Chapter

Co-Pyrolysis of Biomass Solid Waste and Aquatic Plants

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Abstract

Reduction of conventional fuel has encouraged to find new sources of renewable energy. Oil produced from the pyrolysis method using biomass is considered as an emerging source of renewable energy. Pyrolytic oil produced in pyrolysis needs to be upgraded to produce bio-oil that can be used with conventional fuel. However, pyrolytic oil contains high amounts of oxygen that lower the calorific value of fuel, creates corrosion, and makes the operation unstable. On the other hand, the upgradation process of pyrolytic oil involves solvent and catalyst material that requires a high cost. In this regard, the co-pyrolysis method can be used to upgrade the pyrolytic oil where two or more feedstock materials are involved. The calorific value and oil yield in the co-pyrolysis method are higher than pyrolytic oil. Also, the upgraded oil in the co-pyrolysis method contains low water that can improve the fuel property. Therefore, the co-pyrolysis of biomass waste is an emerging source of energy. Among different biomasses, solid waste and aquatic plants are significantly used as feedstock in the co-pyrolysis method. As a consequence, pressure on conventional fuel can be reduced to fulfill the demand for global energy. Moreover, the associated operating and production cost of the co-pyrolysis method is comparatively low. This method also reduces environmental pollution.

Keywords: co-pyrolysis, pyrolytic oil, biomass solid waste, aquatic plants, conventional fuel

1. Introduction

The reduction of conventional fuel sources such as coal, natural gas, and petroleum encourages to search for new sources of renewable energy. Previous literature predicts that coal would be the sole fossil fuel after 2042 [1]. On the other hand, the increase in fossil fuel prices and sustainable effects on the environment are the primary reasons for the use of alternate renewable energy [2–4]. A number of different ways are now underway to search for alternate sources of energy that are environmentally-friendly. However, environmental impact is more apparent after an environmental summit of the earth [5]. Therefore, to reduce environmental warming and pollution, it is required to control emissions produced by fossil fuels. The effective way of reducing environmental pollution and dependency on conventional fuel is to use renewable sources of energy [3, 6, 7].

There are a number of different alternative sources of available energy that can be utilized to substitute conventional sources of energy. The selection of effective and efficient alternative sources of energy is important. In general, an alternate source of energy is suggested to select based on cost, availability, and environmental impact [4]. In this case, biomass is a prospective source of future energy that is abundant in nature, less costly, and environmental-friendly. Biomass is a significant source of bioenergy that can be utilized to generate energy and used to reduce environmental warming [8]. Biomass energy source is significant because it is the only available renewable resources that can be used to produce all three types of fuels, such as solid (char), liquid (oil), and gas (CH_4) [9]. By comparing different biomass conversion methods, such as composting, incineration, landfill, and pyrolysis, it is found that pyrolysis is an effective biomass conversion process [10]. Pyrolysis method can be used to process biomass solids and produce solid, liquid, and gaseous fuel. The pyrolysis method can be used to process biomass solids and produce solid, liquid, and gaseous fuel. This process can also be able to produce the highest quantity of yield in liquid form (~75 wt.%) at a moderate level of temperature (~550 °C) [9]. The remaining quantity of yield can be reduced by changing different operating parameters in the pyrolysis process. The liquid yield produced from the pyrolysis method is called pyrolytic oil and it can be used directly to operate engines, boilers, furnaces, and turbines [11]. Moreover, pyrolytic oil reduces the environmental emissions and global warming [12].

However, pyrolytic oil generated from the pyrolysis method is less efficient on the basis of fuel combustion when compared to conventional fuels, such as diesel, petrol, etc. This is due to the reason that pyrolytic oil usually contains a high quantity of oxygen that creates unnecessary combustion problems. In different previous research, it was found that pyrolytic oil contained approximately 30–60 wt. % of oxygen in the form of water molecules [11, 13–15]. In addition, high oxygen contents in pyrolytic oil cause lower calorific value and instability of operation. As a consequence, it is required to upgrade and improve pyrolytic oil generated in the pyrolysis process.

To improve the quality of pyrolytic oil, it is required to reduce the quantity of dissolved oxygen. It is possible to reduce the dissolved oxygen from pyrolytic oil by catalytic cracking, co-pyrolysis, and catalytic cracking and hydrodeoxygenation (HDO) process.

In the catalytic cracking and hydrodeoxygenation (HDO) method, external catalysts are added in the pyrolysis process. However, the addition of catalysts increases the operating cost of the pyrolysis process. It also increases the number of solid materials at disposal [16]. Overall, this process is costly, complex, and require higher pressure during operation. In contrast, the co-pyrolysis method is an effective and efficient process that can improve the quality of pyrolytic oil.

Therefore, this chapter presents the co-pyrolysis method of biomass feedstocks. This chapter also presents the generation of liquid fuel from solid waste (wood, plastic) and aquatic plants (water hyacinth) using the co-pyrolysis method. Additionally, by using biomass solid wastes (plastic, wood) as feedstock material, the co-pyrolysis method can reduce environmental pollution and help the global waste management system. This method also uses invasive aquatic plants (water hyacinth) as feedstock material and reduces the negative effects of water hyacinth on aquatic flora, fauna. Hence, solid and aquatic plant biomass would be a potential source of energy that produces less impact on the environment.

The outcomes of this chapter will help to decrease the pressure on conventional fuel. On the other hand, the majority of the recent literature shows the use of rice straw, pinewood, and plastic material as feedstocks in the co-pyrolysis method. However, this chapter shows the generation of product yield for two different combinations of feedstocks and compares the performance of them at a different proportion that is rare in previous research. By effectively maintaining the required proportion of biomass feedstock materials, it is possible to generate a significant quantity of solid, liquid, and gas yield. As a consequence, biomass feedstocks would be a feasible option to fulfill the global energy demand.

