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Graduation Project 2

Biochar From Municipal Solid Waste (MSW)

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List of abbreviations

PNA	Palestinian National Authority
MSW	Municipal Solid Waste
EIA	Environmental Impact Assessment
OPT	Occupied Palestinian Territory
MBT	Mechanical Biological Treatment
SOC	Soil Organic Carbon
PAHs	Polycyclic Aromatic Hydrocarbons
VCM	Volatile Combustible Matter
LCA	Life Cycle Assessment
MPSP	Minimum Product Selling Price
PW	Present value
AW	Annual value
SPBP	Simple Payback Period
DPBP	Discount Payback Period
IRR	Internal rate of return

Abstract

This research presents a model for the production of biochar from municipal solid waste using the slow pyrolysis technique. In this research, biochar production methods and the benefit of using them were investigated. The proposed location for establishing the studied plant is in the Nablus waste transfer station. The waste quantity and contents are the main parameters for the initial design. After preparing the process flow diagram, mass and energy balance equations were applied to calculate the products and energy needed. At the end, feasibility and environmental analysis were performed on the suggested plant. The city of Nablus and some neighboring villages export about 250 tons of waste per day, for pyrolysis process, only organic portion (53%) will be considered as the raw material. The amount of solid waste that is entered in a whole day (24 hours) is equal to (120201 kg/day), but this amount is divided into 6 cycles per day, and the duration of one cycle is 4 hours. Any quantity (20033 kg/4 hours) with a moisture content of 40% is entered. Right down to the drying process, the weight was reduced to (12924 kg / 4 hours) with a moisture content of 7%. The second part of the process, the drying process. To facilitate this process, the dryer is supplied with dry and hot steam. The process continues until the humidity reaches 7% where the reactor moisture should be less than 10% and the raw materials are fed into the shredder which reduces the volume of waste. Small dry pieces arrive at the pyrolysis reactor which starts the heating process from 500°C and the materials settle in the reactor for a period of time until biochar, bio-oil and syngas are produced which enter into the process repeatedly as heat energy for the reactor to continue working. The results indicate that for every 1 kg of material 0.35 biochar, 0.35 syngas, and 0.30 biooil at an energy input of 1.8 MJ/kg. Therefore, the energy required for this quantity (12,924 kg / 4 h) is estimated at 36060 MJ / 4 h. Also, the amount of heat required for the drying process is 26,289 MJ / 4 h. Three scenarios were also developed to determine the economic effectiveness of the project. Considering the initial cost of 16 million, the selling price of biochar and bio-oil was estimated as 0.65 ($/kg), 0.79 ($/kg), respectively. In another scenario, the selling price was 0.65 ($/kg), 0.22 ($/kg), respectively. Ending with the scenario that means selling bio-oil only at 0.79 ($/kg). The expected payback period was 1.5, 2.5, and 7.5, respectively.

Constraints

- Economy:

Obtaining material profits from this type of project is not the essence of the goals. Where it may not be economically profitable, provided that the environment is the first beneficiary. Nevertheless, it is preferable that the project has the ability to cover its energy needs.

- Environment:

This project was originally found to solve a real health dilemma, which is the accumulation of waste. In this project, large quantities of waste will be reduced and disposed of in a healthy and environmentally friendly manner. This reduces bad odors in the area. As for the fumes rising from the station as a result of the burning process, they will be controlled by placing highly efficient filters that purify fumes from all sources of pollution. The waste shredder can cause noise, but the sound will be isolated or mitigated.

- Social:

The presence of the project in the lands of the Sarifi landfill, which is close to the town of Al-Bathan and many of the dwellings, makes conducting an opinion poll and obtaining the acceptance of the residents a necessary and inevitable matter for the establishment of the project. In addition to the work of the environmental impact assessment (EIA) report carrying the environmental and social details of the project.

- Health and safety:

Biochar as a fertilizer will be used on the soil. Therefore, it must be subjected to treatment and examination that ensures that the plant, the soil and the consumer are not adversely affected.

Chapter 1

Introduction

Biochar is defined as an organic matter that has been carbonized. It is deliberately produced for several goals related to the environment and soil, it is also used as fertilizer in agricultural operations. Whereas, biochar in language is defined as: “Charcoal for application to soil”. In the physical and chemical sense, biochar and charcoal are basically a single substance. However, the only difference between them is the method of use and the goal to be achieved from them. Charcoal is produced for many reasons including heating, barbecuing, etc. [1].

Biochar is considered as a compound rich in stable carbon (C) that is created in reactors with little or no oxygen concentration under high temperature conditions ranging between 300 - 1000 degrees Celsius. Therefore, it has important applications for carbon sequestration and soil properties. The immediate goal of soil carbon sequestration is to mitigate global warming by fixing carbon dioxide in vegetation. After a while, plant wastes and organic materials are used to produce biochar again. It becomes expected to increase the percentage of carbon in plants and reduce its percentage from the atmosphere. It is estimated that the time of carbon remaining in plant materials lasts for decades, while its residence time ranges from hundreds of thousands of years in biological carbon [1].

We are in the process of conducting a study on biochar production from organic waste, wood, paper and others. Therefore, it is worth noting the situation of waste in Palestine. Unfortunately, the data and statistics available on waste in the country are very limited. However, according to statistics conducted in 2019, the amount of waste is estimated at about 1.53 million tons, and it increases by 4% annually. Where 50% of it is organic materials, 12.5% paper and cardboard, and 14.6% plastic [2].

It is evident that there is an excessive accumulation of waste with the continuous increase of the population in Palestine, as the number, according to the 2020 statistics, reached 5.2 million ton in the West Bank (including Jerusalem) and the Gaza Strip. In addition, the occupation used the West Bank as a scapegoat to avoid the burden of providing basic services such as waste disposal. There are more than 200 settlements that dispose their waste in Palestinian landfills, which will worsen the situation. Afaq magazine revealed, in September 2016, that most of the electrical waste produced by the occupation is dumped in the West Bank, where this type of violations is classified as the most serious and toxic [2].

On the other side, we see the Palestinian agricultural sector, which is the pulse of Palestine. It provides job opportunities for more than 51,500 workers until 2018. Palestinian production reached 1,295 million dollars in 2011. It contributes 6.3% of the total value of Palestinian exports [3]. However, it is well known that the Palestinian agricultural sector suffers from challenges and difficulties related to the practices of the occupation and its settlers. One of the main challenges is preventing the import of many medicines and fertilizers.

As the years progressed, the situation was getting worse and exacerbated by all the pressures exerted by the occupation in the West Bank and Gaza Strip. The expansion of dumpsites or other construction is very costly and difficult due to the occupation's confiscation of many lands or the classifications imposed by it. These restrictions prevent the Palestinians from controlling their lands. In addition, the entry of Israeli agricultural products into the Palestinian market is considered more efficient than the local product. That is because of the fertilizers and services provided to them which threatens Palestinian agriculture. This calls us to find a solution that saves the country from drowning in waste and improves the agricultural environment.

Biochar has become a promising solution to the two dilemmas facing Palestine in recent times. It may be able to solve solid waste problems and support the agricultural sector. So in this report, our aim is to analyze everything related to biochar, summarize the methods of its production, and to mention its advantages and disadvantages based on previous reviews.

1.1 Research Objectives

1. Study the biochar production methods, benefits and uses.

2. Select suitable area to be the case study for the project.

3. Determine the content and the amount of solid municipal solid waste that can be used for pyrolysis process.

4. Perform mass and energy conservation law on each unit in the pyrolysis process.

5. Perform economic and environmental analysis for the suggested plant.

Chapter 2

Literature Review

As the world's population continues to rise at a rapid rate, municipal solid waste (MSW) has become one of the most important concerns in recent decades (11 million tons per day in 2100). According to experts at The World Bank, global waste generation would increase to 6 million tons per day by 2025, and possibly about 11 million tons per day by 2100 [4]. All nations will have to deal with increased soil and water emissions, as well as the potential for health crises. However, developed countries are likely to bear the brunt of inefficient waste management policies. Solid waste management is also a critical problem in Israel and the Occupied Palestinian Territory (OPT): rapid population and demand expansion, lack of land and water supplies, and climate conditions are all key factors to consider for any potential sustainable solid waste management In 2019, Palestinians produced approximately 4,333 tons of solid waste per day, totaling around 1.58 million tons for the year, or around 0.87 kilograms per capita per day (0.9 kilograms per capita per day in the West Bank and 0.7 kilograms per capita per day in Gaza). Due to demographic growth and existing consumption trends, these figures, which include East Jerusalem, are expected to rise by about 4% annually. Around 65 percent of municipal solid waste (MSW) is discarded in sanitary landfills, while the rest is dumped in mostly random/illegal dumping areas, which pollute the Palestinian atmosphere on a regular basis. Despite the fact that 52 random dumping sites were closed between 2010 and 2016, tens more still remain, occupying hundreds of dunums of soil (1 dunum is 1,000 square meters). Add to that the perilous practice of illegally burning electronic waste to remove raw materials such as metals from cables, an operation that is transmitting pollutants at unprecedented rates in many locations, including Ithna in Hebron [2]. Weak waste management is mostly due to the political situation in the West Bank (including Jerusalem) and Gaza Strip. The situation has begun to shift with the signing of OSLO agreements and the creation of the Palestinian National Authority. The condition has begun to change. Under the Oslo Agreement, Palestinian territory was split into three areas: “A,” “B,” and “C,” with Israeli civil and defense authority in “Area C” (over 60% of the West Bank); 2 “Area A” is a built-up area mostly in urban centers that is entirely under Palestinian jurisdiction, and “Area B” has PNA civil administration but Israeli security control. It's worth noting that "Area C" contains significant tracts of farm land and various forms of natural resources [6].

Waste awareness has grown in recent years, and several Palestinian community-based projects have sprung up to address the issue. Their many campaigns and events have rekindled the spirit of volunteerism and encouraged community-based solutions to major issues. One of the most interesting options is the processing of biochar from industrial waste, which is a safe way to dispose of waste while still providing excellent soil fertilizer. This is pumped into a speech that promotes waste prevention and a more environmentally friendly lifestyle. Biochar is a carbon-rich substance produced when biomass is thermally decomposed (pyrolyzed) in confined air at temperatures ranging from 350 to 700 degrees Celsius. Mechanical biological treatment (MBT) and heat treatment are the two most commonly used pre-treatment techniques prior to MSW disposal. Heat treatment, especially pyrolysis, is an effective technique for dealing with solid waste because it allows for immediate volume and mass reduction as well as the conversion of waste into a valuable by-product (biochar) [7], [8]. In a study Municipal soil waste biochars were found to improve a variety of soil functions, including micronutrient abundance, pH and EC values, water and carbon storage [7], [9]. Depending on the processing temperature and application rate, MSW biochars improved soil organic carbon (SOC) by 7.88–30.05 percent. When high-temperature biochar was added at a rate of 2%, the maximum SOC was observed [7], [10]. However, there is concern that during biochar processing, polycyclic aromatic hydrocarbons (PAHs), which are carcinogenic and persistent contaminants, may be formed [7], [11]. Furthermore, if toxicants, such as heavy metals, are released into groundwater and soil, they will cause a slew of environmental and health problems [7], [12]. Before using biochar as a soil modification, it is important to assess both the bioavailability of PAHs and the concentration of heavy metals in it. The supply and composition of feedstock are two of the most significant factors in the sustainable and cost-effective processing of biochar. Even though there is a large supply of feedstocks, proper classification and characterization are needed for their proper use. As a result, the current segment focuses on feedstock capital, compositions, and availability. Agricultural wastes, urban waste, paper waste, woody biomass, marine biomass, animal and human excreta, factory waste, food and kitchen waste, dairy and paper mill waste, poultry waste, and other feedstocks are all used to make biochar [13].

