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RESEARCH ARTICLE

Investigating Bio-Oil Yield from Co-pyrolysis of Mixed Medical Waste and Biomass under Varying Temperature and Residence Time

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ABSTRACT – Co-pyrolysis is a thermochemical process using more than one raw material to become a new energy source without oxygen at high or low temperatures. This study aims to determine the effect of co-pyrolysis if temperature and residence time are varied on the yield of bio-oil mixed with biomass and medical waste. The research was conducted using a small-scale batch reactor equipped with an electrically controlled band heater as a reactor tube heater. Co-pyrolysis was carried out with variations in temperature, namely 300°C, 400°C, and 500°C, as well as three different raw material waiting times in the reactor, namely 10, 15, and 20 minutes. The flow rate of nitrogen gas to the reactor is set at 0.5 liters per minute, and the number of samples taken for each batch procedure is 60 grams. The results showed that increasing the temperature positively affected the yield of bio-oil, but applying very high temperatures had the opposite effect, namely decreasing the amount of bio-oil but increasing the amount of syn-gas produced. Residence time dramatically affects the composition of the bio-oil and syn-gas compounds produced but does not significantly affect the biochar yield. At lower and moderate temperatures, prolonging the residence time enhances bio-oil production. However, at 500°C, extending the residence time diminishes bio-oil yield. The bio-oil obtained has a high calorific value of 46.334 MJ/kg, making it suitable for use as an alternative fuel.

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1. INTRODUCTION

Every year, a large amount of medical waste is generated because of improvements in public health services. Specifically, during the COVID-19 pandemic, medical waste has increased dramatically. Unmanaged medical wastes present a serious threat to public health and safety in addition to contaminating water, the atmosphere, and soil due to the high risk of pathogen transportation. Improper disposal of medical waste can lead to contamination of surface and groundwater, which poses a risk to human health and ecosystems. This contamination can result in toxic chemicals in water sources, leading to long-term environmental damage [1]. Traditional disposal methods, like incineration, can release harmful pollutants, including dioxins and furans, into the atmosphere. These toxic gases contribute to air pollution and pose serious health risks to nearby communities. The generation of greenhouse gases (GHGs) such as CO2 and CH4 from landfilling and incineration of medical waste contributes to global warming and climate change [2]. Medical gloves are one type of waste from medicine; they are a fossil waste that is difficult to break down naturally. Fossil waste cannot be recycled, so its disposal requires a sizable surface area and effective treatment techniques. Conversion technology is one strategy to reduce biological and fossil waste [3], [4].

Incineration, physical procedures, and chemical treatments are typical disinfection techniques for treating medical waste (MW). Disinfection technologies are utilized at numerous points within Waste Management Systems (WMS) to manage diverse categories of trash. High-temperature incineration is a superior and efficient method that may be utilized to manage medical waste (MW). It is a worthwhile investment for effectively cleaning pathological and medicinal MW. Hospitals can employ chemical disinfection with other advanced technologies, such as microwaves or steam disinfection methods, to effectively eliminate microbial contamination [5]. This approach can be particularly beneficial for hospitals with limited financial resources. While incineration technology effectively breaks down viruses and bacteria at elevated temperatures, it does have drawbacks, such as the emission of pollutants into the atmosphere and significant impacts on the immune systems of humans and animals. Therefore, an urgent requirement is for alternative technology to be developed to treat MW. Thermal technology is an effective method for efficiently breaking down waste, and it may be divided into two subcategories: pyrolysis and microwave, which operate at high temperatures and function at medium temperatures.

One of the conversion techniques in waste processing is pyrolysis. Pyrolysis is a thermochemical decomposition process of organic material without air or oxygen. The biomass pyrolysis system yields typical products such as charcoal, bio-oil (liquid smoke), and syngas (gas) [6], [7]. Pyrolysis is a process in which the decomposition of these components occurs at a temperature of 300°C, with the maximum decomposition occurring around 400°C under inert conditions. This

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decomposition releases hydrocarbons and gases, including hydrogen, methane, acetylene, ethylene, and propane. However, when biomass is used, the resulting liquid smoke products tend to be black. It comprises carbon, hydrogen, and oxygen [8], [9]. Pyrolysis is a thermochemical process that involves breaking down the organic chemicals found in solid and liquid medical waste at high temperatures without oxygen or under low-oxygen circumstances. The macromolecular components found in medical waste are decomposed into less complex molecules such as crude synthetic gases, liquid or solid fuels, and carbonaceous materials (coke, biochar). The resulting solid or liquid products have significant commercial value and can be a viable energy substitute for depleting fossil fuels. M.F. Dimin et al. [10] conducted a study on the impact of using biochar as a green binder to bind urea and create fertilizer. The mineralization results revealed that the sample with impregnation retained a more significant amount of nutrients in the soil than the unimpregnated sample. This shows that urea impregnation of biochar has the potential to improve soil nutrient retention through delayed release.