2. Biomass conversion techniques

Biomass can be converted in a number of different ways. The most significant ways are pyrolysis, gasification, combustion, and liquefaction, as shown in **Figure 1**. On the other hand, all biomass conversion techniques are performed using three major process technologies, as depicted in **Figure 2**.

2.1 Pyrolysis

Pyrolysis is defined as the method of heating organic biomass in absence of oxygen. This is due to the reason that without oxygen, there is no combustion occurred in biomass materials. However, applying heat decomposes the chemical components of biomass materials such as lignin, cellulose, and hemicellulose and produce charcoal and combustible gases [17].

In the pyrolysis method, the produced combustible gases are condensed to a combustible liquid called pyrolytic oil. The other products of the pyrolysis method are CO_2, CO, H_2, and HC. Therefore, the pyrolysis method generates three types of products, such as solid (charcoal), liquid (bio-oil/pyrolytic oil), and gas (synthetic gas). **Figure 3** presents the overall schematic diagram of the pyrolysis method that generates pyrolytic oil.

Moreover, in pyrolysis method, biomass feedstock materials are decomposed in pyrolytic oil by the following reaction mechanism Equations [18]:

$$\text{Biomass feedstocks} \rightarrow H_2O + \text{residue materials (unreacted)} \quad (1)$$

$$\text{Residue materials (unreacted)} \rightarrow \text{Volatile matters}_1 + \text{Charcoal}_1 + \text{Gases}_1 \quad (2)$$

$$\text{Charcoal}_1 \rightarrow \text{Volatile matters}_2 + \text{Gases}_2 + \text{Charcoal}_2 \quad (3)$$

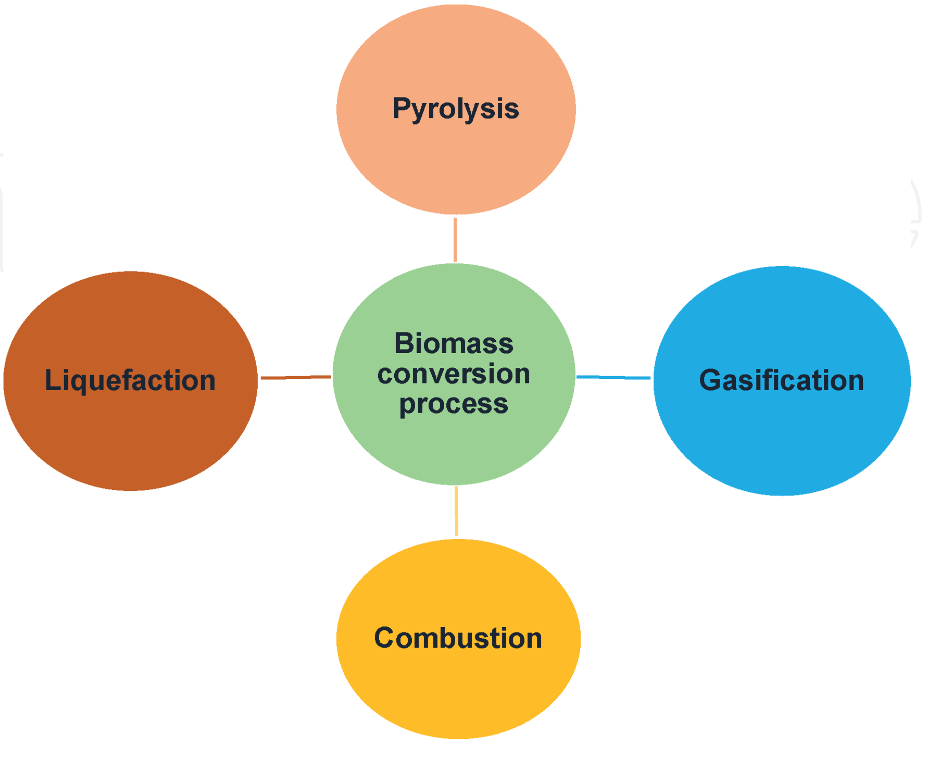

Figure 1.
Biomass conversion techniques.

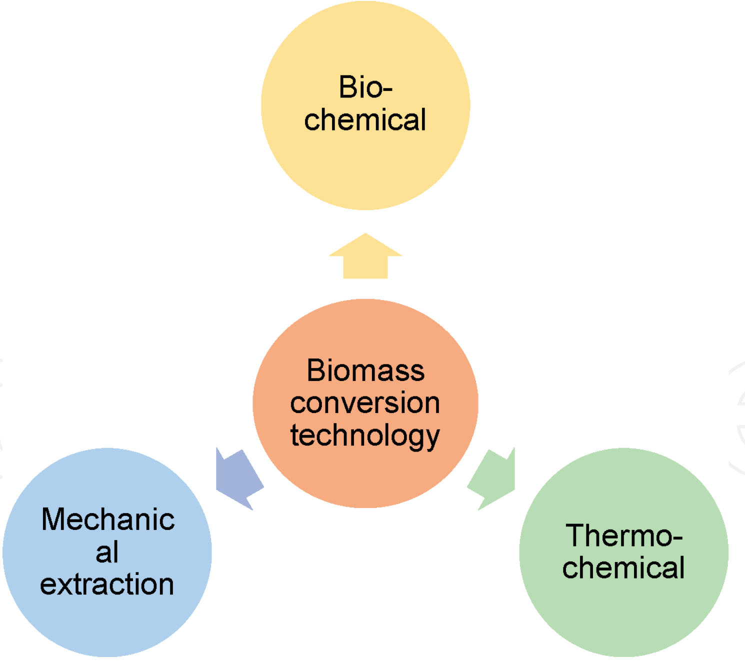

Figure 2.
Flow diagram of the pyrolysis process.

