical waste production at hospitals and associated factors", *Journal of Waste Management*, Vol. 29(1), pp. 440-444.
4. [Online]. Available at: <https://www.bioenergyconsult.com/medical-waste-management/>
5. Bangladesh, P.R.I.S.M., 2005, "Survey report on hospital waste management in Dhaka city", Unpublished Report Dhaka: PRISM Bangladesh.
6. Som, U., Rahman, F., Hossain, S., 2018, "Recovery of Pyrolytic Oil from Thermal Pyrolysis of Medical Waste", *Journal of Engineering Sciences*, Vol. 5(2), pp. H5-H8.
7. [Online]. Available at: <https://www.euractiv.com/section/energy-environment/opinion/chemical-recycling-of-plastic-waste-no-more/>
8. Lopez, A., De Marco, I., Caballero, B. M., Laresgoiti, M. F. and Adrados, A., 2011, "Influence of time and temperature on pyrolysis of plastic wastes in a semi-batch reactor", *Journal of Chemical Engineering*, Vol. 173(1), pp. 62-71.
9. Howell, S. G., 1992, "A ten year review of plastics recycling", *Journal of Hazardous Materials*, Vol. 29(2), pp. 143-164.
10. Lerner, B. J., 1997, "Prevention of dioxin formation in medical waste incineration", *AIR & WASTE MANAGEMENT ASSOC, PITTSBURGH, PA, (USA)*, Vol. 6, p. 1997.
11. Helmenstine, A. M., 2019, "Plastic Definition and Examples in Chemistry", *ThoughtCo*, Jul. 8, [thoughtco.com/plastic-chemical-composition-608930](https://www.thoughtco.com/plastic-chemical-composition-608930).
12. [Online]. Available at: <https://www.qualitylogoproducts.com/promo-university/different-types-of-plastic.htm>

13. [Online]. Available at: <https://repurpose.global/the-7-types-of-plastics-explained/>
14. [Online]. Available at: <http://www.recoup.org/p/36/main-types-and-sources-of-plastic>
15. Prüss-Üstün, A. and Townend, W. K., 1999, "Safe management of wastes from health-care activities", World Health Organization (WHO).
16. Ferdowsi, A., Ferdosi, M., Mehrani, Z. and Narenjkar, P., 2012, "Certain hospital waste management practices in Isfahan, Iran", *International journal of Preventive Medicine*, Vol. 3(Suppl1), p. S176.
17. [Online]. Available at: <http://www.ojhas.org/issue3/2002-3-3.htm>, 2015-08-15
18. Altin, S., Altin, A., Elevli, B. and Cerit, O. R. H. A. N., 2003, "Determination of hospital waste composition and disposal methods: a case study", *Polish Journal of Environmental Studies*, Vol. 12(2), pp. 251-255.
19. Komilis, D. P., 2016, "Issues on medical waste management research" *Journal of Waste Management*, Vol. 100(48), pp. 1-2.
20. Patwary, M. A., O'Hare, W. T., Street, G., Elahi, K. M., Hossain, S. S. and Sarker, M. H., 2009, "Quantitative assessment of medical waste generation in the capital city of Bangladesh" *Journal of Waste management*, Vol. 29(8), pp. 2392-2397.
21. Mbongwe, B., Mmereki, B. T. and Magashula, A., 2008, "Healthcare waste management: current practices in selected healthcare facilities, Botswana", *Journal of Waste Management*, Vol. 28(1), pp. 226-233.
22. Canadian Senate Committee, 2002, "The Health of Canadians e Part VII: Financing Reform", Parliament of Canada, Ottawa.
23. Sarkar, S. K., Haque, M. A. and Khan, T. A., 2006, "Hospital waste management in Sylhet city", *Journal of Engineering and Applied Sciences*, Vol. 1(2), pp. 32-40.
24. Rabeie, O. L., Miranzadeh, M. B., Fallah, S. H., Dehqan, S., Moulana, Z., Amouei, A., Mohammadi, A. A., Asgharnia, H. A. and Babaie, M., 2012, "Determination of hospital waste composition and management in Amol city, Iran", *Journal of Health Scope*, Vol. 1(3), pp. 127-131.
25. Patil, A. D. and Shekdar, A. V., 2001, "Health-care waste management in India", *Journal of Environmental Management*, Vol. 63(2), pp. 211-220.
26. Windfeld, E. S. and Brooks, M. S. L., 2015, "Medical waste management—A