To enhance the product yield from the pyrolysis of medical waste, researchers have investigated co-pyrolysis as a strategy for more efficient utilization of raw materials [11]. For instance, in a study involving the co-pyrolysis of bio-oil with medical masks, researchers identified a significant aromatic content in the bio-oil, while the resulting biochar demonstrated a higher heating value (HHV)[12]. Additionally, Park et al. [13] observed an increased yield of biochar through the co-pyrolysis of masks and food waste[14]. These findings suggest that co-pyrolysis represents an effective approach for enhancing both the quality and yield of products derived from the pyrolysis of medical waste. Numerous studies have demonstrated that the quality and quantity of bio-oil produced from the co-pyrolysis of biomass surpass those obtained from the pyrolysis of individual biomass sources [15], [16], [17]

The oil that is produced through the condensation of vapor due to cooling typically consists of aliphatic, aromatic, alcohol, and various other organic compounds. These compounds can be transformed into commercially valuable additives, fuels, or intermediate organic products[18]. Uzoejinwa et al. [19] examined the benefits of the co-pyrolysis process in terms of output, mechanism, and operational control and determined that it shows promise when compared to biomass pyrolysis alone. Yousaf Ayub and Jingheng in 2023, with their literature review article, stated that Co-pyrolysis studies indicate that higher temperatures generally enhance oil production and reduce char formation, where the optimal oil yields are observed at temperatures ranging from 450 to 700°C [20]. Another study conducted by Motta et al. in 2024 supports this by showing that higher temperatures (500-700°C) increase bio-oil and gas yields due to greater degradation of feedstock structures [21].

The latest development, bio-oil upgrading, is carried out using a co-pyrolysis process, or the pyrolysis of a mixture of biomass with other raw materials that have a higher fuel content [22], [23], [24]. A binary mixture of co-pyrolysis between medical glove waste (MGW) and HVS paper (HVSp) was conducted by Azzalya et al. [25], where the proximate analysis, such as moisture content, volatile matter, ash, and fixed carbon matter is described in Table 1. The study also noted the combined effect of MGW and HVSp in enhancing the bio-oil yield through synergy. The bio-oil product experienced an increase of 40% when the ratio of MGW (75%) to HVSp (25%) was applied (Table 2). Furthermore, the ratio composition serves as the foundation for this study.

Table 1. Proximate analysis [26]

Type of waste	Moisture matter (%)	Volatile matter (%)	Ash matter (%)	Fixed Carbon (%)
Medical glove waste	2.3171	68.0806	13.3767	16.2257
Food waste	26.9518	70.0683	2.5100	0.4700
Garden waste	6.9506	64.1165	24.1534	4.7795
Paper waste (HVSp)	3.0217	65.5465	19.2003	12.2315

Table 2. The ratio composition of MGW with other biomass[26]

Samples	Composition	Bio-oil (%)	Biochar (%)	Syngas (%)
MGW x Food waste	50:50	29.00	33.00	38.00
MGW x Food waste	25:75	35.00	37.50	27.50
MGW x Food waste	75:25	25.00	30.00	45.00
MGW x Garden waste	50:50	33.33	40.00	26.67
MGW x Garden waste	25:75	30.00	48.33	21.67
MGW x Garden waste	75:25	22.50	55.00	22.50
MGW x HVSp	50:50	22.50	40.00	37.50
MGW x HVSp	25:75	28.33	43.33	28.33
MGW x HVSp	75:25	40.00	40.00	20.00

Based on the two tables of previous research results (Table 1 and Table 2) above, with the known physical properties and composition ratio of 75:25, that yields the highest bio-oil yield of 40%, further research is needed to determine the characteristics of the relationship between temperature and residence time of the bio-oil yields from MGW and HVSp.

The co-pyrolysis process was conducted at different temperatures, specifically 300°C, 400°C, and 500°C, along with three different residence times for the raw materials in the reactor, namely 10, 15, and 20 minutes. This research aims to determine the effect of co-pyrolysis of MGW with HVSp if the temperature and residence time are varied on the bio-oil yield.

2. METHODS AND MATERIAL

2.1 Materials

Nitrile and latex gloves are the most effective types for resisting various chemical compounds and other particulates. Usually, these two types of gloves are intended for workers in the health sector or those dealing with chemicals [9], [27], [28]. Gloves (medical gloves) are plastic polymers based on nitrile rubber and latex. Therefore, the identified medical plastics can be recycled for fuel energy because they are polymers [29], [30], [31]. Medical gloves include a type of thermoplastic polymer PVC (polyvinyl chloride), which contains a lot of saturated hydrocarbons. This compound has the potential to increase the level of heating oil [3], [7], [25]. The exact type of gloves used in this experiment were latex gloves. Paper is the largest element of solid waste containing lignocellulose fiber. The non-infectious waste components were collected from various sources and exposed to a drying process in an oven at a temperature of 90°C for 12 hours.