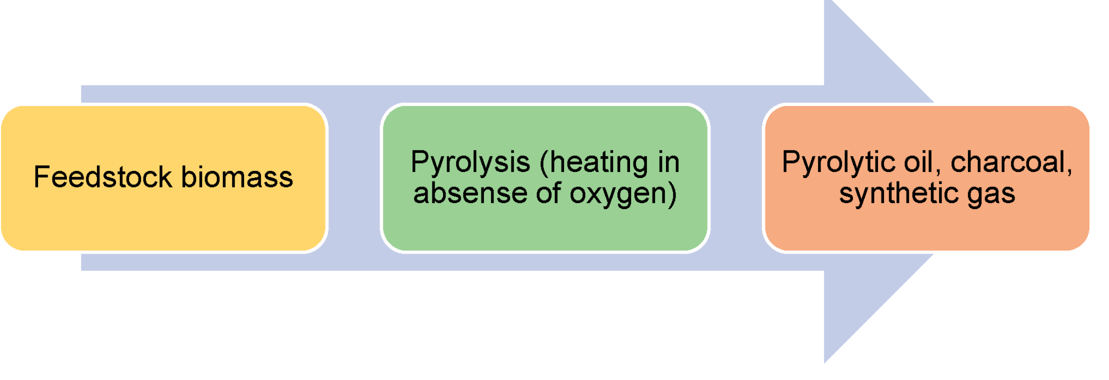

Figure 3.
Biomass conversion process technologies [17].

Therefore, in the biomass pyrolysis method, firstly, moisture contents, and volatile matters are lost as presents by Eq. (1). Secondly, unreacted residue materials are transformed into volatile matters, as shown in Eq. (2). Finally, charcoal material is re-arranged at a slower step, as shown in Eq. (3).

Depending on the reaction temperature, residence time, and rate of heating, the pyrolysis process can be classified as fast, slow, and flash pyrolysis. Pyrolysis process usually occurs in a fixed bed, fluidized bed, moving bed, suspended bed reactors.

However, the generated pyrolytic oil in the pyrolysis process contains a higher quantity of oxygen that decreases internal combustion engines' efficiency. Therefore, up-gradation of pyrolytic oil generated from the pyrolysis method is necessary. The pyrolytic oil generated from the pyrolysis method can be upgraded by esterification, emulsification, or catalytic cracking. All these up-gradation methods include extra operating costs for the pyrolysis process and they are rather costly. The other effective method of producing high-quality pyrolytic oil is the co-pyrolysis method that can produce high-quality pyrolytic oil with less quantity of oxygen.

Figure 4 shows the upgradation methods of pyrolytic oil generated from biomass pyrolysis method.

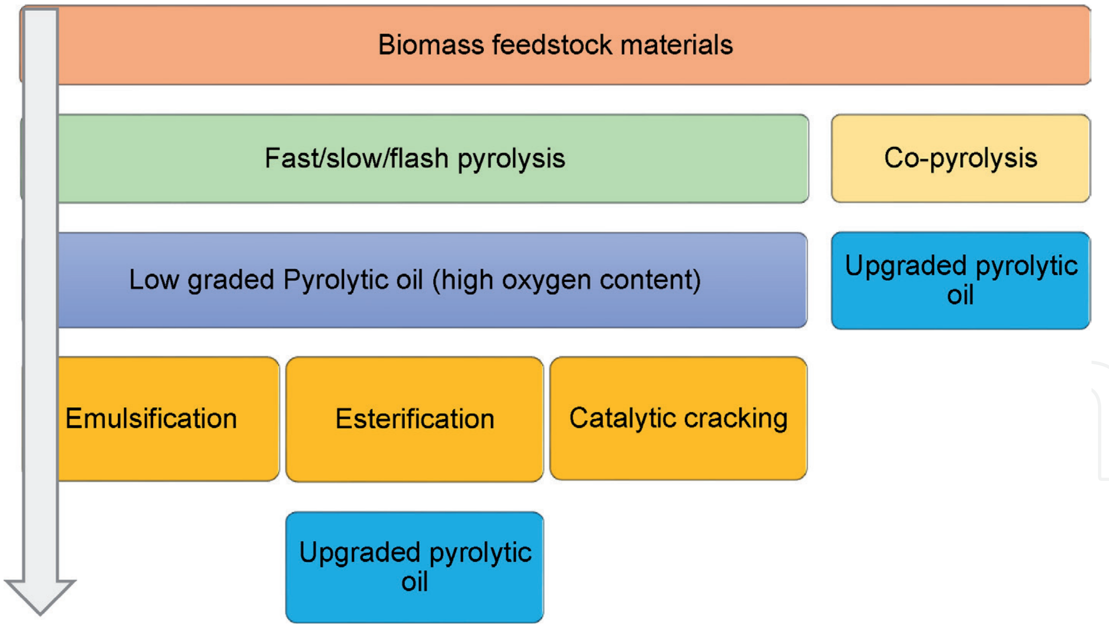

Figure 4.
Upgradation methods of pyrolytic oil [19].

2.2 Co-pyrolysis

Co-pyrolysis is the process where two or more feedstock materials include to improve the quality of pyrolytic oil in absence of oxygen at a moderate temperature (~500 °C). Effectiveness and simplicity are two important characteristics of the co-pyrolysis process. **Figure 5** shows the overall process of co-pyrolysis.

It is seen from **Figure 5** that, in the co-pyrolysis method, two or more feedstock materials are dried and ground to prepare feedstock material. After that inert gases are required to add to the reactor. Inert gases use to speed up the sweeping vapors of feedstock materials from the pyrolysis region to the condenser region. Nitrogen gas is used as an inert gas in the co-pyrolysis process due to its low cost. Initially, charcoal and combustible gases are produced. After condensation, combustible gases generate upgraded pyrolytic oil. Therefore, the co-pyrolysis method requires three steps for the generation of pyrolytic oil, such as preparation of feedstock materials, co-pyrolysis, and condensation.