- review”, *Journal of environmental management*, Vol. 163, pp. 98-108.
27. Ananth, A. P., Prashanthini, V. and Visvanathan, C., 2010, “Healthcare waste management in Asia”, *Journal of Waste Management*, Vol. 30(1), pp. 154-161.
 28. Adsavakulchai, S., 2002, “Study on waste from hospital and clinics in Phitsanulok”, *Online Journal of Health and Allied Sciences*, Vol. 1(3), pp. 6-14.
 29. Bazrafshan, E. and Kord Mostafapoor, F., 2011, “Survey of medical waste characterization and management in Iran: a case study of Sistan and Baluchestan Province”, *Journal of Waste Management & Research*, Vol. 29(4), pp. 442-450.
 30. Phengxay, S., Okumura, J., Miyoshi, M., Sakisaka, K., Kuroiwa, C. and Phengxay, M., 2005, “Health-care waste management in Lao PDR: a case study”, *Journal of Waste Management & Research*, Vol. 23(6), pp. 571-581.
 31. Yong, Z., Gang, X., Guanxing, W., Tao, Z. and Dawei, J., 2009, “Medical waste management in China: A case study of Nanjing”, *Journal of Waste management*, Vol. 29(4), pp. 1376-1382.
 32. Gai, R., Kuroiwa, C., Xu, L., Wang, X., Zhang, Y., Li, H., Zhou, C., He, J., Tang, W., Kuroiwa, C. and Tang, W., 2009, “Hospital medical waste management in Shandong Province, China”, *Journal of Waste management & research*, Vol. 27(4), pp. 336-342.
 33. Hossain, M. S., Santhanam, A., Norulaini, N. N. and Omar, A. M., 2011, “Clinical solid waste management practices and its impact on human health and environment-A review”, *Journal of Waste management*, Vol. 31(4), pp. 754-766.
 34. Eker, H. H. and Bilgili, M. S., 2011, “Statistical analysis of waste generation in healthcare services: a case study”, *Journal of Waste Management & Research*, Vol. 29(8), pp. 791-796.
 35. Rahman, S. A., Akid, A. S. M., Majumder, M. and Khair, S., 2013, “Scenario of Clinical Waste Management: A Case Study in Khulna City”, *Global Journal of Research In Engineering*, Vol. 13(8), Version 1.0.
 36. Rahman, M. S., Moumita, C. and Rikta, K., 2013, “Medical Waste Management System: An Alarming Threat (A Case Study on Jessore Municipality, Bangladesh)”, *Journal of Environmental Science and Natural Resources*, Vol. 6(2), pp. 181-189.
 37. Alam, M. Z., Islam, M. S. and Islam, M. R., 2013, “Medical Waste Management: A Case Study on Rajshahi City Corporation in Bangladesh”, *Journal of*

- Environmental Science and Natural Resources, Vol. 6(1), pp. 173-178.
38. Lin, J. H., Pan, Y. J., Liu, C. F., Huang, C. L., Hsieh, C. T., Chen, C. K., Lin, Z. I. and Lou, C. W., 2015, "Preparation and compatibility evaluation of polypropylene/high density polyethylene polyblends", *Journal of Materials*, Vol. 8(12), pp. 8850-8859.
 39. Shui, S., 2017, "Pyrolysis of medical waste and the pyro gas combustion system", degree project in materials science and engineering, Stockholm, Sweden, KTH Royal Institute of Technology.
 40. Williams, E. A. and Williams, P. T., 1997, "Analysis of products derived from the fast pyrolysis of plastic waste", *Journal of Analytical and Applied Pyrolysis*, Vol. 40, pp. 347-363.
 41. Conesa, J. A., Font, R., Marcilla, A. and Garcia, A. N., 1994, "Pyrolysis of polyethylene in a fluidized bed reactor", *Journal of Energy & Fuels*, Vol. 8(6), pp. 1238-1246.
 42. [Online]. Available at: <https://www.sciencedirect.com/topics/engineering/proximate-analysis>
 43. [Online]. Available at: https://en.wikipedia.org/wiki/Gross_calorific_value
 44. [Online]. Available at: <https://en.wikipedia.org/wiki/Density>
 45. [Online]. Available at: http://www.softschools.com/formulas/physics/kinematic_viscosity_formula/472/
 46. [Online]. Available at: https://en.wikipedia.org/wiki/Pour_point
 47. [Online]. Available at: https://en.wikipedia.org/wiki/Boiling_point
 48. [Online]. Available at: <https://www.definitions.net/definition/cloud+point>
 49. [Online]. Available at: https://en.wikipedia.org/wiki/Gas_chromatography%20%93mass_spectrometry
 50. [Online]. Available at: https://en.wikipedia.org/wiki/Fourier-transform_infrared_spectroscopy
 51. [Online]. Available at: <https://www.sciencedirect.com/topics/materials-science/thermogravimetric-analysis>
 52. [Online]. Available at: <https://www.sciencedirect.com/topics/engineering/fixed-capital-investment>
 53. Rutala, W. A. and Mayhall, C. G., 1992, "Medical Waste", *Journal of Infection Control and Hospital Epidemiology*, Vol. 13(1), pp. 38-48.