(a) (b)

Figure 1. Medical and biomass waste; (a) medical gloves, (b) paper

The HVSp is derived from paper shredding facilities located at the University Muhammadiyah of Riau. The infectious waste components were obtained from a local pharmacy in Pekanbaru rather than healthcare facilities to avoid the risk of spreading dangerous diseases (Figure 1). Lignocellulose biomass is included in renewable resources as a raw material for bioethanol. Paper waste contains lignocellulose, which can be converted into starch and then broken down into glucose, which will later produce bioethanol by utilizing the enzymatic activity of fungi [32].

2.2 Experimental Setup

The research utilized a batch reactor for experimentation. The reactor tube heater is equipped with a ceramics band heater that is controlled electrically by Autonics TZN4S-14S. The co-pyrolysis process takes place in the vertical reactor tube with an effective height of 440 mm and an inner diameter of 170 mm. An electrical heater (1.3 kW) was used to heat the reactor, and a band heater served as the primary component responsible for heating the tube. The band heater is powered by a 220V AC voltage that is connected to the voltage input, resulting in a power consumption of 1300 watts. The gas outlet serves as a conduit for the co-pyrolysis gas to flow from the reactor to the condenser.

The thermocouple is positioned at the sensor input section and is responsible for measuring the temperature within the reactor. The gas inlet refers to the point at which nitrogen gas flows into the reactor. Nitrogen gas helps the motion of the gas produced during co-pyrolysis towards the condenser. Nitrogen gas (N_2) is primarily used to create an inert atmosphere during the co-pyrolysis process. This is crucial because it prevents unwanted reactions that could occur if oxygen were present, such as combustion or oxidation of the feedstock materials[33][34]. The fiberglass cloth acts as a thermal insulator, effectively isolating the temperature within the reactor. The pyrolyzed sample is placed inside the sample container situated on the lower cover of the reactor. The condenser is a heat exchanger that serves as the final stage of the pyrolysis process.

The condenser utilized is made of glass. The cooling water is distributed using a water pump to cool the condenser tube and connecting pipes. The cooling temperature of the condenser tube is a result of the supply of cooling water to the smoke pipe inside the condenser tube. The connecting pipe serves to transport the pyrolysis gas from the reactor to the oil collector, which is utilized for storing the oil.

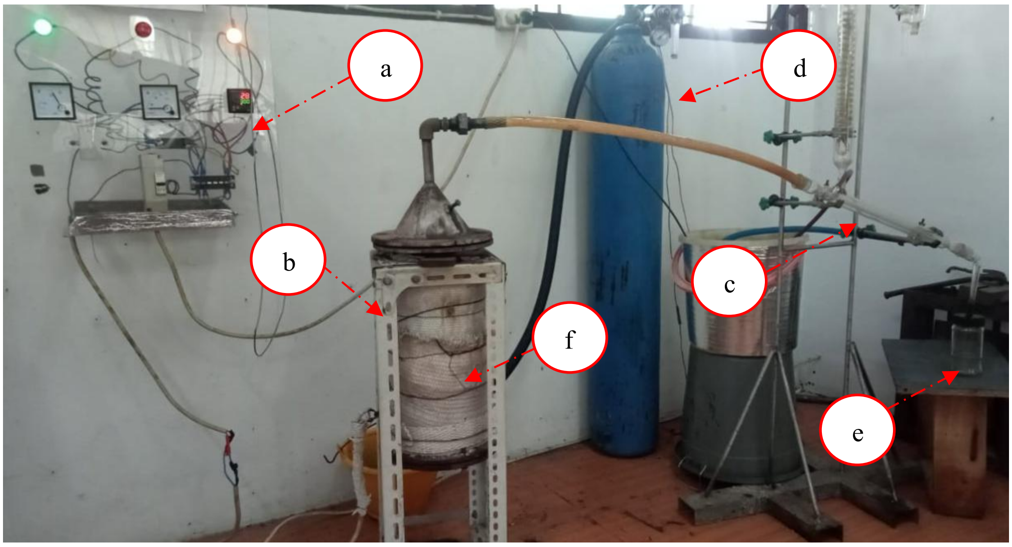

Figure 2. Experimental Setup of the co-pyrolysis equipment; a. control of instrumentation, b. reactor, c. condenser, d. nitrogen gas, e. bio-oil storage, f. glass wool isolator

2.3 Experimental Procedures

The MGW and HVSp have been crushed into small pieces with dimensions ranging from 0.5 to 1 cm. The goal is to achieve a consistent and elevated level of heating. The 60 grams sample is inserted into the reactor. All experiments were conducted using a vertical pyrolysis reactor, as depicted in Figure 2. The system primarily consists of five components: The control of instrumentation (a), reactor (b), condenser (c) for the condensation system, which is integrated with a water-cooling system, nitrogen gas (d), and bio-oil storage (e). The cylindrical reactor system consisted of a stainless steel structure equipped with ceramic band heaters to sustain temperatures up to 500°C, and the experiment was conducted at atmospheric pressure. To ensure consistent temperature throughout the reactor, two thermocouples were placed in both the upper and lower sections of the system.