Drying of feedstock material can be done using the oven method at a higher temperature (~105 °C) for 1 day. The drying process is required to remove the

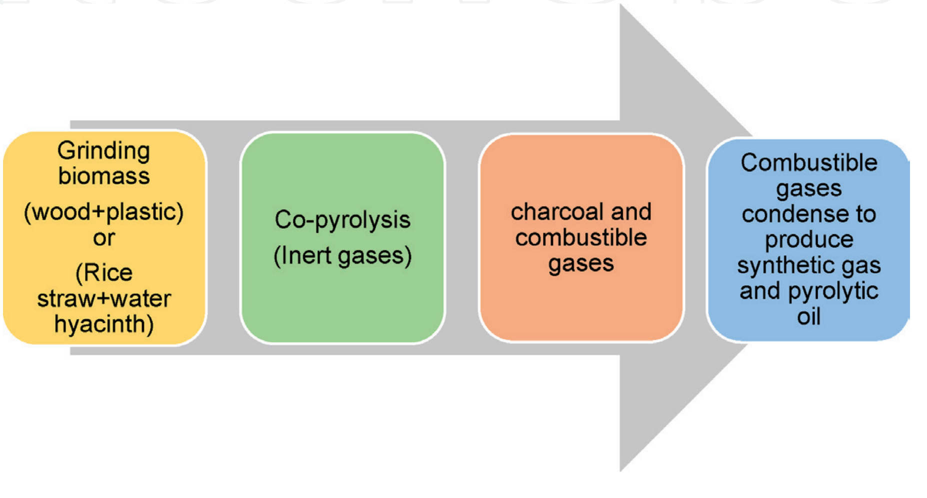

Figure 5.
Overall process of co-pyrolysis [9].

Feedstock materials	Temperature(°C)	Inert gas	Pyrolytic oil (wt.%)
Wood, plastic, rice husk, rice straw, water hyacinth	300 ~ 500	N_2	45–75

Table 1.
Optimum operating conditions of co-pyrolysis method [9].

moisture contents in the feedstock material. However, for industrial purposes, the amount of required heat is higher than lab-scale. Hence, process integration is used to heat feedstock materials [9].

The optimum temperature of the co-pyrolysis process is considered as 400 ~ 600 °C. At this temperature, approximately 45 wt. % of pyrolytic oil is usually produced from feedstock material [9]. **Table 1** presents the optimum operating conditions of co-pyrolysis method for different feedstock materials.

In this chapter, pinewood with plastic material, and rice straw with water hyacinth material is considered as feedstock materials for the co-pyrolysis process. Pinewood [20, 21] and waste plastic [22, 23] materials are commonly available in environment that can create environmental pollution.

3. Reaction parameters of co-pyrolysis process

Reactions of the co-pyrolysis method are complex and it includes a number of different co-pyrolysis reactions. The biomass co-pyrolysis process and their reactions depend on different parameters, such as the effect of feedstock materials, blending ratio, rate of heat, temperature, reactor type, etc. This section of the chapter presents the effect of different parameters on the co-pyrolysis method.

3.1 Effect of different feedstocks

Biomass feed materials consist of lignin, cellulose, and hemicellulose [24]. These components generate synergistic effects on the thermal behavior of biomass. It is considered that the cracking of biomass depends on the H and OH radicals release during biomass pyrolysis [25, 26]. On the other hand, hemicellulose components serve effects of promotion on biomass conversion during co-pyrolysis process [27]. **Table 2** shows the characteristics of different biomass materials.

3.2 Effect of blending ratio

The blending ratio is defined as the proportion of biomass in the blend of feedstock materials during co-pyrolysis. In the co-pyrolysis method, the

Feedstock materials	Lignin (wt. %)	Cellulose (wt. %)	Hemicellulose (wt. %)
Pinewood	24 [28]	42 [28]	23 [28]
Water hyacinth	3 ~ 28 [29]	~30 [30]	~25 [30]
Rice straw	16.5 [31]	29.8 [31]	33.3 [31]
Waste plastic (polystyrene)	10 ~ 15 [32]	35 ~ 55 [32]	20 ~ 40 [32]

Table 2.
Characteristics of different biomass materials.

generated quantity of gas, liquid, and solid materials depends on the blending ratio of feedstock material [33]. It was found that increasing biomass blending ratio reduces the solid charcoal generation, while liquid and gas production increases [34]. The blending ratio of biomass materials can also influence the degree of synergistic effect.

3.3 Effect of rate of heat

The rate of heating is a significant factor that can affect the biomass co-pyrolysis process. The biomass co-pyrolysis process can be distinguished if the rate of heat is low. At a low heating rate, only additive behavior of biomass materials occurs. On the other hand, the devolatilization process of biomass materials becomes slower with the increase in the heating rate.

Synergism of biomass feedstock materials is favored by the increased heating rate of feedstock material [27, 35, 36]. It was found that low heating rate caused lack of synergies. Moreover, a high rate of heat during co-pyrolysis generally produces higher volatile yields [37].

3.4 Effect of temperature

The temperature in the co-pyrolysis process is an important factor for the generation of solid (charcoal), liquid (pyrolytic oil), and gas. By increasing the temperature inside the co-pyrolysis reactor, it is possible to decrease the production of charcoal from biomass co-pyrolysis. As a consequence, the overall efficiency of the co-pyrolysis method can be increased by increasing the temperature [38, 39].

3.5 Effect of types of reactor

Different types of reactors, such as fixed bed, fluidized bed, TG, drop style, auger are commonly used in pyrolysis and co-pyrolysis process. In this chapter, the fixed bed reactor is considered for biomass feedstock materials. However, the TG reactor is most commonly used during the co-pyrolysis method.