54. Li, C. S. and Jenq, F. T., 1993, "Physical and chemical composition of hospital waste", *Journal of Infection Control & Hospital Epidemiology*, Vol. 14(3), pp. 145-150.
55. Lee, B. K., Ellenbecker, M. J. and Moure-Eraso, R., 2002, "Analyses of the recycling potential of medical plastic wastes", *Journal of Waste management*, Vol. 22(5), pp. 461-470.
56. Deng, N., Zhang, Y. F. and Wang, Y., 2008, "Thermogravimetric analysis and kinetic study on pyrolysis of representative medical waste composition", *Journal of Waste Management*, Vol. 28(9), pp. 1572-1580.
57. Zhu, H. M., Yan, J. H., Jiang, X. G., Lai, Y. E. and Cen, K. F., 2008, "Study on pyrolysis of typical medical waste materials by using TG-FTIR analysis", *Journal of Hazardous Materials*, Vol. 153(1-2), pp. 670-676.
58. Marcilla, A., Beltrán, M. I. and Navarro, R., 2009, "Thermal and catalytic pyrolysis of polyethylene over HZSM5 and HUSY zeolites in a batch reactor under dynamic conditions", *Journal of Applied Catalysis B: Environmental*, Vol. 86(1-2), pp. 78-86.
59. Syed, E. H., Mutahara, M. and Rahman, M., 2012, "Medical waste management (MWM) in Dhaka, Bangladesh: it's a review", *Journal of Home Health Care Management & Practice*, Vol. 24(3), pp. 140-145.
60. Subramani, T., Anitha, P. and Sekar, S., 2014, "Health-care waste management system", *International Journal of Engineering Research and Applications*, Vol. 4(6), pp. 255-258.
61. Dash, A., Kumar, S. and Singh, R. K., 2015, "Thermolysis of medical waste (Waste Syringe) to liquid fuel using semi batch reactor", *Journal of Waste and Biomass Valorization*, Vol. 6(4), pp. 507-514.
62. Minoglou, M., Gerassimidou, S. and Komilis, D., 2017, "Healthcare waste generation worldwide and its dependence on socio-economic and environmental factors", *Journal of Sustainability*, Vol. 9(2), p. 220.
63. Pramanik, H. and Gaurh, P., 2019, "Production and characterization of pyrolysis oil using waste polyethylene in a semi batch reactor", *Indian Journal of Chemical Technology (IJCT)*, Vol. 25(4), pp. 336-344.
64. [Online]. Available at: https://en.wikipedia.org/wiki/Pyrolysis#Liquid_and_gaseous_biofuels