The reactor is hermetically sealed with glass wool (f) to prevent any potential oxygen leak into the reactor tube and to make the system adiabatically. The top cover of the reactor is made in a cone shape so that the gas that comes out does not experience any obstruction. Next, the temperature is adjusted to 300°C with temperature variation, initiating the co-pyrolysis process. The temperature of 300°C serves as the setpoint value, and the control mode (Autotuning and PID control) is selected on the temperature controller. The subsequent step involves the continuous addition of nitrogen gas. The nitrogen gas flow rate into the reactor is set at 0.5 liters per minute**,** with variations in the specified waiting time (residence time). The remainder of the co-pyrolysis process, which is bio-char, is collected in the reactor tube, while bio-gas and bio-oil emerge together. The bio-oil produced from co-pyrolysis is collected using an oil collector or storage container.

The co-pyrolysis process is conducted at three different temperatures: 300°C, 400°C, and 500°C, with three different residence times for the raw materials in the reactor, specifically 10, 15, and 20 minutes. Residence time can be controlled by adjusting the rate at which feed is supplied or the rate at which products are discharged. Extended periods of solid residency lead to an increased occurrence of additional reactions that promote the formation of char and other durable byproducts [35]. The use of residence time in the minute range is due to the reactor's inability to sustain the reaction process for several hours, as syngas leakage occurs due to the high temperature and pressure within the reactor. Additionally, biomass has a relatively low-temperature range during pyrolysis, and the chosen residence time is sufficient to observe the trend of decreasing bio-oil production. A. Veses (2018) conducted pyrolysis of biomass in an auger reactor operated at 450 °C with N_2 as the carrier gas, where the residence time of solids in the reactor was 7 minutes [36].

This results in a total of nine separate experiments. The flow rate of nitrogen gas into the reactor was set at 0.5 liters per minute, and each batch procedure involved taking samples of 60 grams. Each procedure is performed in the same manner. Co-pyrolysis can produce three products: bio-oil, bio-char, and syngas. The percentage of yield products resulting from co-pyrolysis is calculated using the following equation:

$$\%\,\text{Bio}-\text{oil} = \left[\frac{\text{Bio}-\text{oil mass}}{\text{Total Mass of Samples}}\right] \times 100\% \tag{1}$$

$$\%\,\text{Bio}-\text{char} = \left[\frac{\text{Bio}-\text{char mass}}{\text{Total Mass of Samples}}\right] \times 100\% \tag{2}$$

$$\%\,\text{Syn}-\text{gas} = 100\% - [\%\,\text{Bio}-\text{oil} + \%\,\text{Bio}-\text{char}] \tag{3}$$

The characteristics of the heat temperature in the pyrolysis reactor were also recorded to determine the characteristics of the heating rate from the heater to the medical waste mixture using the temperature versus time profile.

3. RESULTS AND DISCUSSION

3.1 The Effect of Temperature 300°C with Variations in Residence Time on the Percentage of Bio-Oil Yield

Figure 3 illustrates the percentage of co-pyrolysis results at a temperature of 300°C with variations in residence time. It shows that increasing residence time enhances bio-oil yield while reducing bio-char and syngas yield. The highest bio-oil yield was observed at a residence time of 20 minutes, reaching 25 ±1.4%. As for bio-char and syngas, their percentages decrease to 30 ± 0.3 % and 45 ± 3.8 %, respectively. The trend indicates an increase in bio-oil, although the magnitude of the increase is not substantial for each variation in residence time.

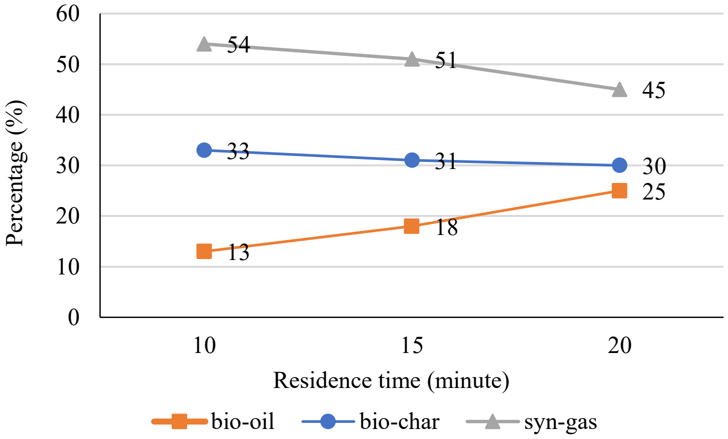

Figure 3. Temperature graph at 300°C with variations in residence time

The residence time of 10 minutes results in a bio-oil yield of 13 ± 2.5%, while a residence time of 15 minutes yields 18±1.3 % bio-oil and a residence time of 20 minutes yields 25 ±1.4% bio-oil. The difference in bio-oil yield between the 15 minutes and 20 minutes variations is 5% and 7%, respectively. With the resulting value, at a temperature of 300°C, the heat produced can only evaporate the water content in the sample and is insufficient for the complete decomposition or breakdown of cellulose in the sample components. Arif Ferdiyanto et al. stated that cellulose and hemicellulose begin to decompose at a temperature range of 350°C and decompose completely at a temperature range of 400°C [37].