In a fixed bed pyrolysis reactor, a large quantity of feedstock materials provides intimate contact between fuel particles and their generated volatiles. Due to this phenomena, synergistic effect is occurred for gas and pyrolysis product yield [40]. Fluidized bed and drop style type reactors are fast pyrolysis reactors that can be used to carry the co-pyrolysis process. Auger reactor is more effective than fixed-bed reactor for co-pyrolysis process. Auger type reactor usually generates higher liquid product yield than fixed-bed reactor [41].

4. Sample preparation and feedstocks for co-pyrolysis

Availability is one of the important factors for the selection of alternative energy sources. With respect to this condition, biomass is considered a potential energy source all over the world. It can be generated from the forest (wood), agriculture (rice husk, rice straw), solid waste (plastic), aquatic plants (water hyacinth), etc. In this work, rice straw, plastic, water hyacinth, and pinewood are considered as feedstock material.

Biomass feedstock materials are required to collect from the local market. They contain moisture and volatile matters that can reduce the overall efficiency of the pyrolysis process. To overcome this problem, biomass materials are dried using the oven for lab-scale operation and process heat through industrial applications. After drying, biomass feedstock materials are crushed and sieved to a particle size of 0.5 ~ 2 mm [42]. Thermogravimetric analysis (TGA) can be carried out to find the measurement of moisture content, thermal degradation, fixed, and volatile carbons in biomass feedstock materials.

Characterizing of biomass feed materials is significant because it provides C, H, N, S, moisture, ash, fixed carbon, and volatiles. **Table 3** shows the ultimate analysis and **Table 4** presents a proximate analysis of rice straw, water hyacinth, pinewood, and plastic biomass materials.

The heating value of biomass feedstock materials is another significant property that can affect the overall efficiency of the co-pyrolysis method. **Table 5** presents the heating value of rice straw, water hyacinth, pinewood, and waste plastic materials.

It is seen from **Table 5** that plastic material generates the highest quantity of heat when combusts. On the other hand, they are available as waste material in the natural environment.

The co-pyrolysis method can use two or more feedstock materials, therefore, this chapter presents and compares the performance of pinewood and waste plastic biomass with rice straw and water hyacinth aquatic plants.

In the co-pyrolysis process, rice straw, water hyacinth, pinewood, and waste plastic material was used to perform the experiment in a fixed bed reactor, as shown in **Figure 6**. The feedstock materials were prepared with a nominal size of 5 mm. All the biomass feedstock materials were added in the fixed bed reactor and nitrogen was used as the carrier gas. An external electrical heater was used to externally heat up the reactor during the co-pyrolysis process. The heater increased the reactor temperature to around 60 °C per minute. The final reactor temperature during the co-pyrolysis process was 550 °C. The overall reaction time for the biomass co-pyrolysis process was ~30 min. The solid and liquid product yields were collected by

Feedstock materials	Carbon (C) (wt.%)	Hydrogen (H_2) (wt.%)	Nitrogen (N_2) (wt.%)	Sulfur (S) (wt.%)
Pinewood [43]	47.5	6.50	0.095	~0.13
Water hyacinth [42]	34.85	6.50	0.8	1.5
Rice straw [42]	36.1	5.20	0.6	0.30
Waste plastic (polystyrene) [44]	90.40	8.60	0.070	0.080

Table 3.
Ultimate analysis of biomass feedstock materials.

Feedstock materials	Fixed carbon (wt.%)	Moisture (wt.%)	Volatile matters (wt.%)	Ash (wt.%)
Pinewood [43]	17.90	14.2	67.70	45
Water hyacinth [42]	4.90	13.15	69.2	25.50
Rice straw [42]	6.90	11.7	78.1	15.2
Waste plastic (polystyrene) [44]	~0.7–12	0.20	99.31	0.50

Table 4.
Proximate analysis of biomass feedstock materials.

Feedstock materials	Heating value (MJ/kg)
Pinewood	18–21.5
Water hyacinth	14.6
Rice straw	14–15.1
Waste plastic (polystyrene)	40

Table 5.
Heating value of biomass feedstock materials.

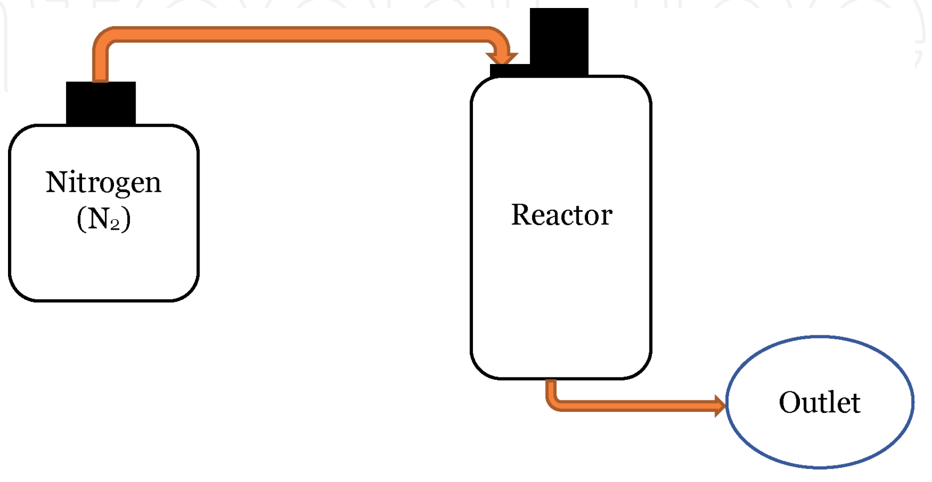

Figure 6.
Schematic diagram of the co-pyrolysis process of rice straw, water hyacinth, pinewood, and plastic biomass.

weight basis, while gas yields collected in a gas reservoir bag. After that, a gas analyzer was required to analyze the composition of gas yield generated in co-pyrolysis of rice straw, water hyacinth, pinewood, and plastic materials.