65. [Online]. Available at: <http://www.fao.org/docrep/T4470E/t4470e0a.htm>
66. Salman, Z., 2009, "Biomass Pyrolysis". Available at: <https://www.altenergymag.com/article/2009/02/biomass-pyrolysis/502/>
67. Abbas-Abadi, M. S., Haghghi, M. N. and Yeganeh, H., 2012, "The effect of temperature, catalyst, different carrier gases and stirrer on the produced transportation hydrocarbons of LLDPE degradation in a stirred reactor", *Journal of Analytical and Applied Pyrolysis*, Vol. 95, pp. 198-204.
68. Demirbas, A., 2004, "Pyrolysis of municipal plastic wastes for recovery of gasoline- range hydrocarbons", *Journal of Analytical and Applied Pyrolysis*, Vol. 72 (1), pp. 97-102.
69. López, A., De Marco, I., Caballero, B. M., Adrados, A. and Laresgoiti, M. F., 2011, "Deactivation and regeneration of ZSM-5 zeolite in catalytic pyrolysis of plastic wastes", *Journal of Waste management*, Vol. 31(8), pp. 1852-1858.
70. López, A., de Marco, I., Caballero, B. M., Laresgoiti, M. F. and Adrados, A., 2010, "Pyrolysis of municipal plastic wastes: Influence of raw material composition", *Journal of Waste Management*, Vol. 30(4), pp. 620-627.
71. Lopez-Urionabarrenechea, A., De Marco, I., Caballero, B. M., Laresgoiti, M. F. and Adrados, A., 2012, "Catalytic stepwise pyrolysis of packaging plastic waste", *Journal of Analytical and Applied pyrolysis*, Vol. 96, pp. 54-62.
72. Donaj, P. J., Kaminsky, W., Buzeto, F. and Yang, W., 2012, "Pyrolysis of polyolefins for increasing the yield of monomers' recovery", *Journal of Waste Management*, Vol. 32 (5), pp. 840-846.
73. [Online]. Available at: [https://en.wikipedia.org/wiki/Cracking_\(chemistry\)](https://en.wikipedia.org/wiki/Cracking_(chemistry))
74. [Online]. Available at: <http://www.prior-scientific.co.uk/chemical-reactions-of-alkanes/>
75. [Online]. Available at: https://en.wikipedia.org/wiki/Fluid_catalytic_cracking
76. [Online]. Available at: <https://www.explainthatstuff.com/zeolites.html>
77. [Online]. Available at: https://en.wikipedia.org/wiki/Catalytic_reforming
78. [Online]. Available at: <https://www.sciencedirect.com/topics/engineering/reformats>
79. [Online]. Available at: <https://www.sciencedirect.com/topics/engineering/catalytic-pyrolysis>
80. Williams, P. T., Elbaba, I. F., Wu, C. and Onwudili, J. A., 2010, November,

- “High yield hydrogen from the pyrolysis-catalytic gasification of waste tyres”, In 3rd International Symposium on Energy from biomass and waste, Venice, Italy (pp. 8-11).
81. Islam, M. R., Parveen, M., Haniu, H. and Sarker, M. I., 2010, “Innovation in pyrolysis technology for management of scrap tire: a solution of energy and environment”, *International Journal of Environmental Science and Development*, Vol. 1(1), pp. 89-96.
 82. Cleetus, C., Thomas, S. and Varghese, S., 2013, “Synthesis of petroleum-based fuel from waste plastics and performance analysis in a CI engine”, *Journal of Energy*, Vol. 2013, pp. 1-10.
 83. Williams, P. T. and Brindle, A. J., 2002, “Catalytic pyrolysis of tyres: influence of catalyst temperature”, *Journal of Fuel*, Vol. 81(18), pp. 2425-2434.
 84. Williams, P. T. and Brindle, A. J., 2003, “Aromatic chemicals from the catalytic pyrolysis of scrap tyres”, *Journal of Analytical and Applied Pyrolysis*, Vol. 67(1), pp. 143-164.
 85. Jouhara, H., Nannou, T. K., Anguilano, L., Ghazal, H. and Spencer, N., 2017, “Heat pipe based municipal waste treatment unit for home energy recovery”, *Journal of Energy*, Vol. 139, pp. 1210-1230.
 86. Williams, P. T. and Besler, S., 1996, “The influence of temperature and heating rate on the slow pyrolysis of biomass”, *Journal of Renewable energy*, Vol. 7(3), pp. 233-250.
 87. Jung, S. H., Cho, M. H., Kang, B. S. and Kim, J. S., 2010, “Pyrolysis of a fraction of waste polypropylene and polyethylene for the recovery of BTX aromatics using a fluidized bed reactor”, *Journal of Fuel Processing Technology*, Vol. 91(3), pp. 277-284.
 88. Zhang, L., Bao, Z., Xia, S., Lu, Q. and Walters, K. B., 2018, “Catalytic pyrolysis of biomass and polymer wastes”, *Journal of Catalysts*, Vol. 8(12), p. 659.
 89. Hwang, I. H., Kobayashi, J. and Kawamoto, K., 2014, “Characterization of products obtained from pyrolysis and steam gasification of wood waste, RDF, and RPF”, *Journal of Waste management*, Vol. 34(2), pp. 402-410.
 90. Ucar, S., Karagoz, S., Ozkan, A. R. and Yanik, J., 2005, “Evaluation of two different scrap tires as hydrocarbon source by pyrolysis”, *Journal of Fuel*, Vol. 84(14-15), pp. 1884-1892.