3.2 The Effect of Temperature 400°C with Variations in Residence Time on the Percentage of Bio-Oil Yield

Figure 4 shows the percentage of co-pyrolysis results at a temperature of 400°C with variations in residence time, showing that increasing residence time increases the yield of bio-oil and reduces the yield of bio-char and syngas. Figure 3 and Figure 4 exhibit identical increments in bio-oil; however, Figure 4 demonstrates a higher percentage value than Figure 3. The percentage of bio-oil increases proportionally with longer residence time.

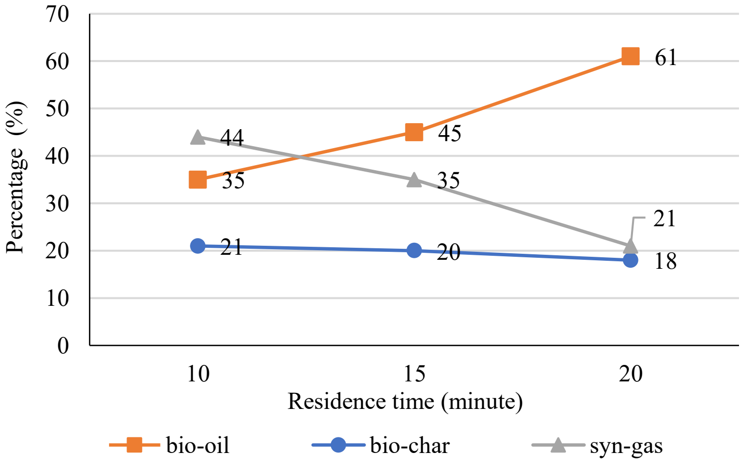

Figure 4. Temperature graph at 400°C with variations in residence time

Specifically, a residence time of 10 minutes results in a bio-oil percentage of 35 ± 1.4%, while 15 minutes yields 45± 1.4% and 20 minutes yields 61 ± 3.8%. At a temperature of 400°C, there was a significant increase in bio-oil, with the difference for each variation of 10 minutes, 15 minutes to 20 minutes being 10% and 16%. This is due to the temperature of 400℃ in co-pyrolysis. The more the sample is decomposed, the greater the smoke volume and the increase in bio-oil, thereby reducing the bio-char value. The difference in bio-oil yield at temperatures of 300℃ and 400℃ is due to the increase in devolatilization reactions at higher temperatures because more energy is available, and this causes the bonds in organic compounds to break, thereby increasing the liquid yield [38]. The observations at temperatures of 300 ℃ and 400 ℃ reveal that an extended residence time during the co-pyrolysis process leads to a more significant augmentation in the quantity of bio-oil. This phenomenon occurs due to the positive correlation between co-pyrolysis time and the amount of heat energy absorbed by the sample. The heat energy is uniformly dispersed throughout each sample, resulting in a greater extent of decomposition across the sample.

3.3 The Effect of Temperature 500℃ with Variations in Residence Time on the Percentage of Bio-Oil Yield

The graph in Figure 5 shows that it is inversely proportional to the values in Figure 3 and Figure 4 for the bio-oil and syngas values. The graph shows that the bio-oil value decreases with increasing residence time, and the syngas value increases with increasing residence time. Biochar continues to decrease with each residence time. The graph shows that the bio-oil value decreases by 55 ± 3.8% at 10 minutes, 50 ± 3.7% at 15 minutes, and 46± 3.8% at 20 minutes. This is because at a temperature of 500 ℃, a secondary cracking reaction occurs from co-pyrolysis vapor, and the higher the temperature, the more the sample decomposes into non-condensable syngas, and the less bio-oil is produced.

