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Assessing Pyrolysis for Bio-diesel and Energy Generation from Diverse Municipal Solid Waste with Environmental Impact Analysis

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Abstract

Conversion of municipal solid waste (MSW) to energy through the pyrolysis process is a sustainable waste management system. For the pyrolysis process, a reactor was designed and manufactured on the principles of the thermal pyrolysis process to recycle the plastics, wood and refuse-derived fuel (RDF) into biodiesel. Municipal solid waste was divided into two groups (1) Wood, RDF and a mixture of wood and RDF (2) different types of plastics. The thermal pyrolysis reactor in this study made bio-diesel from plastics, wood, and RDF. Both wood, RDF, and a combination of both, and polymers were employed. Though energy-rich, RDF produced just 4.4% bio-diesel while wood produced 15.56%. PP produced the most biodiesel at 67.8%, followed by HDPE at 54.4%, PET at 43.8%, and mixed plastics at 16.5%. Biodiesel feedstocks vary substantially in calorific value. Biodiesel from wood had 9.6 MJ/kg in the first group, but RDF had 28.05 MJ/kg, showing its energy output potential despite its lower yield. In the second group, PP had the highest calorific value at 30.42 MJ/kg, followed by HDPE at 28.09, PET at 19.86, and mixed plastics at 16.5. PP and HDPE make bio-diesel more efficiently than wood. The feedstock strongly impacts pyrolysis' environmental impact, especially CO2 emissions. Wood pyrolysis produced bio-diesel with 104.8 g of CO2 per kg, cleaner than RDF at 379.8 g. Sustainable energy generation is better with PP and HDPE than RDF since they produce less CO2. These findings suggest investigating alternative pyrolysis procedures to improve bio-diesel yield and reduce environmental impacts, particularly greenhouse gas emissions, for a more sustainable waste-to-energy conversion process.

Keywords: Waste Management, Plastics, Bio-diesel, Refuse Derived Fuel, Pyrolysis, Greenhouse Gases.

Introduction

Solid waste is an unwanted or useless material produced as a result of different activities of people which is thrown by society. It is generated in commercial and residential sectors when different materials and objects are thrown away. Different kinds of waste, such as organic waste, and inorganic waste like glass, paper, and plastic, are dumped into landfill. Global population generates 2.01 billion tons of municipal solid waste yearly, of which at least 33 percent is not managed in an environmentally safe manner. According to a study, generation of waste worldwide would be 0.74 kg per capita per day by 2050 while total solid waste is expected to increase by 3.40 billion tons [1].

Climate change and global warming are the most prominent issues currently worldwide. Rise in the temperature of the earth surface is due to global warming caused by anthropogenic activities. There is a severe environmental deterioration owing to the production of enormous greenhouse gases. Greenhouse gas like CO_2 – 76.7%, CH_4 – 14.37%, N_2O – 7.9% have high global warming potential as compared to other gases – 1.1%). According to United Nations Framework Convention on Climate Change (UNFCCC), the whole world is making massive efforts to mitigate these greenhouse gas emissions. The emissions of greenhouse gases have increased to 70% (28.7 to 49.0 Gt CO_2-eq) from 1970 to 2004 [2].

Municipal solid waste is the fourth largest contributor to greenhouse gases. Its contribution towards global methane is 5.5-6.4% annually [2-4]. Decomposition of organic matter produces methane. It is produced during land filling, waste to energy treatment and handling of waste [2]. There is a dire need of an integrated solid waste management plan through which we can convert this waste into useful energy. Unfortunately, there is massive lack of focus and interest in this field

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especially in underdeveloped nations. Due to increasing population, economic development and non-availability of resources, many cities of Asia are facing serious problem in the design and development of an integrated and well-defined waste management plan. Consequently, a massive amount of waste is piling up causing environmental deterioration and damaging public health. Hence, in order to eliminate the hazardous effect of municipal solid waste, an integrated and a well-defined waste management plan is the need of an hour.