91. Sharuddin, S. D. A., Abnisa, F., Daud, W. M. A. W. and Aroua, M. K., 2016, "A review on pyrolysis of plastic wastes", *Journal of Energy Conversion and Management*, Vol. 115, pp. 308-326.
92. Debono, O. and Villot, A., 2015, "Nitrogen products and reaction pathway of nitrogen compounds during the pyrolysis of various organic wastes", *Journal of Analytical and Applied pyrolysis*, Vol. 114, pp. 222-234.
93. Mohan, D., Pittman Jr, C. U. and Steele, P. H., 2006, "Pyrolysis of wood/biomass for bio-oil: a critical review", *Journal of Energy & fuels*, Vol. 20(3), pp. 848-889.
94. Ahmad, I., Khan, M. I., Khan, H., Ishaq, M., Tariq, R., Gul, K. and Ahmad, W., 2015, "Pyrolysis study of polypropylene and polyethylene into premium oil products", *International journal of Green Energy*, Vol. 12(7), pp. 663-671.
95. Khan, M. Z. H., Sultana, M., Al-Mamun, M. R. A. and Hasan, M. R., 2016, "Pyrolytic waste plastic oil and its diesel blend: fuel characterization", *Journal of Environmental and Public Health*, Vol. 2016, pp. 1-6.
96. Adrados, A., De Marco, I., Caballero, B. M., López, A., Laresgoiti, M. F. and Torres, A., 2012, "Pyrolysis of plastic packaging waste: A comparison of plastic residuals from material recovery facilities with simulated plastic waste", *Journal of Waste Management*, Vol. 32(5), pp. 826-832.
97. Onwudili, J. A., Insura, N. and Williams, P. T., 2009, "Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: effects of temperature and residence time", *Journal of Analytical and Applied Pyrolysis*, Vol. 86(2), pp. 293–303.
98. Brems, A., Baeyens, J., Vandecasteele, C. and Dewil, R., 2011, "Polymeric cracking of waste polyethylene terephthalate to chemicals and energy", *Journal of the Air & Waste Management Association*, Vol. 61(7), pp. 721-731.
99. Muhammad, C., Onwudili, J. A. and Williams, P. T., 2015, "Catalytic pyrolysis of waste plastic from electrical and electronic equipment", *Journal of Analytical and Applied Pyrolysis*, Vol. 113, pp. 332–339.
100. Widiyannita, A. M., Cahyono, R. B., Budiman, A., Sutijan and Akiyama, T., 2016, July, "Study of pyrolysis of ulin wood residues", In *AIP Conference Proceedings* (Vol. 1755, No. 1, p. 050004), AIP Publishing LLC.
101. Zeng, K., Minh, D. P., Gauthier, D., Weiss-Hortala, E., Nzihou, A. and Flamant, G., 2015, "The effect of temperature and heating rate on char properties obtained