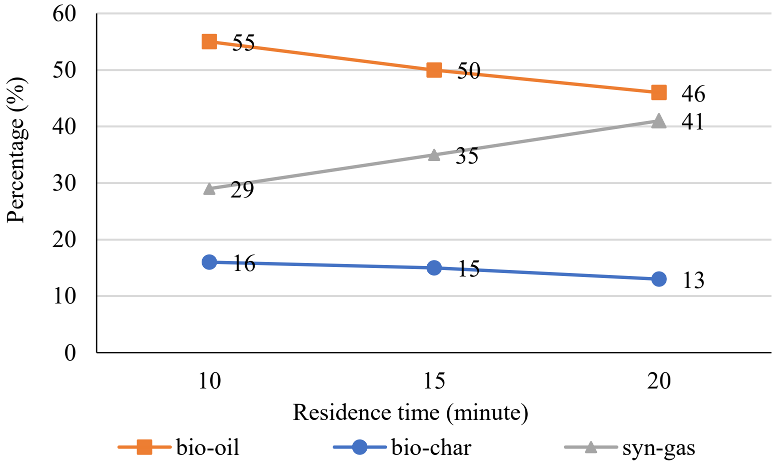

Figure 5. Temperature graph at 500℃ with variations in residence time

Kartika Udyani et al. stated in their research that the higher the temperature, the more non-condensable gas products there are, so the value of bio-oil products decreases [39]. At very high process temperatures, light organic materials will be released in the form of vaporized gas [40]. At a temperature of 500℃ with decreasing bio-oil at each residence time, it can be said that the increase and decrease in the amount of bio-oil at residence time depends on the operating temperature. The influence of residence time on the amount of bio-oil is dominated by temperature. The bio-oil and biochar products are shown in Figure 6.

(a) (b)

Figure 6. Medical waste-biomass pyrolysis product; (a) bio-oil, (b) biochar

Furthermore, a research report that conducted pyrolysis on plastic materials supports this agreement, revealing that there were minimal enhancements in the gas and oil end products beyond a temperature of 685°C. Furthermore, it was found that a higher oil yield at temperatures below 685°C resulted in an extended residence time [41]. Consequently, owing to the diminished effects observed at elevated temperatures, the majority of researchers conduct plastic pyrolysis experiments without accounting for the influence of residence time. Nevertheless, it is imperative to regard residence time as a significant variable when the temperature decreases below 450°C[42]. In this study, the co-pyrolysis of glove waste with HVS paper will result in the production of bio-oil. The amount of bio-oil produced is directly related to the residence time, as long as the operating temperature remains below 500 °C. Papuga et al. have conducted pyrolysis experiments on plastic waste using a fixed-bed reactor. They found that the optimal residence time is 45 minutes when the pyrolysis temperature is kept at a maximum of 500°C. Therefore, as the residence time increased, there were no notable alterations in the conversion of raw materials or the yields of gas and liquid products. [43].

3.4 Thermal Characteristics Inside the Reactor

The thermal characteristics during the co-pyrolysis process were monitored using a temperature profile over time. The thermal characteristic graph refers to temperature profile data against time in the co-pyrolysis process. Figure 7 shows the graphic trend of temperature increase during the co-pyrolysis process against time. Figures 7(a), (b), and (c) show the same graph, which tends to increase over time. This occurs at a temperature of 28°C to 300°C in around 35 minutes. Figure 7(a) shows a graph of the temperature increase from 300°C to 400°C. A gradual increase takes about 40 minutes, while Figure 7(b) shows that going from 300°C to 400°C takes about 20 minutes faster than Figure 7(a).