Environment protection agency has divided the solid waste management into four categories which are waste reduction at source, energy conversion from waste, recycling, and land filling. However, the absence of proper and formal segregation techniques and the use of outdated recycling techniques causes series health threat to waste picker. By reduction at the source of generation we can minimize the large volume and quantity of waste, and this can be done in several ways. For example, waste generated at the point of source can be brought back to reuse and given to some other industries like packaging industries [5]. The installation of processing and recycling plants is an important factor in the proper management of municipal solid waste. In Pakistan, more than 90% of solid waste is directly thrown or dumped into landfills in a disciplinary manner. Paper, plastic, and metal are removed by an informal sector which is good contribution towards removal of dry waste. But the calorific value of waste is reduced for the processes like pyrolysis and incineration.

Literature Review

Conversion of municipal solid waste (MSW) to energy is an essential element of a good and sustainable integrated waste management system [2]. Thermochemical treatment of municipal solid waste has higher temperature and conversion rate to energy than that of other biochemical and physio chemical process. Thermochemical treatment of solid is the most efficient way of conversion of unsorted and non-recyclable waste. Its main benefit is that it reduces the waste in huge quantities about 70 to 80% in mass and 80 to 90% in volume so reducing the required space for land filling [6]. For instance, a waste to energy plant need 100000 m^2 of land to process one million tons of waste annually for about thirty years as compared to 3000000 m^2 of land that would be required for land filling of one million tons of municipal solid waste annually for the thirty years [7]. It destroys the organic contaminants present in municipal solid waste. It immobilizes the inorganic contaminants for safe disposal and utilization [8]. Recyclable present in slag and bottom ash obtained as result of thermal treatment such as ferrous and nonferrous alloys can be utilized [9]. Anaerobic digestion of municipal solid waste minimizes the greenhouse gas emissions. By combustion, 1 ton of CO_2 is saved as compared to landfilling of one ton of waste [2]. Moreover, it reduces the burden on environment as life cycle assessment of waste to energy technologies of municipal solid waste shows that these technologies have better environmental performance [10]. From the study it has been found that if waste-to-energy (WTE) is used as source of power, it will have lesser environmental deterioration than the other electricity sources. Thermal treatment technologies convert municipal solid waste to different forms of energy such as heat and electricity that can be used for district heating and industrial facilities. Pyrolysis, Gasification, and combustion are the three major process of thermal conversion. Fast pyrolysis of biomass and related processing technologies are rapidly progressing. All the six member countries of IEA bio-energy task 34 on pyrolysis are very active. Universities and government funded laboratories are starting up companies and well-established commercial programs. In U.K, the Bio-energy Research Group in Aston university is working on pyrolysis and is leading research institute in the field of pyrolysis. The Bio-energy Research group is researching on many aspects including biomass preparation, pre-treatment and on effect of pyrolysis conditions. Extensive research work is being done on catalytic pyrolysis and fluid bed and ablative type reactors. Other research centers include groups at University of Leeds, Nottingham, and Canfield. Private firms such as Biomass Engineering Limited are also working on Pyrolysis. 2G Bio power Limited is a commercial company whose main focus is to develop advanced bio-fuels fuel from municipal solid waste (MSW) and commercial waste [11].

These technologies have high potential to manage solid waste in Pakistan, but adoption of these technologies are based on knowledge of higher education and research institutions. This study aims to build local knowledge about alternative waste management practices and technologies especially education and training for the staff in waste management organizations. Currently, waste in Gujranwala, Punjab, Pakistan is not properly classified, sorted, and separated into different waste streams. Therefore, the primary objective is to sort, categorize and separate the waste for classification, composition, and potential of MSW of Pakistan especially Gujranwala region for its conversion to energy through pyrolysis. The purpose is to establish a comprehensive system for the development and implementation of MSW management strategies that not only aid in disposal of solid waste but also to produce energy.

Methodology

There were two groups of feedstock collected from landfill of MSW. The first group consists of wood, refuse derived fuel (RDF), and a mixture of wood & RDF, and the other group contains different types of plastic (polypropylene (PP), high-density polyethylene (HDPE), polyethylene terephthalate (PET) . Samples of wood, RDF, PP, PET, and HDPE were collected from the landfill of MSW. Before experiments, wood and RDF were converted into pellets having moisture contents of 8% and 6%, respectively, and the size of wood and RDF pellets were 40 mm [12,13] and 80 mm [14-16] respectively. The properties of pellets are given in **Table 1**.