- from solar pyrolysis of beech wood”, *Journal of Bioresource Technology*, Vol. 182, pp. 114–119.
102. Nahil, M. A. and Williams, P. T., 2010, “Activated carbons from acrylic textile waste”, *Journal of Analytical and Applied Pyrolysis*, Vol. 89(1), pp. 51-59.
 103. Bernardo, M., Lapa, N., Gonçalves, M., Mendes, B., Pinto, F., Fonseca, I. and Lopes, H., 2012, “Physico-chemical properties of chars obtained in the co-pyrolysis of waste mixtures”, *Journal of Hazardous Materials*, Vol. 219, pp. 196-202.
 104. Park, J., Lee, Y., Ryu, C. and Park, Y. K., 2014, “Slow pyrolysis of rice straw: analysis of products properties, carbon and energy yields”, *Journal of Bioresource Technology*, Vol. 155, pp. 63–70.
 105. Akhi, A. G., Koya, M. A., Akhilesh, S., Ashif, M., Khan, S. and Kanna, R., 2017, “Determination of Cloud And Pour Point of Various Petroleum Products”, *Journal of Engineering and Science*, Vol. 6(9), pp. 01-04.
 106. [Online]. Available at: https://www.engineersedge.com/fluid_flow/kinematic-viscosity-table.htm
 107. Md. Shameem Hossain, 2015, “Extraction of Liquid Fuel from Pyrolysis of Waste Tyres with Catalyst”, Postgraduate Project, Department of Energy Science and Engineering, Khulna University of Engineering & Technology.
 108. Farzana Yeasmin Nipa, 2019, “Pyrolysis of Organic Waste: A Way to Solid Waste Management and Extraction of Fuel”, Postgraduate Project, Department of Energy Science and Engineering, Khulna University of Engineering & Technology.
 109. Hossain, M. S., Abedeen, A., Karim, M. R., Moniruzzaman, M. and Hosen, M. J., 2017, “Catalytic Pyrolysis of Waste Tires: the influence of ZSM-catalyst/tire ratio on Product”, *Iranica Journal of Energy and Environment*, Vol. 8(3), pp. 189-193.
 110. [Online]. Available at: https://en.wikipedia.org/wiki/Thermogravimetric_analysis
 111. Haarlemmera, G., Guizani, C., Anouti, S., Déniel, M., Roubaud, A. and Valin, S., 2016, “Analysis and comparison of bio-oils obtained by hydrothermal liquefaction and fast pyrolysis of beech wood”, *Journal of Fuel*, Vol. 174, pp. 180-188.
 112. [Online]. Available at: <https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/index-11.html>

Appendix

A-1: Pyrolysis Data of Syringe Waste at 150 °C

Feed Materials: 1.5 kg					
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)
		Oil	Char	Gas	
01	150	320	747	433	118
02	150	328	766	406	122
03	150	373	704	423	125
Average	150	340	739	421	122

A-2: Pyrolysis Data of Syringe Waste at 200 °C

Feed Materials: 1.5 kg					
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)
		Oil	Char	Gas	
04	200	399	675	426	113
05	200	431	638	431	128
06	200	488	583	429	129
Average	200	439	632	429	123

A-3: Pyrolysis Data of Syringe Waste at 250 °C

Feed Materials: 1.5 kg					
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)
		Oil	Char	Gas	
07	250	453	613	434	134
08	250	527	536	437	117
09	250	539	526	435	124
Average	250	506	558	435	125

A-4: Pyrolysis Data of Saline Bottle Waste at 150°C

Feed Materials: 1.5 kg						
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)	
		Oil	Char	Gas		
10	150	311	767	422	133	
11	150	340	739	421	127	
12	150	350	728	422	118	
Average	150	334	745	422	378	

A-5: Pyrolysis Data of Saline Bottle Waste at 200°C

Feed Materials: 1.5 kg						
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)	
		Oil	Char	Gas		
13	200	404	672	424	122	
14	200	417	656	427	137	
15	200	467	608	425	141	
Average	200	429	645	425	133	

A-6: Pyrolysis Data of Saline Bottle Waste at 250°C

Feed Materials: 1.5 kg						
Sample No.	Operating Temperature (°C)	Evolved Products (gm)			Operating Time (Min)	
		Oil	Char	Gas		
16	250	458	614	428	129	
17	250	524	546	430	136	
18	250	542	525	433	143	
Average	250	508	562	430	136	

A-7: Temperature Effect on Pyrolytic Products of Syringe Waste

Serial No.	Set No.	Weight of Syringe Waste (kg)	Temperature (°C)	% of Product Yield (w/w)		
				Oil	Char	Gas
01	01	1.5	150	21.36	49.78	28.89
02			200	26.60	45.02	28.38
03			250	30.17	40.86	28.97
04	02		150	21.86	51.08	27.06
05			200	28.75	42.56	28.69
06			250	35.12	35.73	29.15
07	03		150	24.89	46.90	28.21
08			200	32.56	38.87	28.57
09			250	35.94	35.08	28.98

A-8: Temperature Effect on Pyrolytic Products of Saline Bottle Waste

Serial No.	Set No.	Weight of Saline Bottle Waste (kg)	Temperature (°C)	% of Product Yield (w/w)		
				Oil	Char	Gas
01	01	1.5	150	20.73	51.15	28.12
02			200	26.94	44.77	28.29
03			250	30.53	40.90	28.57
04	02		150	22.64	49.29	28.07
05			200	27.81	43.76	28.43
06			250	34.92	36.41	28.67
07	03		150	23.32	48.53	28.15
08			200	31.11	40.54	28.35
09			250	36.14	34.99	28.87