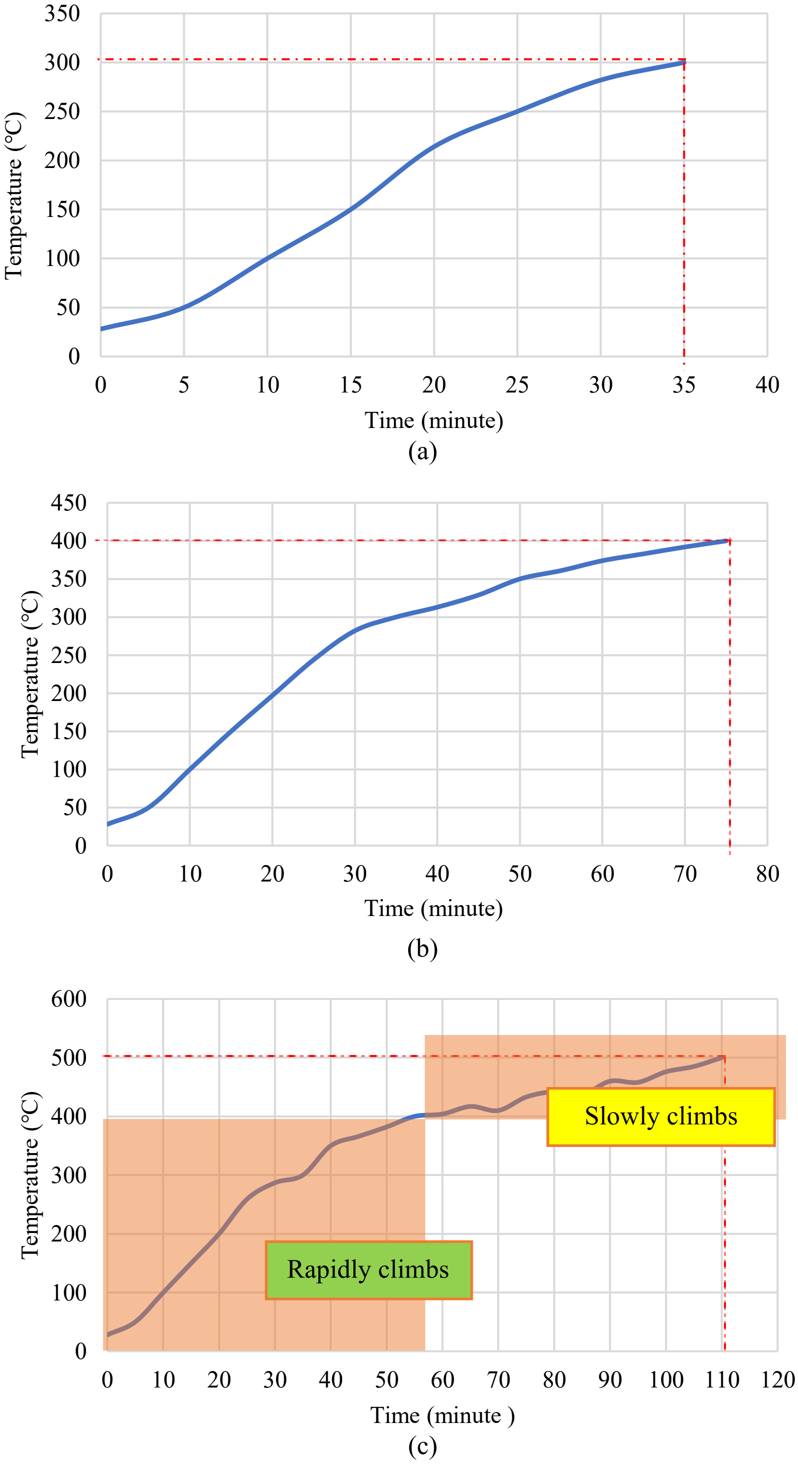

Figure 7. Thermal Characteristics Graph of the co-pyrolysis process at different temperatures; (a) 300°C, (b) 400°C and (c) 500°C

Between 0-30 minutes, the temperature increases at a relatively uniform rate, which indicates that the reactor is heating up at a steady pace. This uniform increase suggests good thermal conductivity and stability within the system, allowing the biomass to gradually reach the required temperature for pyrolysis. The heating rate plays a significant role in the pyrolysis process. Slow and steady heating rates, as observed in the initial 0-30 minutes, are characteristic of slow pyrolysis, which favors the production of biochar and ensures thorough thermal decomposition of biomass[44].

From 0 to around 35 minutes, the temperature climbs more rapidly compared to the later stages. This could indicate an initial phase of rapid heating, possibly because the reactor is quickly raising the temperature to the lower threshold for pyrolysis. In pyrolysis processes, the initial phase often involves quick heating to reach the required reaction temperature. After the 35-minute mark, the rate of temperature increase begins to decelerate, suggesting that the reactor is approaching its maximum operating temperature (approximately 400°C). The reduced steepness of the temperature rise indicates that the reactor is stabilizing as it nears thermal equilibrium or a steady-state condition. This behavior was further confirmed during testing at 500°C, as shown in Figure 7(c), where the rate of temperature increases also started to slow down.

The graph in Figure 7(c) depicts a fluctuating trend, with temperatures ranging from 400°C to 500°C at minutes 70, 85, and 95. Subsequently, the temperature increases to 500°C between minutes 100 and 110. The temperature of the system is determined by a batch reactor, which utilizes a ceramic band heater as its heat source. The ceramic band heater can heat the reactor to an optimal temperature of 400°C.

Table 3. The heating rate at each temperature

No	Temperature (°C)	Heating rate (°C/min)
1	300	8
2	400	5
3	500	4

The heating rate, as indicated in Table 3, exhibits three temperature variations: 8, 5, and 4°C per minute. The heating rate derived from this study is categorized as slow pyrolysis. Slow pyrolysis operates within a temperature range of 300 - 600°C, with a heating rate of 3 - 10°C per minute and a residence time of 5 - 60 minutes [45]. The reactor used in this research adheres to these specifications. This gradual thermal process is effective for maximizing char production. Slow pyrolysis is divided into two categories: carbonization and torrefaction. Carbonization occurs at higher temperatures, typically between 300 °C and 400 °C, and involves a longer residence time. In contrast, torrefaction operates at much lower temperatures, ranging from 200 °C to 300 °C, and has a shorter residence time. During carbonization, the feedstock is transformed into highly stable carbon-rich products, such as charcoal or char, along with non-condensable gases that serve as excellent fuel sources.

In the metallurgical industry, charcoal is commonly used as a reducing agent in smelting and sintering operations. Charcoal is produced through slow pyrolysis, and with additional processing, it can be transformed into activated carbon, known for its excellent absorbent properties. Torrefaction is a thermal treatment that changes feedstock into coal-like materials, which are very brittle, require less energy to produce, and can also be utilized as fuels [46].