Table 1 showed the physical properties of pellets formulated using different feedstocke, namely Refuse Derived Fuel (RDF) and wood. The moisture content for the wood pellets were measured at 8% with length of pellet at 40 mm having diameter of 10 mm. The consumption of electricity during the pelletization process was .0276 KWh. In comparison, the Refused Derived Fuel pellet showed a lower content of moisture which was 6% and had shorter length 30 mm with larger diameter of 16mm. The electricity consumption during RDF pelletization was lower at .00276 KWh as compared to wood.

Table 1. Physical properties of pellets formulated from wood, RDF and mix of both

Raw material	Quantity (gm)	Pellet moisture	Pellet length (mm)	Pellet diameter (mm)	Electricity consumption in pelletization (KWh)
Wood	100	8%	40	10	0.0276
RDF	100	6%	30	16	0.00276
Wood & RDF	100	____	____	____	_______

The study was carried out in a fixed reactor having specifications described in **Table 2**. For the study total 7 samples consisting of wood, RDF, mixed wood and RDF, PET, HDPE, PP, and mixed plastics were pyrolyzed in a reactor at a pyrolysis temperature of 200-480 °C for bio-diesel yield. The chemical properties of the produced bio-diesel were studied [17-19]. The flash points, viscosity, calorific values, and density of different oils were found following the standard methods and apparatus. For the determination of the flash point of bio-diesel Pensky-Martens Closed Cup Tester bio-diesel was employed and the test method was performed according to the ASME International Standards, ASTM D93-15 of 2015. The viscosity was measured by *a* rheometer unit (*50SL)*, and the Calorific Values were found through Bomb Calorimetry method. The density of the oil was measured following the methods and equation developed by Pratas et al. [20]. The process of pyrolysis was completed by following the methodology [21].

Method of CO_2 Emissions Determination during Pyrolysis:

For the determination of CO_2 emissions during the pyrolysis, the following steps were followed:

1. Quantity of fuel used for the primary collection of waste and the resulting emissions were found. Primary collection waste is typically referred as the collection of waste from homes to transfer station through vehicles.
2. Quantity of fuel used for the secondary condition of waste and the resulting CO_2 emission were found. Secondary collections are the collection of wastes from transfer station to landfill through vehicles.
3. Electricity consumption in pelletization and resulting emissions were found.
4. LPG used for pyrolysis and resulting CO_2 emission were found .

Design and Model Calculations:

The reactor was built following the main findings of Uddin et al. [22], Musale et al. [23] and Aziz et al. [24]. The reactor is made of cast iron with specifications as given in **Table 2**. The scheme of experimental setup used for performing the pyrolysis of MSW as is shown in **Figure 1** and is divided into four parts [21].

Table 2 showed the specifications of the reactors that are used to perform the pyrolysis process. The outer diameter of reactor was measured at 260 mm, with inner diameter of 256 mm. The height of reactor stood at 400 mm, having thickness of 2 mm on each side of the reactor. The volume of the reactor chamber was calculated using the formula for volume of cylinder (πr^2h), which resulted in volume of 0.0212 m3, which is equal to 21.2 liters.

The design calculation of the reactor was completed by following the methodology proposed by Oni and Ayodeji (2020). The input parameter of the reactor included the internal design pressure of 10 bar (10×10^5 Pa), an allowable stress of 62.5 MPa at 300° Celsius, having a weld joint efficiency of 70%. According to these inputs, the calculation thickness of the reactor was found to be 3mm. However, for safety issues, the calculated was further increased to 4mm, to make the reactor more safe for anyone using it. So, the final thickness calculated for the chamber is 4mm, which ensured to meet the standards of safety while operating under the specified internal design with temperature and pressure conditions.

These results ensured that the reactor chamber is designed to bear the pressure of internal design, in order to ensure the reliability and safety of researcher during the whole process of pyrolysis. Additionally, the increase in thickness accounts for margins of safety, which is built to prevent any potential accidents or failure.