Biochar is produced in anaerobic conditions, and although there are numerous biochar processing methods, the proper classification is lacking [13]. When opposed to other biochemical and thermochemical approaches, pyrolysis is an environmentally safe alternative treatment system for biomass waste. Given the large quantities of food waste produced globally, pyrolysis of food wastes with the goal of generating various value-added goods has a lot of potential. Biochars made from pyrolyzed food waste may be added to soils to improve water and nutrient retention, but those features must be present in these biochars. Biochars may also be converted into other higher-value-added materials, such as activated carbons. Biochars' properties and yield are strongly influenced by the process conditions as well as the form and composition of the food waste used to make them [14].

Chapter 3

Biochar

3.1 Definition

Biochar: It is a solid product rich in carbon that is produced by one of the thermochemical methods such as pyrolysis in an environment with limited or no oxygen from organic waste such as municipal solid waste that contains many organic materials such as wood, paper, animal dung, etc., or waste agriculture. This product has been described as a soil conditioner and fertilizer. Despite these benefits, there are some risks resulting from its production. For this, consideration should be given to understanding the physical and chemical properties of this product before adding it to soil. On the other hand, it is a promising product for one of the problems that the world suffers from in the collection and disposal of waste.

3.2 Feedstocks

The primary materials for the formation of biochar are those that are widely available, such as organic solid waste such as wood, paper and animal dung (cattle and chicken), and agricultural crop waste such as corn, wheat straw, rice straw, potato peel, soybeans, sugar cane, bagasse, cotton, grapes, oranges, and peanuts. The manures bio solids dataset included biochars made from paper mill sludge, cattle and dairy manure, horse manure, swine manure, poultry manure and litter, and bio solids. Among all feedstocks, poultry manure, pig manure, cattle and dairy manure, and bio solids were the most common feedstocks employed to produce biochars [15].

3.3 Production methods

Depending on the thermochemical operating parameters and the intrinsic nature of biomass, biochar has different physical and chemical properties. Several units and reactors have been developed for the production of biomass in order to achieve higher yield and quality of target product. These reactors are similar in terms of principle, but differ in the use of oxygen, heating rate, and final temperature, which may change the quality and distributions of final products. Figure 1 shows various types of thermochemical processes for biochar production including slow pyrolysis, fast pyrolysis, gasification and Torrefaction. Based on different reaction conditions, especially the amount of oxygen available, the yield and quality of biochar produced in these processes are vastly different. For instance, high yield and quality biochar can be obtained through prolonging the residence time of biochar to many hours even several days at around 400 °C pyrolysis temperature, which typically belongs to biomass slow pyrolysis [16].

3.3.1 Pyrolysis

Pyrolysis is a thermochemical process in which the biomass is heated to different degrees of temperature under a specific oxygen medium and at different speeds. The pyrolysis process can be classified into several types according to the process parameters and conditions.

3.3.1.1 Slow pyrolysis

Slow pyrolysis is one of the most common methods used for biochar production with a low heating rate (lower than 10 °C/min) and a residence time of few minutes to several hours and the yield of biochar is high (35%) [17]. Slow pyrolysis yields biochar as a major product (35–45%) along with other products as bio-oil (25–35%), and syngas (20– 30%) [13], [18]. Used wood chips to produce biochar by slow pyrolysis, keeping temperature range between 290 to 700 °C with a heating rate of 3 °C min^{-1} for 2 h [13], [18]. Various feedstocks such as wood, cotton, cedar husk and coconut have been used in this type of slow decomposition.

3.3.1.2 Fast pyrolysis

Fast pyrolysis is nothing but a high efficiency thermochemical process to produce biomass derived biofuels [13], [19]. The advantages of fast pyrolysis include short retention time and high product recovery[13]. However, in the case of fast pyrolysis with a high heating rate (~ 1000 °C/S) biochar production is less (10%), whereas it produces bio-oil as the major product (70%) [17]. The main objective of the fast pyrolysis process is to expose the biomass feedstock to a temperature sufficiently high to achieve thermal cracking, while minimizing the exposure time which favors the formation of chars. Also, the undesired char formation is avoided through the application of high heating rates during the process of fast pyrolysis for the purpose of converting the feed biomass into biofuel oil liquid products[14].

3.3.2 Torrefaction

Torrefaction is a pyrolysis process, which occurs at a low temperature (200–280 °C) and provides partially decomposed biomass. Regarding the municipal solid waste, many studies have focused their attention in slow/moderate pyrolysis of municipal solid waste[20]. Torrefaction is a thermochemical process for treating biomass in the absence of oxygen and at atmospheric pressure. The torrefaction procedure is usually carried out in a fixed bed reactor. Several studies have shown that torrefaction and densification technology is an efficient tool for producing high-quality torrefied wood pellets as opposed to raw managed pellets [17].

3.3.3 Gasification

Gasification is a popular method for generating syngas from a variety of solid fuels. Gasification produces more syngas volume and lower Levelized emissions than other traditional processes such as pyrolysis, combustion, and fermentation[13]. Gasification is the method of transforming the carbonaceous material of different forms of biomass into gaseous fuel by reacting with gaseous media such as steam, carbon dioxide, nitrogen, or a mixture of these gases at elevated temperatures between 700–900 °C[14], [21]. Heat transfer within a particle that raises the localized temperature of biomass leads to the elimination of water and the gradual release of pyrolytic volatiles during the gasification process. Cellulose, hemicellulose, lignin, and extractives containing permanent gas species are the precursors of primary volatiles (e.g., CO2, CO, and CH4). While each part of the biomass decomposes at a different temperature, the average decomposition temperature is close to 400–500 °C, where biochar is a key commodity[13].

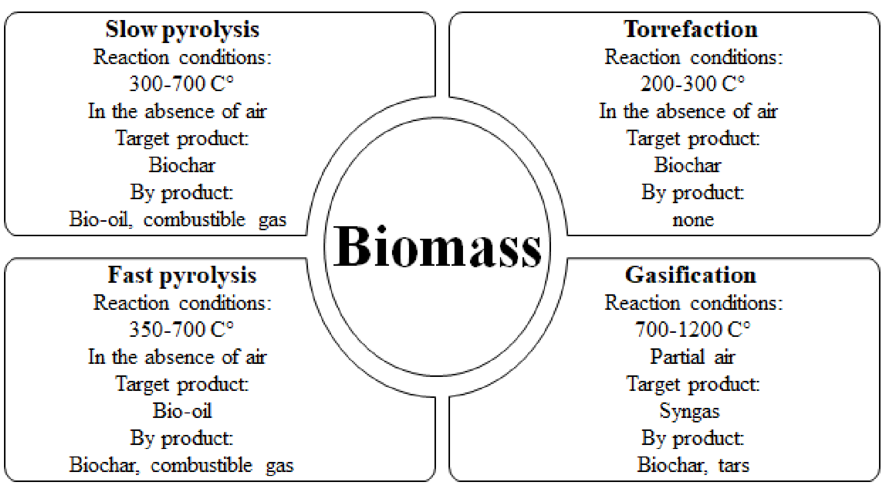


Figure 1: Biomass thermo-chemical conversion technologies for biochar production

3.4 Biochar uses

3.4.1 Biochar for soil improvement

Biochar affects the properties of the soil, which may have a direct effect on the growth and enhancement of the plant and the improvement of crop productivity. It works to amend the soil from lack of nutrients and improve the efficiency of fertilizer use and maintain suitable moisture for plants.

Plant stress is one of the major problems encountered in agricultural environments. Biochar has been reported to display great potential to mitigate plant stresses for both biotic and abiotic types of stresses. For example, amending soils with biochar addition improved the antioxidant response of quinoa in addressing the complex conditions of drought and salt accumulation by increasing plant-promoting hormones. Biochar application to saline and sodic soils displays the beneficial influence on alleviating the negative effects of salts, because the more surface charges on biochar can substitute for Na by K, Ca, and Mg, thus resulting in reduced levels of exchangeable sodium percentage. In addition to the biotic stresses, biochar application can trigger microbial activities to mitigate plant pathogenicity that threatens plant health; the release of microbial inhibitors like volatile organic compounds can deter soil pathogens thereby, enhancing plant growth [16].

3.4.2 Biochar for soil remediation and water treatment

Since biochar has an effect on plant growth and soil consolidation, it is also a treatment for soil pollution from organic and inorganic materials. The presence of heavy metals in the soil raises concerns about the environment and health. Generally, biochar impacts both metal mobility and bioavailability in soils. The mineral elements contained in biochar may precipitate with metals, forming insoluble precipitates. In addition, some biochars are alkaline, the application of biochar could then cause liming effects in soils and thus induce heavy metal precipitation[16], [22]. Several indirect actions may also be responsible for the beneficial effect of heavy metal immobilization by biochars , such as modification of soil pH, CECs, changes in the redox state of heavy metals, and increases in soil mineral contents and soil organic carbon content [16], [23].

Meanwhile, biochar addition can promote the occurrence of soil oxidation-reduction reactions by mediating microbial activities [14],[22].Unlike inorganic contaminants, biochar used for remediation of organic contaminants in soils is not widely reported, although biochar contains a fraction of colloidal and dissolved C, which can be used for absorbing organic compounds like PAHs [16], [25].

3.4.3 Biochar for the mitigation of greenhouse gas emissions

The importance of biochar is not limited to crops, soils, etc., but it also works to reduce greenhouse gas emissions such as CH_4, N_2O, NH_3 and CO_2, and by mentioning that carbon dioxide emissions from soil respiration are nearly ten times higher than emissions from combustion of fossil fuels, it is important to reduce emissions of CO_2. Carbon dioxide from agricultural soils to mitigate climate change, moreover, biochar indirectly reduces greenhouse gas emissions.

3.5 Benefits and concerns

Adding biochar to the soil has proven to have many advantages. Several studies have shown that there is a significant improvement in soil when biochar is added. It has improved water retention capacity due to the ability of carbon biochar to retain water, which has reduced the total water requirement. It also improves the ability to retain nutrients due to the ability of carbon biochar to retain nutrients and fertilizers. It also has the ability to remove cations from the soil, such as heavy metals, by absorbing carbon in addition to removing organic matter, such as hydrocarbons and pharmaceuticals. All this, in turn, will improve the quality of the soil and agricultural crops.

There are several ways to use biochar, the main one being mixing biochar with compost and placing it in the soil during the cultivation or tillage process. It is considered a less harmful method than others as the compost will help reduce the damage that will affect the soil, such as increasing the proportion of nitrates in the soil or the arrival of biochar impregnated with carbon. On the other hand, there are many concerns when using it, other toxic elements enter the groundwater, which leads to destroying the aquatic environment, which in turn will adversely affect human, animal and plant health. Biochar top dressing is the spread of biochar (mostly dust fraction) over the soil surface and reliance on natural processes of incorporating biochar into the topsoil. The disadvantages of this method are the erosion processes due to water and wind, as it will easily transfer to the human respiratory system, and it is also expected to reach surface water and other ecosystems.