5. Co-pyrolysis using biomass solids and aquatic plants

Co-pyrolysis of pinewood and waste plastic feedstock material is a potential source of energy. On the other hand, rice straw and water hyacinth is another significant source of biomass energy that can be used as feedstocks in the co-pyrolysis process. Individually rice straw, plastic, water hyacinth, and pinewood biomass materials, when used in the pyrolysis process, produce less efficient pyrolytic oil that creates unnecessary combustion problems due to high oxygen contents. As a consequence, different proportions of two or more feedstock materials are usually used in the co-pyrolysis method that can provide better performance. This section of the chapter presents the performance analysis of pinewood with waste plastic and rice straw with water hyacinth biomass feedstock materials during the co-pyrolysis method at different proportions of feedstock materials. The product yields were solid (charcoal), liquid (pyrolytic oil), and gas. Likewise. the co-pyrolysis of rice straw, water hyacinth, pinewood, and plastic materials provide product yield of charcoal, pyrolytic oil, and gas.

In pinewood and waste plastic feedstocks, the products of charcoal production do not depend on the addition of waste plastics. It was also found that very little quantity of charcoal produced from the co-pyrolysis of waste plastic [45, 46]. While, in the co-pyrolysis of rice straw and water hyacinth feedstocks, the production of bio-oils depends on the reactor temperature, and with the increase of reactor temperature up to 400 °C, the pyrolytic oil production is also increased. After that, above temperature 400 °C, generation of pyrolytic oil decreases [42].

5.1 Performance analysis

In the co-pyrolysis method of pinewood-waste plastic and rice straw-water hyacinth, it was observed that liquid yield generation was higher in pinewood-waste plastic feedstocks than rice straw-water hyacinth feedstocks. This is due to the higher heating value of pinewood and plastic material than water hyacinth. The porosity of water hyacinth feedstocks can also negatively affect the generation of product yield during the co-pyrolysis process. In addition, the density of rice straw and water hyacinth is lower than the density of pinewood and waste plastic that can negatively influence the generation of pyrolytic oil for the co-pyrolysis method.

In this process, initially pinewood with waste plastic (polystyrene) and rice straw with water hyacinth materials were added in a 1: 1 ratio.

Figure 7 presents the generation of liquid yield from the co-pyrolysis process for pinewood-plastic (polystyrene) and rice straw-water hyacinth feedstock materials. It is seen from **Figure 7** that the liquid yield (pyrolytic oil) of pinewood with plastic (polystyrene) feedstocks in co-pyrolysis was higher than rice straw with water hyacinth feedstock materials at 400 °C temperature [9, 42].

In the co-pyrolysis method, the amount of solid, liquid, and gas yield depends on the type of biomass feedstocks and the proportion at which they are added in the co-pyrolysis process. In this chapter, three different ratios of feedstocks have been considered to analyze the performance of co-pyrolysis.

The co-pyrolysis of rice straw with water hyacinth feedstock materials produced the highest yield of liquid (pyrolytic oil) than solid (charcoal) and gas yield at an equal proportion of rice straw and water hyacinth (1:1). It was also found that with the increase of water hyacinth proportion with rice straw, the liquid (pyrolytic oil) yield was decreased but solid (charcoal) yield increased, while gas yield remained almost same [42]. This trends were statistically significant. On the other hand, a high proportion of rice straw with water hyacinth reduced the liquid yield from the liquid yield of an equal amount of rice straw and water hyacinth, as shown in **Figure 8**.

Figure 9 presents the mean and standard deviation of the product yield wt. % for three different compositions of rice straw and water hyacinth. It is seen from **Figure 9** that the variation of solid yield (charcoal) with the change of composition of rice husk and water hyacinth was lower than liquid (pyrolytic oil) and gas yield.

Figure 10 shows the product yield of co-pyrolysis for different proportions of pinewood and waste plastic (polystyrene) biomass materials. It was found that

Figure 7.
Pyrolytic oil generation from biomass co-pyrolysis process at 400 °C [9, 42].

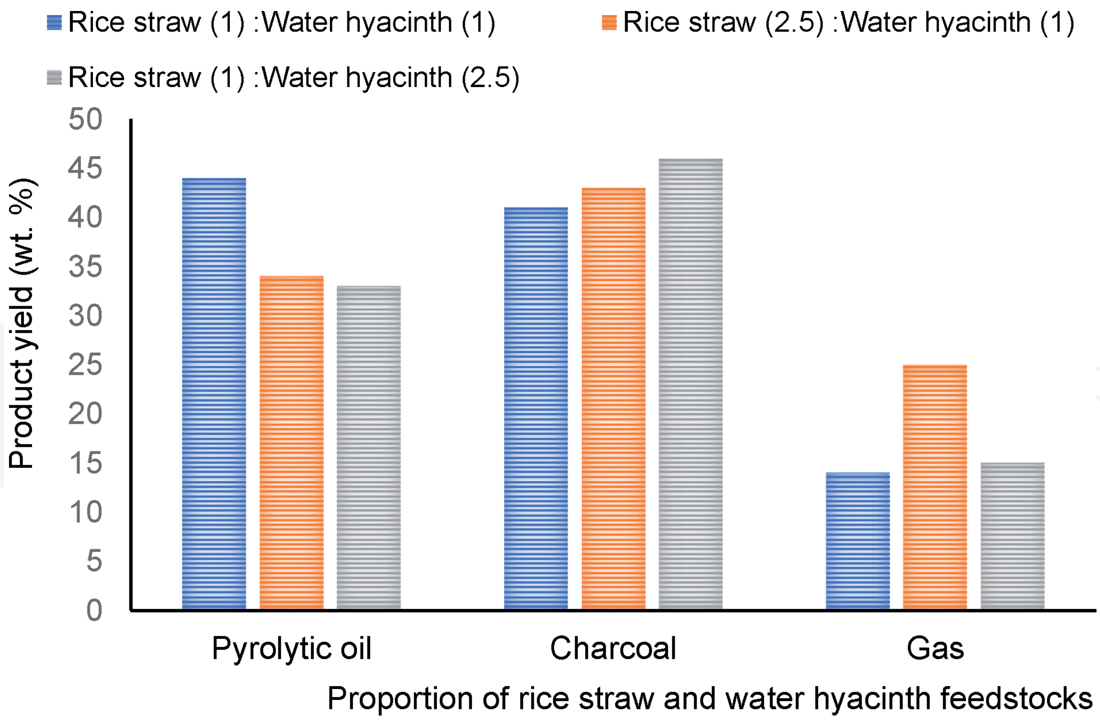

Figure 8.
Product yield generation from different proportion of rice straw and water hyacinth in co-pyrolysis process [42].