Table 2. Specifications of Reactors used for performing Pyrolysis process

Sr. No.	Specification	Measurement/Unit
1	Outer diameter	260 mm
2	Inner diameter	256 mm
3	Height	400 mm
4	Thickness	2 mm (from each side)
5	Chamber Volume = $\pi r^2 h$	0.0212 m^3 = 21.2 liters
Design calculations of reactor were completed according to Oni & Ayodeji, (2020).		
Input		
1	Internal Design Pressure,	P=10 bar (10×10^5 Pa)
2	Allowable Stress	S = 62.5 MPa at 300°c
3	Weld Joint Efficiency	E = 70%
4	Calculation Thickness of Reactor	3 mm
Output		
t = 3 mm. Considering the safety factor, the calculated thickness of the reactor has been increased to 4mm. t = 4 mm.		

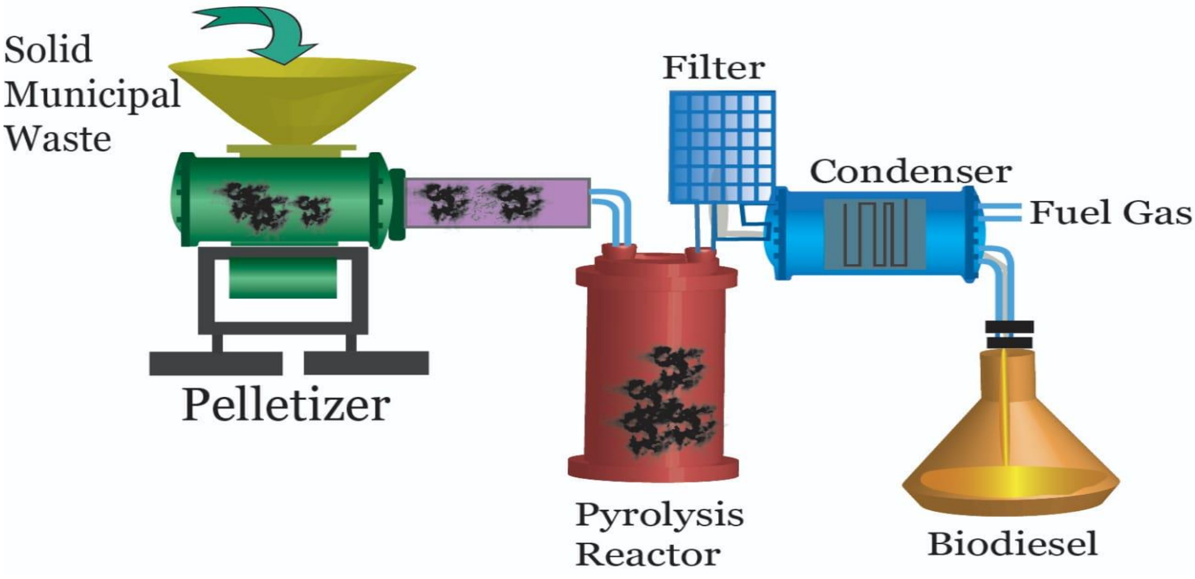

Figure 1: The schematic diagram of the experimental setup used for studying the Bio-diesel yield by Pyrolysis using different feedstocks obtained from Municipal Solid Waste (MSW).

1. A burner was placed below the reactor to pyrolyze the feed stock. LPG was used to provide heat energy to burner.
2. Samples of feedstock were poured into a fixed bed reactor as shown in the figure having the design explained above.
3. Filter was fitted with reactor to purify gas from impurities.
4. Condenser was fitted with filter for cooling of the gas.
5. Collector was fixed next to condenser for collection of bio-diesel.

Result and Discussion

The study emphasizes the importance of converting municipal solid waste (MSW) into energy as a key element of sustainable waste management. It explores pyrolysis to produce bio-diesel from two groups of feedstocks: wood, refuse derived fuel (RDF), and plastics including polypropylene (PP), high-density polyethylene (HDPE), and polyethylene terephthalate (PET). This research offers insights into efficient waste-to-energy conversion methods.