3.6 Biochar production process

Step 1 Collect the solid waste or go to the collection point and then work to separate the materials to be introduced into the pyrolysis process, such as wood, paper, organic materials, etc.

Step 2 Pre-drying to get rid of 10% of the high moisture present in the feedstock. In order to determine the amount of heat required for the drying process, it is calculated using *Equation 5*.

Step 3 Chop the dried materials into 2 cm pieces. This step is important to facilitate the process of transporting and burning. It is also important for reducing its size.

Step 4 Prepare the reactor to receive the incineration process. This can be made by raising its temperature and ensuring that no heat or materials resulting from any part of the process leak out. The required temperature can be calculated with *Equation 6.*

Step 5 Preheat and pre-drying by passing small pieces into a feeder containing hot and dry air.

Step 6 inter the biomass into the oxygen-free reactor. From this point the pyrolysis process starts, the biochar starts to form, and biogas rises inside the tubes that are prepared for receptor.

Step 7 place the biochar in special bags to prevent moisture from reaching it. This is vital for its movement, which should be moved very carefully away from any source of heat to prevent ignition.

Mechanism:

Biomass storage and drying

Wooden or agricultural biomass stored in a dedicated storage facility is transported to the pyrolysis reactor via a bucket feeder. The raw biomass is pre dried inside the feeder through the use of hot and dry air flowing in the crossflow. Biomass pre-drying has a positive impact on the reduction of the moisture content inside the process material by a few percent. In addition, it increases the pace of the processes occurring in the following stages.

Biochar production

Pre dried and preheated biomass then goes to the pyrolysis reactor where the following full processes take place.

The moisture evaporation process

All the moisture accumulated in the raw biomass has to evaporate in order to initiate the carbonization process. Depending on the type of biomass and the amount of moisture accumulated in the process material, they may take from several to more than dozen seconds. Its efficiency is due to the high temperature in the upper path of the reactor.

The degasification process

In the next stage in the biomass is degasified in the temperature range of 370 to 400 degrees Centigrade. Within this range the removal of volatile particles is most efficient. Chemical compounds like nitrogen, carbon monoxide, carbon dioxide, hydrogen and others are flammable. It is consumed by the pyrolysis process in approximately 40% of the energy yield. After mixing with the humid air from the preceding process, the remainder gases can be used for energy.

The carbonization process

Dried and degasified biomass is treated with high temperature. This process results in the quick concentration of elemental carbon and disappearance of the fibrous structure improving its grind ability. Depending on the temperature inside the reactor and the duration of the carbonization process, the ready material can have a calorific value in the range of 21 to 29 mega joules per kilogram.

The Cooling process

The reading material is cooled to ambient temperature with the use of the Crossflow water cooler. In the next stage carbonized biomass (biochar) is loaded to big bags pelletized.

Heat generation

The flammable gas has a relatively low caloric value, so the best way to make use of it, is by conversion to hot water. Pyrolysis system's productivity is from 300 to 1000 kilograms per hour which can supply district heating networks with a maximum capacity from 1 to 3 megawatts respectively. The yield flammable gasses depend on the type and quality of the processed biomass, and the expected characteristics of the carbonized biomass.

In order to maximize the efficiency of the pyrolysis process, hot air taken from the coat of the reactor is used in the biomass pre-drying process. Hot air is transferred to the bucket feeder which has illustrated some time ago.

The Pyrolysis Reactor (PR) produces:

1. Biochar, which is used as a fertilizer, is rich in important elements for soil, the quantity of the resulting biochar can be calculated through *Equation 1*, and the amount of energy produced from it with *Equation 2.*

2. Bio-gas and Bio-oil will be exploited to reheat the pyrolysis process again and reheat it. , That the amount of energy produced from them is calculated with *Equation 7.*

The stages of formation of biochar and the produced components are shown in the picture below in the *Figure 2*.

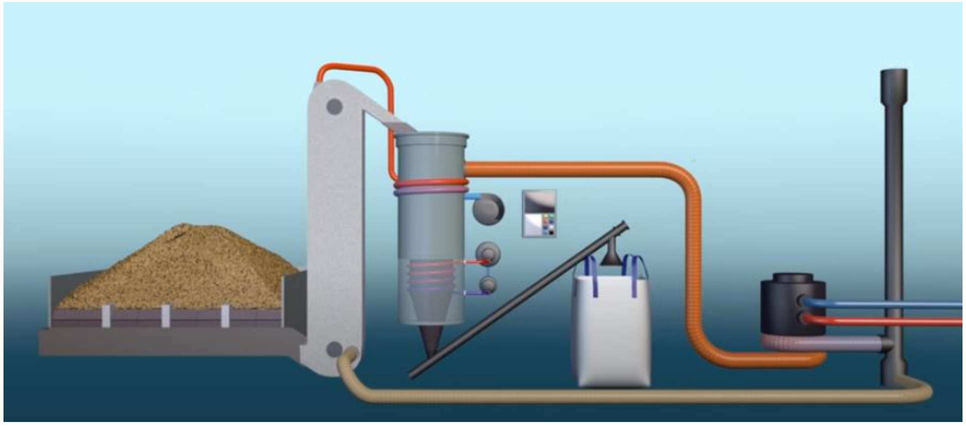


Figure 2: Illustrates the pyrolysis process

Chapter 4

MSW to Biochar by Slow Pyrolysis

Biochar is produced from various raw materials such as wood, rice husks and other wastes by one of the thermochemical methods, especially the slow pyrolysis method. Slow pyrolysis is the process of introducing (burning) the biomass at moderate temperatures between 350-300 ℃, in which there is an adequate residence of the vapor resulting from the decomposition of the thermal mass [16]. Pyrolysis occurs in nature when vegetation is exposed to contact with volcanic lava or forest fires. Pyrolysis, in a simple definition, is the chemical decomposition of an organic matter by heating in the absence of oxygen [1].

In general, during the pyrolysis process, we have materials with the three physical states, solid, liquid, and gas, which are called biochar, bio-oil, and synthetic gases, respectively. There are several types of pyrolysis, and in each type there is a main product that controls the overall production of the process. For example, rapid pyrolysis is the main product represented by bio-oil, synthesis gas, and biochar is a by-product. While the slow pyrolysis process is the main production biochar. Nevertheless, what we are interested in in our research is biochar production, and the slow pyrolysis process was the best, least expensive, and therefore the most important contribution to environmental sustainability. So in this Chapter it will shed light on the slow pyrolysis [16],[26].

The dried and milled solid municipal waste (MSW) is introduced into a steel reactor to resist rust, and the reactor is sterilized with nitrogen gas through the holes to ensure that there is no oxygenation and the heating is done at the required temperature inside the control oven, after reaching the temperature, the process is stopped and waiting for it to reach room temperature and collect the resulting biochar [27]. It must be noted that it is not possible to build an environment completely free of oxygen, so some materials have to be oxidized, but in relatively small quantities [1].

Pyrolysis occurs at high temperatures (the temperature varies according to the feedstock, for example 300 ° C for wood) [1]. Slow pyrolysis is at an average temperature as mentioned previously, and there are studies saying that the temperatures are between 300-800℃, in addition to a heating rate between 5-7 minutes / degree and a residence time usually estimated at more than 60 minutes [28]. The longer residence time leads to a lower production of biochar and re-polymerization of char [29],[30].

In general, this process produces biochar at a rate of 35% as a main product and there is a by-product such as bio-oil at a rate of 30% and synthetic gas at a rate of 35% [28],[31].Therefore, the slow pyrolysis process is considered the best for biochar production compared to others as shown in the table below[1].

Table 1:The mean post-pyrolysis feedstock residues resulting from different temperatures and residence times [1]

Mode	Conditions	Liquid	Biochar	Syngas
Fast pyrolysis	Moderate temperature, ~500 C°, short hot vapor residence time of ~1 s.	75%	12%	13%
Intermediate pyrolysis	Moderate temperature, ~500 C°, moderate hot vapor residence time of 10-20 s.	50%	20%	30%
Slow pyrolysis	Low temperature, ~400 C°, very long solids residence time.	30%	35%	35%
Gasification	High temperature ~800 C°, long vapor residence time.	5%	10%	85%

The high quality of biochar depends on many transactions, including the pH and its carbon content on the one hand, on the other hand there is a correlation with the lower heating rate, moderate temperature and long residence time. The high temperature in the slow decomposition process is necessary to improve the quality of the biochar and ensure its removal. In addition to all volatile substances, the carbon content of biochar is of prime importance. The carbon content may reach 88% when the decomposition of some biomass such as wood [16].

We previously mentioned the positives of biochar, including the absorption of pollutants from the soil. It has been discovered that the absorption capacity of biochar varies according to the heating temperature. Studies have shown that an increase in the temperature of pyrolysis usually leads to an increase in the surface area and the charred part of the biochar, which in turn leads to an increase in the absorption capacity of the material. In short, the pyrolysis temperature on the biochar component, surface structure, functional groups etc., which may affect the physical and chemical properties of the polluted soil that we want to treat [1].

At the extremes of possible temperatures, only carbon is leftover and is called carbonation. The higher temperatures used in pyrolysis can lead to the polymerization of molecules within the feedstock, in addition to the production of larger molecules (including aromatic and aliphatic compounds), and the thermal decomposition of some components of the feedstock into very small particles [1]. So it is necessary to pay attention to the heat of slow pyrolysis to get the biochar with excellent quality and high efficiency [24].

In general, biochar produced at high pyrolysis temperature makes the material effective in absorbing organic pollutants by increasing the surface area, fine porosity, and hydrophobicity. Where a study showed that the biochar that is produced at a temperature of 500 ℃ can reduce the amount of moving, leaked and bioavailable nickel, and at the same time it led to a reduction in the emissions of carbon dioxide in the soil, in contrast that the biochar obtained at 300 ℃ can improve biological activity of soil [24].

In addition, the slow pyrolysis process produces a more stable biochar and contains significant impact on the availability of plant nutrients such as potassium, calcium and magnesium [1], [15]. Based on the fact that flammable gas is present in the end products of the process, it can be recycled in the pyrolysis unit thus saving energy for subsequent pyrolysis cycles, costs, and reducing carbon emissions [1]. After a long search, we chose the lands of the city of Jenin to conduct biochar experiments on its soil, and we hope that the results will be satisfactory and benefit the Palestinian farmers.

Chapter 5

Theoretical background

5.1 Parametric effect of slow pyrolysis to yield biochars from MSW

There are many operating parameters that affect the pyrolysis process such as temperature, time holding and humidity. It is important to study these operating parameters and their effect on the desired results when designing and operating, and each of them will be clarified.

5.1.1 Effect of moisture

In the pyrolysis process, the moisture rate of the biomass should be less than 30% by weight, the lower moisture content of the mass is necessary, otherwise the energy saved will be used to remove moisture from the raw materials instead of raising the system temperature in the thermochemical conversion process [27].

5.1.2 Effect of Holding Time

Based on many studies, it was revealed that increasing the time of residence of samples at a temperature led to a decrease in the percentage of biochar production, more decomposition of biomass occurs, which leads to the release of gases and the reduction of the produced biochar [27].