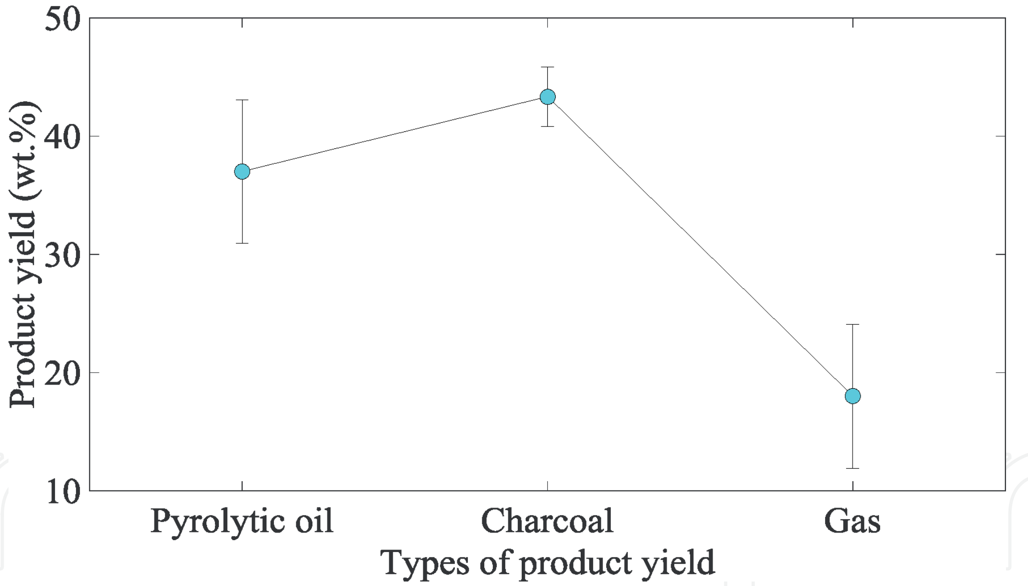

Figure 9.
Statistical analysis of product yield generation from the different proportion of rice straw and water hyacinth feedstocks (rice straw (1): Water hyacinth (1), rice straw (2.5): Water hyacinth (1), and rice straw (1): Water hyacinth (2.5)) in co-pyrolysis process.

co-pyrolysis of pinewood with waste plastic (polystyrene) feedstock materials produced the highest yield of liquid (pyrolytic oil) than solid (charcoal) and gas yield at an equal proportion of pinewood and waste plastic (polystyrene) (1:1). It was also found that with the increase of waste plastic (polystyrene) proportion with pinewood, the liquid (pyrolytic oil) yield was increased but solid (charcoal) yield decreased [47]. This trends were statistically significant. On the other hand, a high proportion of pinewood with waste plastic (polystyrene) reduced the liquid yield from the liquid yield of an equal amount of pinewood with waste plastic (polystyrene), as shown in **Figure 10**.

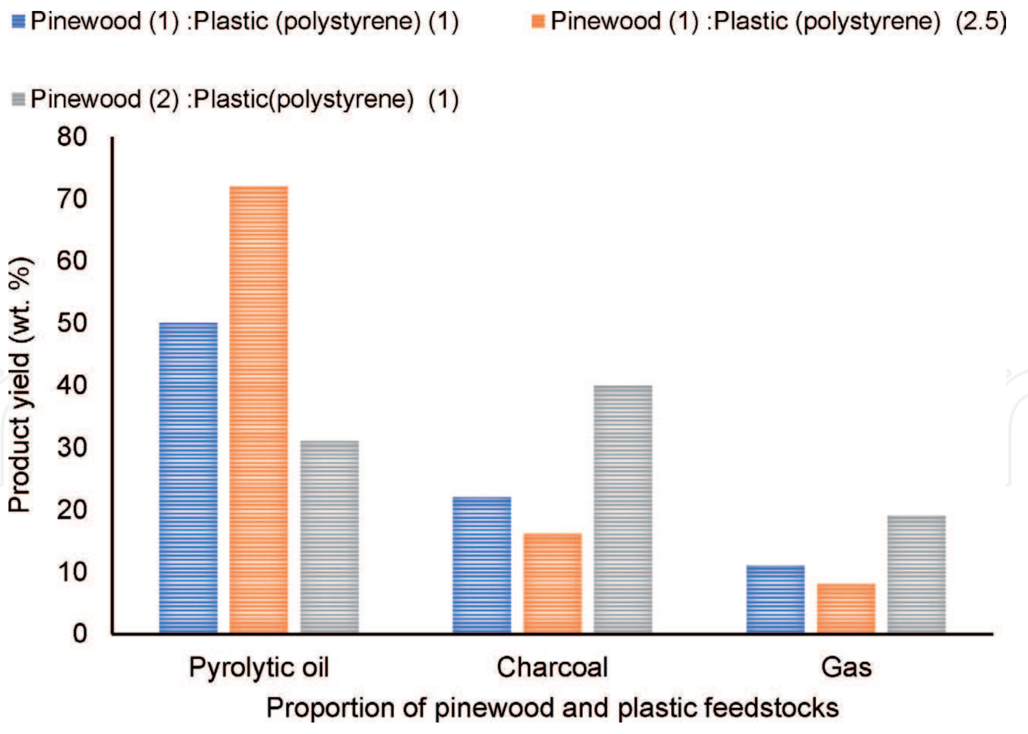

Figure 10.
Product yield generation from different proportion of pinewood and waste plastic (polystyrene) in co-pyrolysis process [47].