3.5 The Characteristics of Bio-oil

The bio-oil generated through thermal pyrolysis was examined for its physicochemical characteristics and subsequently compared to diesel fuel. The results of this analysis are presented in Table 4. Both varieties of bio-oil exhibit a dark brown hue and a smoky scent. Furthermore, Table 4 illustrates the physical properties of bio-oil, which closely align with those of conventional fuels, particularly in terms of calorific values, with gasoline and diesel recorded at 44.4 MJ/kg and 45.4 MJ/kg, respectively. The calorific value data was obtained in accordance with the ASTM D5865M-19 standard. The viscosity of waste pyrolysis oil is comparable to that of crude oil, measured at 52.483 cSt, which can be attributed to the significant presence of solid particles and impurities. Moreover, its density is nearly equivalent to that of diesel fuel [47], [48], [49].

Table 4. The comparison of physicochemical of Bio-oil and SNI Biodiesel

Parameters	SNI Biodiesel	Bio-oil of co-pyrolysis
Density (kg/m3)	850-890	839.1
Viscosity (cSt)	2.3-6.0	21.592
Acidity number (mg-KOH/g), max	0.5	0.25
Moisture content (%)	0.05	0.611
Calorific value (MJ/Kg)	42.493	46.334

The increased water content in bio-oil, which is 0.611% compared to SNI Biodiesel, which is only 0.05%, is also caused by the presence of HVS paper, which is derived from biomass. However, the moisture content of the bio-oil in this study remains within acceptable limits when compared to other bio-oil products due to the composition ratio of biomass in HVS paper being lower (25%) than MW (75%). It is apparent that HVSp derived from biomass is composed of hemicellulose and cellulose and produces a wide range of acidic compounds upon pyrolysis of hemicellulose and cellulose. The utilization of catalysts resulted in a reduction in the acidity of the bio-oil as a consequence of the deoxygenation reaction [50].

Pyrolysis processes do not benefit from high moisture content in biomass because the presence of high moisture content decreases the reaction temperature and slows down the heating rates. A portion of the heat energy is utilized to evaporate the moisture instead of facilitating the pyrolysis reactions. Furthermore, when the water content of the biomass condenses during the final stage of the process, it is completely incorporated into the bio-oil fraction. This has an impact on the stability, viscosity, and pH of the bio-oil and also reduces the rate at which the process generates heat [51], [50]. The elevated water content suggests a considerable concentration of oxygen within the bio-oil. In this study, the water content is relatively low compared to scenarios where the feedstock contains a substantial amount of water, such as food waste and biomass. The water produced is attributed to the initial moisture present in the feedstock as well as the dehydration reactions that take place during pyrolysis. From a fuel standpoint, the presence of water in bio-oil can reduce viscosity and facilitate a uniform temperature distribution within the reaction chamber.

The presence of water in bio-oil exerts both adverse and beneficial effects on its storage and utilization. On one hand, it diminishes heating values and may lead to phase separation of the bio-oil. Additionally, it prolongs ignition delay, decreases combustion rates, and decreases adiabatic flame temperatures during combustion. Furthermore, water can result in premature evaporation and subsequent challenges with injection during the preheating phase. Conversely, it can also aid in reducing viscosity and enhancing atomization [52]. The liquid oils derived from biomass pyrolysis are characterized by high viscosity and intense coloration, typically appearing dark red, brown, or black, as illustrated in Figure 6(a). Their chemical composition and physical properties exhibit significant variations depending on the feedstock, preparation method, and the age of the sample.

4. CONCLUSIONS

Co-pyrolysis of medical waste (gloves) mixed with biomass (HVS paper) with variations in temperature and residence time was conducted. The best or optimal conditions for the co-pyrolysis process occur at a temperature of 400°C. At this point, there is a very significant increase, namely residence time of 10 minutes by 35± 1.4%, 15 minutes by 45± 1.4%, and 20 minutes by 61± 3.8%. Elevating the temperature positively influences the yield of bio-oil; however, applying excessively high temperatures (≥400 °C) has the contrary effect of reducing bio-oil production while increasing the yield of syngas. This phenomenon occurs because, at elevated temperatures, secondary cracking reactions take place among the co-pyrolysis vapors, resulting in higher gas yields. In this study, the amount of bio-oil produced is directly related to the residence time. As long as the operating temperature remains below 500 °C, residence time greatly influences the composition of bio-oil and syngas compounds produced from the co-pyrolysis process but does not significantly affect the biochar yield. At low and medium temperatures, increasing residence time increases bio-oil yield, while at high temperatures, increasing residence time reduces bio-oil yield.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

A. Ridwan (Conceptualization; Methodology; Resources; Data curation; Writing - original draft; Resources)

B. Istana (Methodology; Supervision; Writing - review & editing)

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Israyandi (Visualisation; Formal analysis; Data curation)

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