5.1.3 Effect of Temperature

The temperature has the largest effect on the production of biochar and its properties. It has been observed that increasing the temperature to more than 400 ℃ leads to a decreasing trend in the amount of biochar produced, due to the fact that when raising the temperature of pyrolysis, it leads to an increase in the release of volatile substances and a reduction of solid waste. Produced, although lower temperatures favor biochar production, incomplete decomposition and decomposition may occur resulting in higher yields but with non-decomposing or partially decomposing materials [27], [32]. Also, increasing the temperature of pyrolysis leads to breaking the bonds and increasing the formation of gases more than coal [26], [19].

5.2 Reactive substances

In a previous study, to study the reactants, the sample used waste is composed of solid waste of plastic, wood, metal, paper, fabric and other wastes, and therefore these wastes are dried in the sun and dried in the oven at a temperature of 60 degrees Celsius for 48 hours and then grind and cut these materials and are placed in sealed containers to prevent moisture absorption and sieving each component of MSW to obtain samples with a particle size ranging from 0.85 mm to 2.0 mm, after sieving the MSW sample consists of food waste (32.78%), plastic (8.52%), paper (10.62%), glass (7.01%), Other organic matter (31.85%), and inorganic materials (9.23%) [27],[33].

5.3 Outputs substance

An approximate analysis is made to determine the moisture content, volatile combustible matter (VCM), ash and fixed carbon of solid waste, as mentioned previously, the moisture level must be less than 30%, its increase leads to the formation of gas, which reduces the production of biochar, ash It is a gray solid residue after the complete combustion of the sample and the content varies according to the type of the raw material, it is possible that the ash percentage is high due to the glass components and inorganic materials of this solid waste, as for the increase in the ash percentage, the production of biochar will increase. The high percentage of fixed carbon because it increases biochar production and improves its high quality as a solid, and the fixed carbon contributes to the biomass as heat in the pyrolysis process [27], [34].

As for the initial analysis, it helps in determining the characteristics of the product to be used. The fixed expectations for the products are biochar and certain percentages of carbon, hydrogen and nitrogen, and each of them will be calculated in the next section [35].

5.4 Theories of slow pyrolysis experiment to produce biochar from MSW

As mentioned previously in the process used to produce biochar, the yield of biochar was calculated using Equation 1.Biochar yield was defined as the mass yield of biochar divided by the mass of initial feedstock on DW basis *[35]*.

$$\textbf{\textit{Biochar yield}}\ \mathbf{(\%)} = \frac{\boldsymbol{mb}}{\boldsymbol{Initial\ feedstock\ mass\ (kg)}} \mathbf{*100\ \%} \quad \mathbf{(1)}$$

Where:
mb: is the mass of biochar (kg)

The energy recovery of biochar in (MJ/kg) was calculated using *Equation 2.*

$$\mathbf{E\_}\boldsymbol{energy} = \mathbf{Biochar}\ \boldsymbol{yield}\mathbf{*}\ \frac{\boldsymbol{HHVb}}{\mathbf{HHVmsw}} \qquad \mathbf{(2)}$$

Where:

HHVb: is the higher heating value of biochar (MJ/kg)

HHVmsw: is the higher heating value of raw MSW (MJ/kg)

Carbon, and nitrogen mass fraction (%) on DW basis in *Equation 3, Equation 4*

$$\textbf{Carbon in biochar (kg C / kg biomass)} = \frac{\boldsymbol{Biochar\ mass(kg)*Biochar\ carbon}(\%)}{\boldsymbol{Initial\ feedstock\ mass\ (kg)}} \qquad \mathbf{(3)}$$

$$\textbf{Nitrogen in biochar (kg N / kg biomass)} = \frac{\boldsymbol{Biochar\ mass(kg)*Biochar\ nitrogen}(\%)}{\boldsymbol{Initial\ feedstock\ mass\ (kg)}} \qquad \mathbf{(4)}$$

5.5 Life cycle assessment (LCA)

Life cycle assessment is a tool used to study the feasibility of an existing project, and to assess the environmental impacts of products and processes from start to finish[35], [36].In the study published by (F. Cheng, H. Luo, and L. M. Colosi), part of the life cycle of biochar was evaluated: biomass production, harvesting, pretreatment, pyrolysis, use of products such as biochar in various fields, gas and oil to generate heat, and studying the properties of biochar derived from different raw materials [35].

5.5.1 Biomass and harvested

The available waste will be collected in abundance from solid municipal waste such as wood, paper, and organic materials such as food and others [35].

5.5.2 Pretreatment

According to the study, After the waste is harvested, there will be electricity consumption (kWh/t on DW) to treat these wastes from moisture, which varies from one component to another, and then electricity consumption (kWh/t on DW) for the process of cutting these components into small particles since small particles are useful in transferring heat in slow pyrolysis, and the electricity consumption (kWh/t on DW) associated with the process of drying these components to reduce Moisture level up to 10% [35].

There is a heat loss coefficient during the drying process. The amount of heat required for drying can be calculated in *Equation 5* [35].

$$\mathbf{H = \frac{[Mass\ water \times \Delta T \times Cp\_\ water + Mass\_biomass \times \Delta T \times Cp\_\ biomass + \Delta Hvap \times Mass\_water]}{0.75}} \qquad \mathbf{(5)}$$

Where:

H: represents the required heat (MJ/kg biomass on DW basis)

Cp_water and Cp_biomass: represent the specific heat capacity of water (4.2 kJ/ (kg ℃)) and biomass (1.25 kJ/(kg ℃))

ΔHvap: represents the specific heat of evaporation of water, which is 2260 kJ/kg at a normal boiling point (i.e., 100 ◦C)

ΔT: represents the temperature difference (75 ℃)

5.5.3 Pyrolysis

Depending on the study referred to previously, after the drying process, the materials are analyzed by heat in an oxygen-free environment under certain operating conditions, and assuming electricity consumption for the pyrolysis unit, the temperature required for the process is determined on the basis of evaporating moisture and reaching the required temperature in *Equation 6.* Bio-gas and non-condensable gases as for the energy content of petroleum gas, it can be calculated by *Equation 7 [35].*

$$\boldsymbol{H = \Delta \mathrm{H}vap \times Mass\_water + \mathrm{Cp}\ biomass \times Mass\_feedstock \times (T - 100)} \qquad \mathbf{(6)}$$

$$\boldsymbol{Eoil\ gas = Efeedstock - Ebiochar} \qquad \mathbf{(7)}$$

Where:

E oil gas: represents the energy content of oil and gas (MJ/kg biomass)

E_biochar: represents the energy content of biochar (MJ/kg biomass)

E_feedstock: represents the HHV of feedstock (MJ/kg biomass)

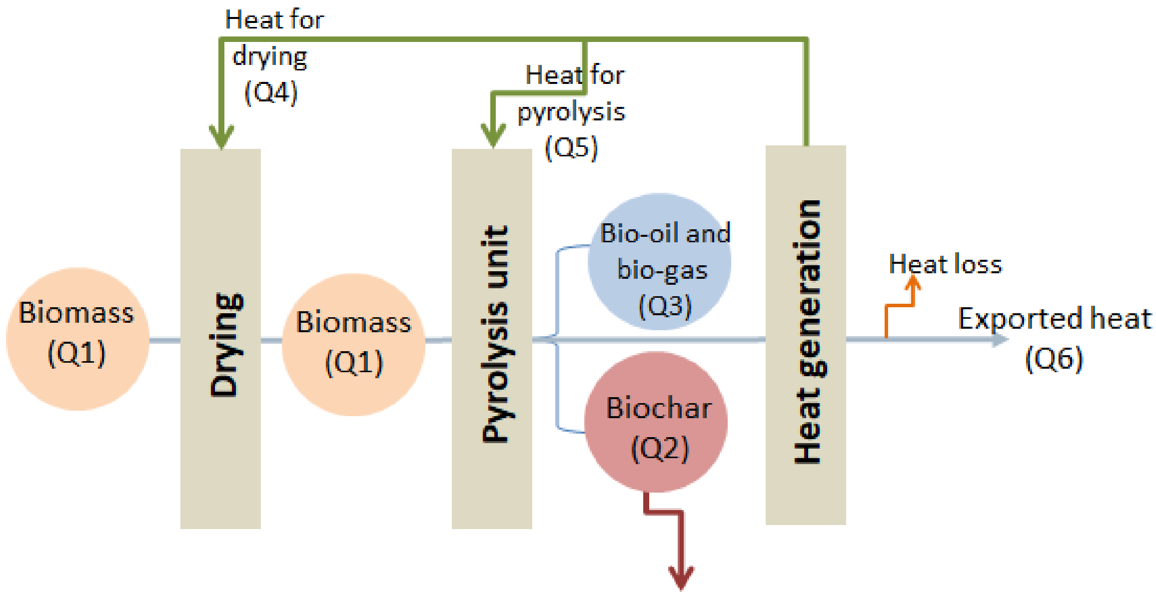


Figure 3: Diagram showing the energy flow for the biomass slow pyrolysis system

Q1: Biomass HHV

Q2: Biochar predicted

Q3: Q1 –Q2 (eqn (7))

Q4: Calculate by (eqn (5))

Q5: Calculate by (eqn (6))

Q6: (Q3 * Thermal efficiency (%)) – Q4 – Q5

5.5.4 Minimum product selling price (MPSP)

The economic model expresses the costs of capital, operating, maintenance, labor costs and revenues throughout the life of the project, the amount of the annual raw materials, and the annual biochar production that qualifies the calculation of the minimum product selling price (MPSP) in the *Equation 8* [35].

$$\textbf{MPSP} = \frac{\textit{sum of cost over lifetime}}{\textit{Sum of biochar produced over life time}}$$

$$= \frac{Io + \sum_{t=1}^{n}(OMt+Lt+Ft-Ht)/(1+r)^{t}}{\sum_{t=1}^{n} M\_biochar/(1+r)^{t}} \qquad \textbf{(8)}$$

Where:

Io: Initial cost

OMt: Annual operating and maintenance cost

Lt: Annual labor cost

Ft: Annual feedstock cost,

Ht: The benefit from heat production

M_biochar: Is the annual biochar production

r: Is the discount rate

t: Is the individual year of lifetime (1,2, …n)

n: Is the project lifetime (i.e., 20,30… years)

Chapter 6

Analysis, Results and Discussion

This section details the calculation methods used to determine the values depicted in the diagram for slow pyrolysis processes.

In the process of conducting a study on biochar production from organic waste, wood, paper, etc. Therefore, it is worth noting the waste situation in Palestine. Unfortunately, the data and statistics available on waste in the country are very limited. However, according to statistics conducted in 2019, the amount of waste is estimated at 1.53 million tons, and it is increasing by 4% annually.

The light will focus on Nablus' waste collection area called Al-Serafy (located at this coordinate: 32°15-42″N 35°19′41″E). To build a processing plant in it, from which we will produce biochar. This area is located within the land of the town of Badhan. This is a Palestinian village in the Nablus Governorate in the north-central West Bank, located 7.28 kilometers (4.52 mi) northeast of Nablus. The area is characterized by an abundance of springs and a diversity of wildlife. The town's population reached 3,394 people in mid-2021, according to the Palestinian Central Bureau of Statistics.

Figure 4: Map showing the location

This area is considered a collection point for solid waste from the city of Nablus, its classification, and its transfer to Zahrat Al-Finjan landfill. The city and some neighboring villages export about 250 tons of waste per day, and the amount increases during the seasons and holidays. The quantity is expected to increase in the coming years as the population increases. The percentage of solid waste in this area is distributed as shown in Table (2).