Figure 11 presents the mean and standard deviation of the product yield wt. % for three different compositions of pinewood and plastic (polystyrene) feedstocks. It is seen from **Figure 11** that the variation of a gas yield with the change of composition of pinewood and plastic (polystyrene) was lower than liquid (pyrolytic oil) and solid yield (charcoal) yield.

5.2 Characteristics analysis

In the co-pyrolysis process, the quality of the generated pyrolytic oil is better than the pyrolysis process. As a consequence, the oxygen content in the pyrolytic

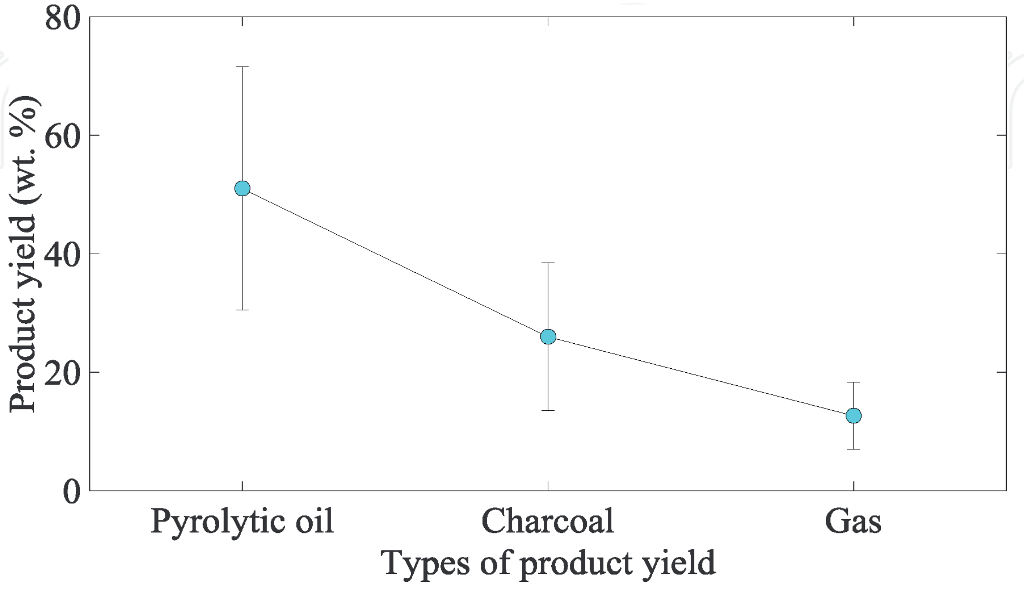

Figure 11.
Statistical analysis of product yield generation from the different proportion of pinewood and plastic (polystyrene) feedstocks (pinewood (1): Plastic (polystyrene) (1), pinewood (1): Plastic (polystyrene) (2.5), and pinewood (2): Plastic (polystyrene) (1)) in co-pyrolysis process.

Feedstock materials	Calorific value (MJ/kg) of solids	Calorific value (MJ/kg) of liquids	Calorific value (MJ/kg) of Diesel
Pinewood- plastic (polystyrene) [47]	33 ~ 45	32 ~ 45	45.5
Rice straw-water hyacinth [48]	32 ~ 42	33 ~ 42	45.5

Table 6.
Calorific value of product yield of co-pyrolysis process.

oil generated from the co-pyrolysis method is lower than the pyrolysis process. However, to improve or upgrade pyrolytic oil in the pyrolysis method requires an intermediate process that increases the complexity and cost. Hence, this chapter considers only the co-pyrolysis process of biomass feedstock materials and their related characteristics.

However, the calorific value of pyrolytic oil and gas generated in the co-pyrolysis process for pinewood-waste plastic or rice straw-water hyacinth was higher than the calorific value of product yield when used only pinewood or rice straw or water hyacinth feedstock biomass. **Table 6** presents the calorific value of different feedstock materials in pyrolysis and co-pyrolysis process.

Overall, the generation of liquid yield (pyrolytic oil) and solid yield (charcoal) in the co-pyrolysis method increases with the increase of temperature of the pyrolysis reactor. However, the required temperature of the co-pyrolysis process (300–450 °C) is lower than the temperature required for the pyrolysis process (550–750 °C).

6. Conclusion

Biomass is a bio-renewable source of energy. It can be used to generate energy through the pyrolysis and co-pyrolysis process. The generated liquid and gas yield in the pyrolysis and co-pyrolysis method can be used with conventional fuel. However, due to higher dissolved oxygen in pyrolytic oil produced in the pyrolysis process, they are required to be improved or upgraded that makes the process complex and costly. Therefore, the co-pyrolysis process is used that can generate better quality and, upgraded liquid and gas yield. The co-pyrolysis process requires a lower reactor temperature than the pyrolysis process. In this study, co-pyrolysis of rice straw with water hyacinth and pinewood with waste plastic feedstock materials have been analyzed. It is seen that with the increase of pyrolysis reactor temperature, the liquid yield (pyrolytic oil) production also increases. However, if the reactor temperature exceeds 400 °C then the generation of liquid yield decreases. On the other hand, the generation of solid (charcoal), liquid (pyrolytic oil), and gas yield depend on the proportion of feedstock biomasses in the co-pyrolysis process. The calorific value of product yield in the co-pyrolysis process is higher than the pyrolysis process and comparable with conventional fuel, such as diesel. Therefore, the biomass co-pyrolysis process would be a potential source of bio-renewable energy that can fulfill the global energy demand with conventional fuel.

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