Table 2: Percentage of solid waste in Al-Serafi landfill

Type	Percentage %
Organic waste	53
Paper & carton	21
Plastic	11
Metals	3
Glass	2
Wood	2
Rubber	2

6.1 Overview of the Process:

Before starting the process, the solid waste collected at Al-Serafi landfill will first be separated, where only organic materials are taken as raw materials for biochar production. No other material will be taken in order to maintain the excellent quality of biochar to be used as fertilizer. In addition, the amount of organic matter is large, so there is no need to increase other types of materials. In order for the biochar to be easy to process and to be a good fertilizer for the soil and the plant, the type of raw material should be taken care of. The proportion and quantity of raw materials required in the process in the sewage landfill is 53%, equal to 120,201 kg/day.

Moving on to the second part of the process, the drying process. To facilitate this process, the dryer is supplied with hot, dry steam. The process continues until the humidity reaches 7% since the reactor moisture should be less than 10% [37], and the raw materials will be fed into the shredder, reducing the volume of waste. The dry small pieces arrive at the pyrolysis reactor which starts the heating process from 500°C and the materials settle in the reactor for a period of time until the biochar, bio-oil, and synthesis gas that will go into the process repeatedly are produced. So that each 1 kg of the material gives 0.35 biochar, 0.35 syngas gas, and 0.30 bio-oil at an energy input of 1.8 MJ / kg [38]. Therefore, the energy required for this quantity is estimated at 36060 MJ / 4 h. Figure (5) shows the biochar production process from the municipal solid waste by slow pyrolysis.

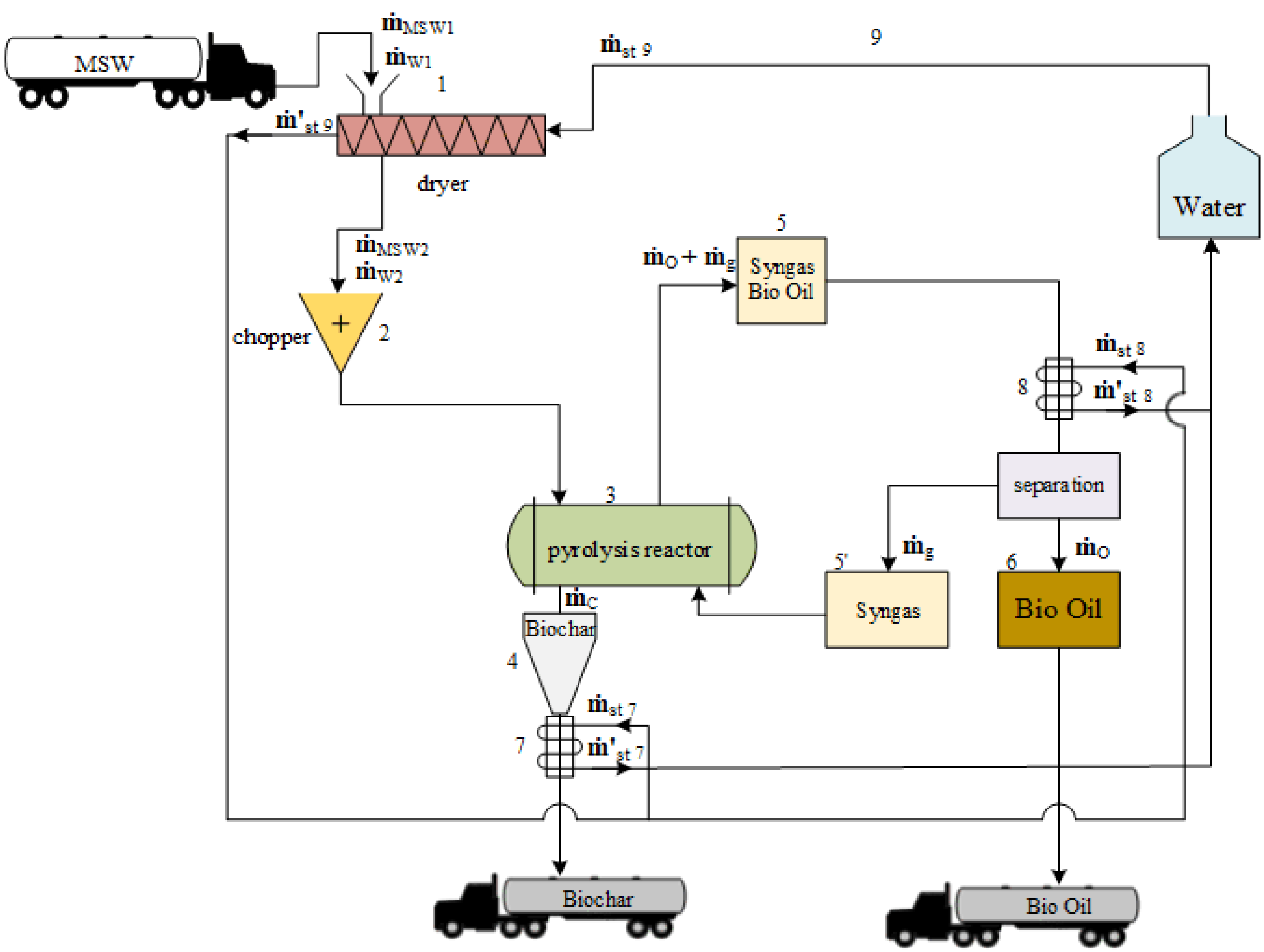


Figure 5: Process Flow Diagram
1: dryer, 2: chopper, 3: pyrolyzer, 4: biochar storage, 5: syngas- bio-oil product, 5': syngas

Table 3:Abbreviation of each symbol for the Process Flow Diagram

$\dot{m}_{MSW1}$	Mass of feedstock before drying
$\dot{m}_{W1}$	Water content in feedstock before drying
$\dot{m}_{MSW2}$	Mass of feedstock after drying
$\dot{m}_{W2}$	Water content in feedstock after drying
$\dot{m}_{st9}$	Mass of sat vapor steam inlet to drying
$\dot{m}'st_9$	Mass of sat liquid steam exit from drying
$\dot{m}o+\dot{m}g$	Mass of syngas and bio-oil
$\dot{m}_C$	Mass of biochars
$\dot{m}_O$	Mass of bio-oil
$\dot{m}g$	Mass of syngas
$\dot{m}_{st7}$	Mass of sat liquid (inlet)to cooling biochar
$\dot{m}'st_7$	Mass of sat vapor (exit) from cooling biochar
$\dot{m}_{st8}$	Mass of sat liquid (inlet)to cooling syngas and bio-oil
$\dot{m}'st_8$	Mass of sat vapor (exit) from cooling syngas and bio-oil

6.2 Feedstock

The total amount of solid waste introduced in a whole day (24 hours) is equal to (120201 kg/day), but we will divide this amount into 6 cycles per day, the time of one cycle is 4 hours. Any quantity (20033 kg / 4 hours) with moisture content 40% will be entered [39]. Right down to the drying process, which weight has been reduced to 12924 kg/4h with a moisture content of 7%.

The feedstock data have been summarized in table 4:

Table 4: The feedstock data in the slow pyrolysis process

Feedstock	Organic material
Raw biomass moisture %	40%
Dried biomass moisture %	7%
Dried biomass LHV (MJ/kg)	19.5

The mass and energy balances for all primary unit operations involved in the slow pyrolysis process were performed as described in Section 3.

6.3 Major Processes

6.3.1 Drying

The biomass feedstock is dried in a dryer from an initial moisture content of 40% to a final moisture content of 7%. The minimum drying energy requirement was calculated by determining the amount of heat required to evaporate moisture in the feedstock from 40% to 7%. the amount of heat required in the drying process is calculated based on equation (5), therefore, the amount of heat required for the drying process is equal to 26289 MJ /4h, Figure (6) shows the drying process and mass balance.

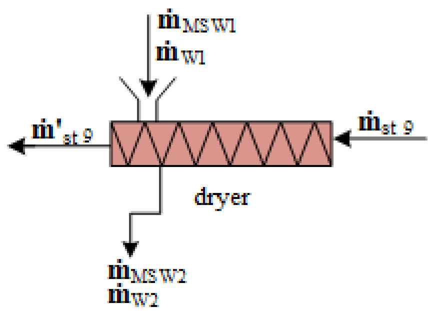


Figure 6:Drying Process and Mass Balance

The amount of steam needed for drying is calculated from equation 9

Q = m_steam (kg) * hfg **(9)**

Q: Amount of heat required in the drying process

m_steam: Amount of steam required to dry in (kg)

hfg: Enthalpy of water at temperature = 110 ℃

Drying process results are summarized in Table 5:

Table 5:Drying process results

Stream	Unit (kg/batch)
$\dot{m}_{MSW1}$	12,020
$\dot{m}_{W1}$	8,013
$\dot{m}_{MSW2}$	12,020
$\dot{m}_{W2}$	904
$\dot{m}_{st9}$ (sat vapor)	11,788
$\dot{m}'_{st9}$ (sat liquid)	11,788

6.3.2 Slow Pyrolysis

The dry small pieces arrive in the pyrolysis reactor which starts the heating process from 500°C and the materials settle in the reactor for a period of time until the biochar, bio-oil, and syngas that will go into the process frequently are produced. The reaction water in the pyrolyzer is less than 10% [37].

Based on the products of the slow pyrolysis process from Biochar 35%, Syngas 35%, and Bio-oil 30% (including 10.4 % reaction water) [37], the amount of each substance will be as shown in Figure 6.

The volume of the reactor required for the slow pyrolysis process and the amount of waste estimated at 12924 kg is estimated at 40 cubic meters.

Mass balance, also called material equilibrium, is a mass conservation application of the analysis of physical systems. The exact conservation law used in the analysis of the system depends on the context of the problem, but it is all about mass conservation, that is, this substance cannot disappear or be created automatically.

The general form quoted for mass equilibrium is the mass that must enter the system, by conserving mass, either leave the system or accumulate within the system.

Mathematically, the mass balance of the system is as follows:

$$\sum m\_input = \sum m\_output$$

This allows us to fully achieve mass equilibrium in a system with limited information and use mass equilibrium relationships across system boundaries. The mass balance of this system can be described as follows:

$m_{MSW} = m_{biochar} + m_{syngas} + m_{bio\text{-}oil}$

m: material mass (kg)

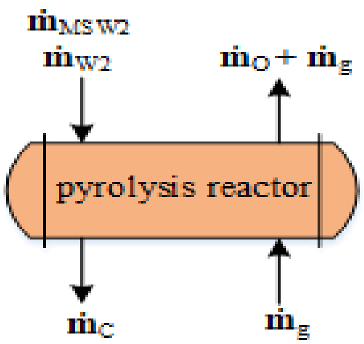


Figure 7: Each substance produced by the pyrolysis process

Reactor pyrolysis process results summarized in table 6:

Table 6: Reactor pyrolysis process results

Stream	Unit (kg/batch)
$\dot{m}_{MSW2}$	12,924
$\dot{m}_{C}$	4523
$\dot{m}_{O}$	1357 (10% water)
$\dot{m}_{g}$	4523

As for the energy associated with all the outputs, it is calculated using *Equation 10*.

$$E = m * LHV \quad \textbf{(10)}$$

m: mass of substance (kg)
LHV: Lower Heating Value (MJ/kg).

The amount of LHV for each product is shown in table 7:

Table 7: The amount of LHV of each products

Type	Lower Heating Value (MJ/kg)
Biochar	15.6
Syngas	13.3
Bio oil	18

Therefore, we can calculate the energy associated with the products based on *Equation 11, Equation 12, and Equation 13.*

$$E_{Biochar} = m_c * LHV_{Biochar} \quad \textbf{(11)}$$

$$E_{Syngas} = m_g * LHV_{Syngas} \quad \textbf{(12)}$$

$$E_{Bio\ oil} = m_o * LHV_{Bio\ oil} \quad \textbf{(13)}$$

Therefore, the amount of energy associated with each of the products is indicated in the figure (8).

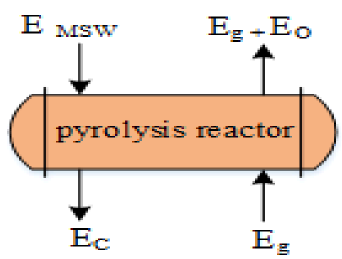


Figure 8: The amount of energy associated with each of the products

Energy cannot be created or destroyed, it can only be changed in form. For any system, energy transfer is related to mass and energy crossing the control boundary, external work and/or heat crossing the boundary, and changing energy stored within the control volume. Fluid mass flow is related to kinetic, potential, and internal and "flow" energies that affect the system's overall energy balance.

The exchange of external work and / or heat completes the energy balance. The first law of thermodynamics is referred to as the principle of conservation of energy, which means that energy cannot be created or destroyed, but rather converted into various forms as the state within the control volume is studied. The modern energy balance is maintained here within the system under study. The system is an area in space (control volume) through which municipal solid waste passes.

The various associated energies are then observed as they cross the boundary of the system and equilibrium is achieved. The system may be one of three types: isolated, closed or open. An open system, the most general of the three, indicates that mass, heat, and external action are allowed to cross the limits of control. Equilibrium is expressed in words as follows: all energies in the system are equal to all energies leaving the system plus the change in the storage of energies within the system. Remember that energy in thermodynamic systems consists of kinetic energy (KE), potential energy (PE), internal energy (U), and flow energy (P); As well as heat and work processes.

The energy balance is achieved through the following equation:

$$\sum E_{input} = \sum E_{output} + \Delta\, E_{stored}$$

The syngas energy from the reactor will be used to operate the reactor, and the energy generated from the syngas will cover the energy needs of the reactor, which in turn will increase the efficiency of the system.

Biochar and Bio-Oil will also be cooled by passing them between closed-loop cold water tubes, and the heat of the water will be tapped into the dryer, which needs loads of hot and dry steam. Biochar will be stored in special bags and then sold as a soil fertilizer. As for the bio-oil, it is processed and then used to generate energy or sold to the concerned authorities, Table (10) summarizes all the inputs and results obtained in this study.

It must be noted that it is certain that there are residues that come out of the reactor after the operation. It may contain bits of metal or some other material that has not burned completely. These are separated from biochar, purified, collected and disposed of in a safe and environmentally friendly manner.

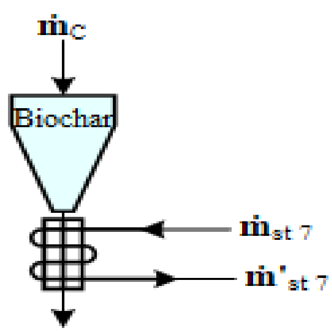
Table 8: Characteristics of slow pyrolysis

TPYR	500 ℃
Raw biomass moisture %	40%
Dried biomass moisture %	7%
Dried biomass LHV (MJ/kg)	19.5
$\dot{m}_{MSW1}$ (kg/ batch)	12,020
$\dot{m}_{W1}$ (kg/ batch)	8,013
$\dot{m}_{MSW2}$ (kg/ batch)	12,020
$\dot{m}_{W2}$ (kg/ batch)	904
$\dot{m}_{st9}$ (sat vapor) (kg/ batch)	11,788
$\dot{m}'_{st9}$ (sat liquid) (kg/ batch)	11,788
$\dot{m}_{MSW2\ (all)}$ (kg/ batch)	12,924
$\dot{m}_{C}$ (kg/ batch)	4,523
$\dot{m}_{O}$ (kg/ batch)	1,357 (10% water)
$\dot{m}_{g}$ (kg/ batch)	4,523
E input (MJ/ batch)	36,060
E_C (MJ/ batch)	70,565
E_O (MJ/ batch)	24,426
E_g (MJ/ batch)	60,161

6.3.3 Heat exchanger (cooling of biochar and bio-oil)

A heat exchanger is a system used to transfer heat between two or more liquids. Heat exchangers are used in both cooling and heating processes. Liquids can be separated by a solid wall to prevent mixing or may be in direct contact.

In the process of cooling biochar and bio-oil, cold water will be introduced to reduce their temperature from 500℃ to 110℃, so the amount of water required to cool the biochar can be calculated in the equation 14.



$$mc * Cp * \Delta T = mst * hfg \qquad \textbf{(14)}$$

mc: Mass of biochar

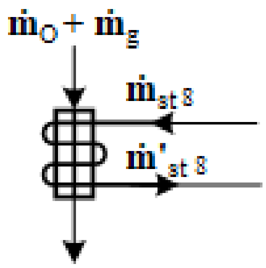
Cp: Specific heat of biochar (1.5 kJ/ (kg.k))

ΔT: Difference temperature of biochar and water

ms : Amount of steam required

hfg: Enthalpy of water at temperature = 110 ℃

Also, the amount of water required to cool the the bio-oil can be calculated in equations (15) or (16).



$$mo\ (h_{500} - h_{110}) = mst * hfg \quad \textbf{(15)}$$

$$(mo * Cp * \Delta T) + \quad hfg\_o = mst * * hfg \quad \textbf{(16)}$$

mo: Mass of bio-oil

Cp: Specific heat of bio-oil) 2.4 kJ/ (kg.k))

ΔT : Difference temperature of bio-oil and water

ms : Amount of steam required

hfg_o: Enthalpy of bio oil

hfg: Enthalpy of water at temperature = 110 ℃

(Assume bio oil like crude oil, so the hfg of bio-oil equal hfg of crude oil)

Heat Exchanger (cooling of biochar and bio oil) results summarized in table 9:

Table 9: Heat Exchanger (cooling of biochar and bio oil) results

Stream	Unit (kg/batch)
$\dot{m}_{st}7$	1,757
$\dot{m}_{st}8$	571

$\dot{m}_{st7} = \dot{m}'_{st7}$

$\dot{m}_{st8} = \dot{m}'_{st8}$

$\dot{m}'_{st9} = \dot{m}_{st7} + \dot{m}_{st}$

6.4 Economic analysis

Economic analysis essentially entails the evaluation of costs and benefits. It starts by ranking projects based on economic viability to aid better allocation of resources. It aims at analyzing the welfare impact of a project.

There are several ways to determine the feasibility of a project:

- Present value (PW)
- Annual value (AW)
- Simple Payback Period (SPBP)
- Discount Payback Period (DPBP)
- Internal rate of return (IRR)

6.5 Simple Payback Period Calculation

Simple Payback Period (SPBP) indicates the amount of time it takes to recover the cost of an investment, and this metric is useful before making any decisions, especially when an investor needs to make a quick judgment about an investment project. The Simple Payback Period must be taken in consideration during economic analysis stage.

It can be calculated by using following formula:

$$\text{SPBP} = \frac{\textbf{Initial investment}\ (\$)}{\textbf{Cash flow per year}\ (\textbf{Saving})(\$)}$$

Key economic and financial accounting assumptions are summarized in Table 10. The project timeline is 10 years. Depreciation is calculated using the variable declining balance method. In this study, an inflation rate of 2.5% is applied to all future costs and revenues in cash flow calculations. The real discount rate is 10%, which is composed of the nominal discount rate of 7.5% and the 2.5% inflation rate.

Table 10: Financial accounting assumptions

Parameter	Input Value
Nominal discount rate	7.5%
Inflation rate	2.5%
Plant life	10

The initial cost of the project which is the cost of equipment, the cost of construction, land, etc., is estimated at $1.6 million in the first year of the project was estimated by simple costs from [40], [41]. But the initial cost of the project will be multiplied by ten times due to the enormity of the project, bringing the initial cost to 16 million dollars. There are annual costs of maintenance & repair cost and labor cost estimated at $14,600/year, $262,800/year [40], [41]. Table 11 summarizes all the simple prices that were adopted.

Table 11:Equpment initial costs [40, 41]

Equipment	Cost (USD)
Pyrolyzer	250,000
Dryer	42,000
Grinding	500,000
(3) Tractor	45000
(3) Storege /Proccesing	711,513
Genset	39,000
Skid Loader	64,000

There are annual returns (profits) resulting from biochar Selling Price [$/kg] = 0.65, Bio oil Selling Price [$/kg] = 0.79 or 0.22 [42], [43]. Where the annual production amount of both biochar and oil is estimated at 9905370 kg/year, 2971830 kg/year, respectively.

It is worth noting that the municipality in Nablus pays 12 $/ ton to transport one ton of waste to Zahrat Al-Finjan, which is an amount of 525,600 $ annually. Therefore, the project would reduce the annual payments in addition to the profits gained from selling Biochar and Bio-Oil.

In this work, a comprehensive Life Cycle Cost Assessment (LCCA) for the production of biochar based on municipal solid waste and its application on the ground was carried out according to three different scenarios in terms of sales and returns, Table 12 summarizes all the scenarios.

Table 12: Cost of Selling Scenarios

Initial cost = 16 million $	Biochar Selling Price	Bio oil Selling Price	
Scenario	0.65 ($/kg)	0.79 ($/kg)	0.22 ($/kg)
1	✔	✔	
2	✔		✔
3		✔	

Scenario 1

The annual net profit results from the summation of annual profits and considering the maintenance and labor costs, is estimated to be 8.5 $ million. Figure 9 shows the cash flow diagram for Results of the simulation of the first scenario of a biochar production project from MSW, where all economic parameters of the project are set.

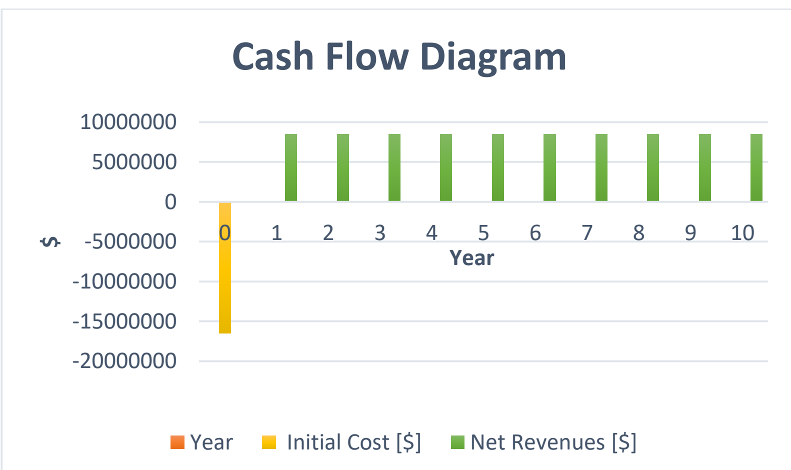


Figure 9: Cash flow diagram of the simulation of the first scenario

Scenario 2

The annual net profit results from the summation of annual profits and considering the maintenance and labor costs, is estimated to be 6.8 $ million. Figure 10 shows the cash flow diagram for Results of the simulation of the second scenario of a biochar production project from MSW, where all economic parameters of the project are set.

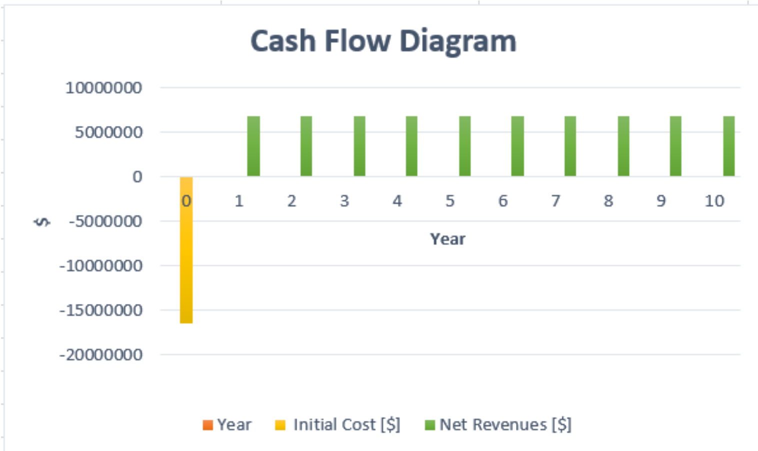


Figure 10:Cash flow diagram of the simulation of the second scenario

Scenario 3

The annual net profit results from the summation of annual profits and considering the maintenance and labor costs, is estimated to be 2 $ million. Figure 11 shows the cash flow diagram for Results of the simulation of the third scenario of a biochar production project from MSW, where all economic parameters of the project are set.

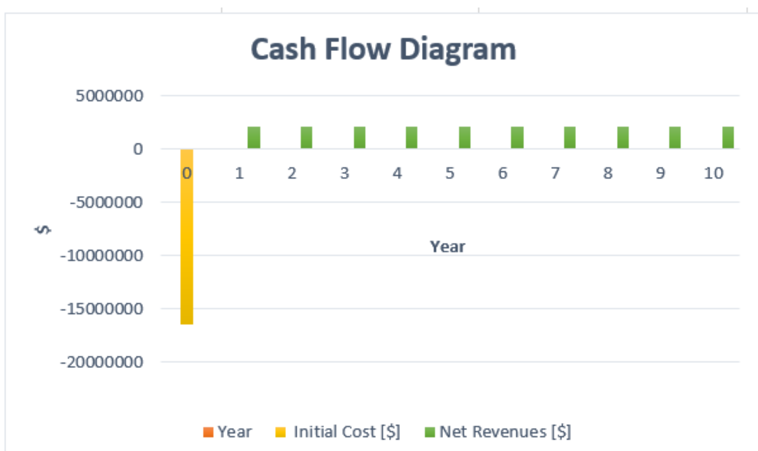


Figure 11: Cash flow diagram of the simulation of the third scenario

Simple Payback period was calculated for each scenario, Table 13 shows the simulation results:

Table 13: Simple payback period for each scenario

Initial cost = 16 million $	Simple Payback Period (SPBP)
Scenario	Years (y)
1	1.5
2	2.5
3	7.5

The accumulation of waste in large quantities in unprocessed landfills has very significant impacts on the environment and health. According to a study conducted in 2019, it is estimated that the amount of waste will increase by 4% annually, which means that we will be dealing with even greater quantities every year. Therefore, an effective and radical solution must be found to stop or reduce the accumulation and exploitation of waste for the benefit of the environment and society.

In addition to the benefit that the environment will have because of the biochar. Since biochar is a compound rich in stable carbon (C), it is expected to increase carbon in plants and reduce carbon presence in the atmosphere. It is estimated that the remaining time for carbon in plant material lasts for decades, while its lifespan ranges from hundreds of thousands of years in biological carbon. Biochar also affects soil properties, which may have a direct impact on plant growth and enhancement and crop yield improvement. So that it works to compensate for the poor soil nutrients, improve the efficiency of fertilizer use, and maintain the appropriate moisture for plants.

There is no doubt that the process of accumulating harmful waste in landfills that are not qualified to receive all these quantities will continue for long periods. This, in turn, will affect the soil in that area, and in turn affect plants, animals, and humans. In addition to the accumulation of unpleasant odors in the area and its surroundings.

The Palestinian market will also need to import fertilizers from the occupation, which gives the occupation the ability to control the quality of Palestinian soil and plant products.

Failure to establish the project will deprive the state of a good source of energy, as this waste is of high value that must be used and converted into fuel. Which gives the country even a little hope of independence in the field of energy from occupation.

As for the economic aspect of the project, it has proven its ability to achieve profits in record time. So that the numbers show, at the worst, that the capital can be recovered in the seven and a half year of the project's life.

In addition to creating job opportunities for Palestinian youth of all categories and experiences that must be exploited inside the country and to serve Palestine.

6.6 Environmental Analysis

The continuous work to separate and take more than half the amount of waste periodically and continuously reduces the volume of waste and the time of its condensation in the landfill, and this leads us to reduce the unpleasant smell and reduce the chance of soil and water pollution in the area and its surroundings.

The establishment of the project will improve the economy resulting from the sale of biochar and bio-oil, as well as create job opportunities for many workers and add a good brand to the Palestinian market.

On the other hand, as with all projects, it has many drawbacks. In the construction phase represented by excavation and construction, many pollutants will be produced that will negatively affect the environment represented in air, water, plants and animals as well. All the way to the operating stages that start with cutting, which will affect health in terms of the noise it produces. Drying will also affect the air from emissions. In addition to the reactor, which can release heat and toxic emissions that affect the health of the worker or the surrounding population and the quality of air and water.

As for the stage of operation and production, it is divided into several stages. Some risks that can be addressed at each stage will be presented, and then mitigating measures will be proposed that must be followed to reduce the negative effects of the project.

Drying:

At this stage, we are likely to face problems in the leakage of juices and fluids that come out of the waste, and this in turn can affect groundwater and soil, and thus plants and animals. In addition to the leakage of very hot and dry steam, this could affect the health of workers and the surrounding climate in the area.

Reactor:

The slow pyrolysis reactor reaches high temperatures, so there is a fear of the reactor exploding or leaking its heat to the outside, which negatively affects the factory environment, which includes the workers.

Bio-Oil, Bio-Gas and Biochar stores:

As it is clear, we are dealing with flammable materials. Therefore, bio-oil must be stored before selling it in special containers away from any source of heat or pressure, otherwise it could explode and cause a disaster for the factory and its surroundings, as well as dealing with biogas. As for biochar, it is important to put it in special bags away from moisture and tightly closed to ensure that mice do not enter the area.

Cooling system:

To obtain bio-oil, we need to cool the syngas released from the pyrolysis process. The water from the waste drying process is reused to cool the biochar and the syngas. But what causes concern at this stage is the possibility of water leaking from the cooling pipes, which will cause the facility to overheat. It is also worth noting that the water runs at a high pressure, so any leakage, no matter how small it seems, causes problems for the facility and the machines used.

Mitigation

As a mitigation measure for the drying stage, we can arm the lands used to put waste before it enters the drying machine. A suitable drying machine must also be chosen that does not allow the juice to leak out except through special tubes that collect liquids and dispose of them in proper ways and in accordance with Palestinian and international laws. It must also choose high-efficiency and strong pipes that can withstand the pressure and temperature of the steam that will be used at this stage, but this must be combined with periodic checks and repairs.

The temperature increase with time must be controlled in carefully studied and precise ways to ensure that no explosion accidents occur. The walls of the reactor must be insulated with special materials.

The containers that will contain Syngas and Bio-oil are among the most important dilemmas that must be taken care of and choosing the appropriate containers with high characteristics. As for the biochar bags, the appropriate ones should be purchased or the storage period should not be prolonged, and the stores should be equipped with good ventilation to ensure the removal of moisture.

The cooling system depends mainly on the quality of the pipes used, so the pipes must be designed in proportion to the pressure, temperature and quantity of water needed, and the appropriate type must be chosen. In addition to insulating pipes and regular maintenance by using devices that detect heat or water leakage.

The construction phase of the project would negatively affect the air and water. Where excavations can pollute the air with dust and pollutants can reach the water. Drilling will negatively and temporarily affect air, water, health, etc., while it will positively affect employment. Therefore, some mitigating measures can be taken. First, the drilling should not be for continuous hours, so the drilling can be fragmented for intermittent periods. Water sprinklers can also be used while drilling to reduce dust flying while drilling. As for the health of workers, they can be provided with protective supplies to protect them from the danger of digging or inhaling dust. It is worth noting that if drilling is done in the winter, it will negatively affect the rainwater, and therefore it is preferable to start the project and dig in the summer.

Chapter 7

Conclusion and Recommendations

Biochar is an ingredient that is added to the soil to make it richer and more fertile. Biochar is produced from organic materials. It can store carbon so it has the potential to mitigate climate change. After long research, it was found that slow pyrolysis is the best way to get the largest amount of biochar from the organic portion of MSW.

It became clear that Biochar can alleviate the waste problem in Palestine. It also offers hope for energy independence. Where it is possible to produce enough quantities of bio-oil that can be used in the production of electrical energy.

120 tons of waste was disposed of per day over 6 cycles, the duration of one cycle is 4 hours. The amount of input per 4 hours after drying (12924 kg / 4 hours) with a moisture content of 7%, the amount of heat required for drying to reach this amount of waste Dried was 26,289 MJ /4h. The initial energy required for the pyrolysis process for the amount of waste entered into the reactor after drying (36060 MJ/ batch), however, the energy of the syngas will be utilized for the continuation of the following cycles.

The results indicate also indicated that each cycle would produce Biochar, Bio-Oil, and Syngas with an amount of 4,523 kg /4h, 1,357 (10% water) kg/4h, and 4,523 kg /4h, respectively. As for the syngas energy, which is estimated at 60,161 (MJ/ batch) is sufficient as an energy input to the pyrolysis reactor, therefore, we do not need another energy source to continue the process.

The initial cost was estimated at 16 million dollars, based on several previous studies, in addition to an interview we conducted with Eng. Aktham Badran, who works as the director of the Services Council in the city of Tulkarm. The project has proven its ability to recover the capital over a period of 1.5-7.5 years.

Most recommend making a detailed EIA report so that all aspects of the project are seen. It must also be attached to the opinions and approval of the concerned population. Also, more focus is given to bio-oil and methods of treating, utilizing, and storing it. It is also important to expand the study of the appropriate filters to ensure that the surrounding air is not polluted and methods of controlling fumes.

References

[1] Jeffery, S., Verheijen, F., van der Velde, M., & Bastos, A. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture, Ecosystems & Environment, 144(1), 175–187.

[2] N. Atallah, N. (2020) “فلسطين: إدارة النفايات الصلبة تحت الاحتلال | Heinrich-Böll-Stiftung | مكتب فلسطين والأردن,” Heinrich-Böll-Stiftung. https://ps.boell.org/ar/2020/10/07/palestine-solid-waste-management-under-occupation.

[3] “The_Palestinian_Farmer-English.pdf.” Accessed: May 06, 2021. [Online]. Available https://www.arij.org/files/arijadmin/IDRC/baselineenglish/The_Palestinian_Farmer-English.pdf.

[4] V. Thöni, S. K.I. Matar “SWM-in-Palestine-report-Thoni-and-Matar-2019_compressed-1.pdf.”, vol. 102, Sep. 2019. https://www.cesvi.eu/wp-content/uploads/2019/12/SWM-in-Palestine-report-Thoni-and-Matar-2019_compressed-1.pdf .

[5] R. Musleh, “Country report on the solid waste management.pdf.” vol. 92, April. 2014 Available: http://www.environment.pna.ps/ar/files/Country%20report%20on%20the%20solid%20waste%20management.pdf.

[6] R. Musleh, “Country report on the solid waste management.pdf.” vol. 92, April. 2014 Available: http://www.environment.pna.ps/ar/files/Country%20report%20on%20the%20solid%20waste%20management.pdf.

[7] S. Taherymoosavi, V. Verheyen, P. Munroe, S. Joseph, and A. Reynolds, “Characterization of organic compounds in biochars derived from municipal solid waste,” *Waste Management*, vol. 67, pp. 131–142, Sep. 2017, doi: 10.1016/j.wasman.2017.05.052.

[8] M. Becidan, “Experimental Studies on Municipal Solid Waste and Biomass Pyrolysis “Theses at NTNU, 2007:125 .vol. 163, Trondheim, May 2007 .Available : http://hdl.handle.net/11250/233333.

[9] P. Randolph *et al.*, “Effect of biochars produced from solid organic municipal waste on soil quality parameters,” *Journal of Environmental Management*, vol. 192, pp. 271–280, May 2017, doi: 10.1016/j.jenvman.2017.01.061.

[10] G. Liu, M. Xie, and S. Zhang, “Effect of organic fraction of municipal solid waste (OFMSW)-based biochar on organic carbon mineralization in a dry land soil,” *J Mater Cycles Waste Manag*, vol. 19, no. 1, pp. 473–482, Jan. 2017, doi: 10.1007/s10163-015-0447-y.

[11] S. E. Hale *et al.*, “Quantifying the Total and Bioavailable Polycyclic Aromatic Hydrocarbons and Dioxins in Biochars,” *Environ. Sci. Technol.*, vol. 46, no. 5, pp. 2830–2838, Mar. 2012, doi: 10.1021/es203984k.

[12] “Edosomwan, N.L., Onwumah, B.I., 2008. Impact of municipal solid waste on some soil properties in Central Southern Nigeria. Indian J. Agric. Res. 42 (4), 244–251.”

[13] J. W. Gabhane, V. P. Bhange, P. D. Patil, S. T. Bankar, and S. Kumar, “Recent trends in biochar production methods and its application as a soil health conditioner: a review,” *SN Appl. Sci.*, vol. 2, no. 7, p. 1307, Jul. 2020, doi: 10.1007/s42452-020-3121-5.

[14] S. Elkhalifa, T. Al-Ansari, H. R. Mackey, and G. McKay, “Food waste to biochars through pyrolysis: A review,” *Resources, Conservation and Recycling*, vol. 144, pp. 310–320, May 2019, doi: 10.1016/j.resconrec.2019.01.024.

[15] J. A. Ippolito *et al.*, “Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review,” *Biochar*, vol. 2, no. 4, pp. 421–438, Dec. 2020, doi: 10.1007/s42773-020-00067-x.

[16] D. Wang, P. Jiang, H. Zhang, and W. Yuan, “Biochar production and applications in agro and forestry systems: A review,” *Science of The Total Environment*, vol. 723, p. 137775, Jun. 2020, doi: 10.1016/j.scitotenv.2020.137775.

[17] V. Gunarathne, A. Ashiq, S. Ramanayaka, P. Wijekoon, and M. Vithanage, “Biochar from municipal solid waste for resource recovery and pollution remediation,” *Environ Chem Lett*, vol. 17, no. 3, pp. 1225–1235, Sep. 2019, doi: 10.1007/s10311-019-00866-0.

[18] A. Méndez, J. Paz-Ferreiro, E. Gil, and G. Gascó, “The effect of paper sludge and biochar addition on brown peat and coir based growing media properties,” *Scientia Horticulturae*, vol. 193, pp. 225–230, Sep. 2015, doi: 10.1016/j.scienta.2015.07.032.

[19] L. Dai *et al.*, “Production of bio-oil and biochar from soapstock via microwave-assisted co-catalytic fast pyrolysis,” *Bioresource Technology*, vol. 225, pp. 1–8, Feb. 2017, doi: 10.1016/j.biortech.2016.11.017.

[20] M. J. Kabir, A. A. Chowdhury, and M. G. Rasul, “Pyrolysis of Municipal Green Waste: A Modelling, Simulation and Experimental Analysis,” *Energies*, vol. 8, no. 8, Art. no. 8, Aug. 2015, doi: 10.3390/en8087522.

[21] M. Tripathi, J. N. Sahu, and P. Ganesan, “Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review,” *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 467–481, Mar. 2016, doi: 10.1016/j.rser.2015.10.122.

[22] H. Yu *et al.*, “Biochar amendment improves crop production in problem soils: A review,” *Journal of Environmental Management*, vol. 232, pp. 8–21, Feb. 2019, doi: 10.1016/j.jenvman.2018.10.117.

[23] K. N. Palansooriya *et al.*, “Impacts of biochar application on upland agriculture: A review,” *Journal of Environmental Management*, vol. 234, pp. 52–64, Mar. 2019, doi: 10.1016/j.jenvman.2018.12.085.

[24] P. Yuan, J. Wang, Y. Pan, B. Shen, and C. Wu, “Review of biochar for the management of contaminated soil: Preparation, application and prospect,” *Science of The Total Environment*, vol. 659, pp. 473–490, Apr. 2019, doi: 10.1016/j.scitotenv.2018.12.400.

[25] L. Qian *et al.*, “Effective removal of heavy metal by biochar colloids under different pyrolysis temperatures,” *Bioresource Technology*, vol. 206, pp. 217–224, Apr. 2016, doi: 10.1016/j.biortech.2016.01.065.

[26] J. Wang and S. Wang, “Preparation, modification and environmental application of biochar: A review,” *Journal of Cleaner Production*, vol. 227, pp. 1002–1022, Aug. 2019, doi: 10.1016/j.jclepro.2019.04.282.

[27] K. J. T. Castillo, M. C. Maguyon-Detras, V. P. Migo, and C. G. Alfafara, “Parametric and optimization studies for biochar production from municipal solid wastes (MSW) via pyrolysis,” *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 778, p. 012078, May 2020, doi: 10.1088/1757-899X/778/1/012078.

[28] K. Vijayaraghavan, “Recent advancements in biochar preparation, feedstocks, modification, characterization and future applications,” *Environmental Technology Reviews*, vol. 8, no. 1, pp. 47–64, Jan. 2019, doi: 10.1080/21622515.2019.1631393.

[29] D. Pandey, A. Daverey, and K. Arunachalam, “Biochar: Production, properties and emerging role as a support for enzyme immobilization,” *Journal of Cleaner Production*, vol. 255, p. 120267, May 2020, doi: 10.1016/j.jclepro.2020.120267.

[30] H. J. Park, Y.-K. Park, and J. S. Kim, “Influence of reaction conditions and the char separation system on the production of bio-oil from radiata pine sawdust by fast pyrolysis,” *Fuel Processing Technology*, vol. 89, no. 8, pp. 797–802, Aug. 2008, doi: 10.1016/j.fuproc.2008.01.003.

[31] O. D. Nartey and B. Zhao, “Biochar Preparation, Characterization, and Adsorptive Capacity and Its Effect on Bioavailability of Contaminants: An Overview,” *Advances in Materials Science and Engineering*, vol. 2014, p. e715398, Oct. 2014, doi: 10.1155/2014/715398.

[32] A. Sharma, V. Pareek, and D. Zhang, “Biomass pyrolysis—A review of modelling, process parameters and catalytic studies,” *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 1081–1096, Oct. 2015, doi: 10.1016/j.rser.2015.04.193.

[33] S. Tupsakhare, T. Moutushi, M. J. Castaldi, M. A. Barlaz, S. Luettich, and C. H. Benson, “The impact of pressure, moisture and temperature on pyrolysis of municipal solid waste under simulated landfill conditions and relevance to the field data from elevated temperature landfill,” *Science of The Total Environment*, vol. 723, p. 138031, Jun. 2020, doi: 10.1016/j.scitotenv.2020.138031.

[34] M. I. Jahirul, M. G. Rasul, A. A. Chowdhury, and N. Ashwath, “Biofuels Production through Biomass Pyrolysis —A Technological Review,” *Energies*, vol. 5, no. 12, Art. no. 12, Dec. 2012, doi: 10.3390/en5124952.

[35] F. Cheng, H. Luo, and L. M. Colosi, “Slow pyrolysis as a platform for negative emissions technology: An integration of machine learning models, life cycle assessment, and economic analysis,” *Energy Conversion and Management*, vol. 223, p. 113258, Nov. 2020, doi: 10.1016/j.enconman.2020.113258.

[36] G. Finnveden *et al.*, “Recent developments in Life Cycle Assessment,” *Journal of Environmental Management*, vol. 91, no. 1, pp. 1–21, Oct. 2009, doi: 10.1016/j.jenvman.2009.06.018.

[37] Y. Makkawi, Y. El Sayed, M. Salih, P. Nancarrow, S. Banks, و T. Bridgwater, "Fast pyrolysis of date palm (Phoenix dactylifera) waste in a bubbling fluidized bed reactor", *Renew. Energy*, 2019 ,730–719 ص ,143 م, doi: 10.1016/j.renene.2019.05.028.

[38] P. Baggio, M. Baratieri, A. Gasparella, and G. A. Longo, “Energy and environmental analysis of an innovative system based on municipal solid waste (MSW) pyrolysis and combined cycle,” Applied Thermal Engineering, vol. 28, no. 2, pp. 136–144, Feb. 2008, doi: 10.1016/j.applthermaleng.2007.03.028.

[39] P. Dianda, Mahidin, و E. Munawar, "Production and characterization refuse derived fuel (RDF) from high organic and moisture contents of municipal solid waste (MSW)", *IOP Conf. Ser. Mater. Sci. Eng.*, ,012035 ص ,334 م 2018, doi: 10.1088/1757-899x/334/1/012035.

[40] A. Wrobel-Tobiszewska, M. Boersma, J. Sargison, P. Adams, و S. Jarick, "An economic analysis of biochar production using residues from Eucalypt plantations", *Biomass Bioenergy*, 2015 ,182–177 ص ,81 م, doi: 10.1016/j.biombioe.2015.06.015.

[41] G. Agegnehu, A. K. Srivastava, و M. I. Bird, "The role of biochar and biochar-compost in improving soil quality and crop performance: A review", *Appl. Soil Ecol.*, 2017 ,170–156 ص ,119 م, doi: 10.1016/j.apsoil.2017.06.008.

[42] J. Yoder, S. Galinato, D. Granatstein, و M. Garcia-Pérez, "Economic tradeoff between biochar and bio-oil production via pyrolysis", *Biomass Bioenergy*, 2011 ,1862–1851 ص ,5 عدد ,35 م, doi: 10.1016/j.biombioe.2011.01.026.

[43] A. Eicher, “Comparison of Biomass to Bio-oils Reactor Systems: Direct Conversion vs. Companion Coal Gasification,” p. 55.