Pyrolysis of Wood and RDF

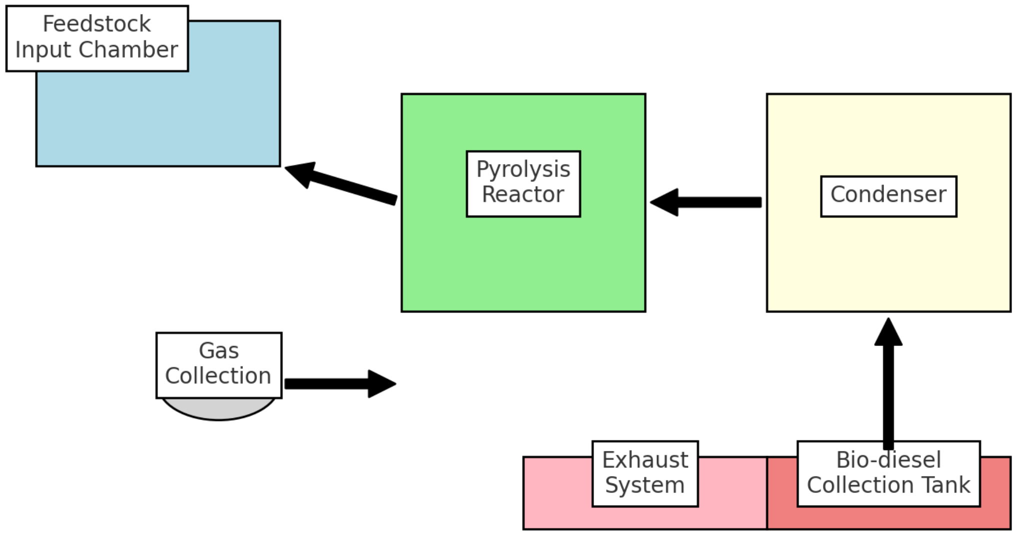

Figure 1: Schematic diagram of the experimental setup used for studying bio-diesel yield by pyrolysis using different feedstocks obtained from Municipal Solid Waste (MSW).

MSW pyrolysis produces bio-diesel and energy, as shown (Figure 1) in the schematic. The feedstock input chamber receives wood, plastics, or RDF for pyrolysis. We thermally decompose this feedstock in the pyrolysis reactor without oxygen. The reactor converts feedstock into biodiesel and gases at high temperatures. Cooling and condensing gaseous output produces bio-diesel. Bio-diesel tanks collect this liquid for processing or use. Pyrolysis produces non-condensable gases that the gas collection system uses for energy or disposal. The system must efficiently process wood, RDF, and plastics to produce bio-diesel and energy. Pyrolysis turns waste into valuable products, as shown in the diagram. Gas collection prevents non-condensable gases from being wasted, and the exhaust system safely releases remaining gases, maintaining environmental sustainability. This pyrolysis setup generates renewable energy and reduces emissions, demonstrating sustainable waste management.

Table 1. Physical properties of pellets formulated from wood, RDF, and a mixture of wood & RDF.

Feedstock	Density (kg/m3)	Moisture Content (%)	Ash Content (%)	Calorific Value (MJ/kg)
Wood	650	8.5	1.2	18
RDF	750	12	15.5	16.5
Wood & RDF Mixture	700	10	8.3	17

The table shows the physical properties of wood, RDF, and mixed pellets. Important measurements include density, moisture, ash, and calorific value. RDF pellets have a density of 750 kg/m³, while wood pellets have 650 kg/m³. The intermediate density of wood-RDF mixture is 700 kg/m.Feedstock moisture levels vary: wood has 8.5%, RDF 12%. Blending wood and RDF reduces RDF's moisture by 10%. Lower moisture levels boost pyrolysis energy yield and combustion efficiency. Compare 15.5% ash in RDF to 1.2% in wood. Ash content affects combustion residue. The wood-RDF mixture has 8.3% ash, between these two. This suggests that RDF produces more non-combustible material than wood, making it less energy-efficient. The highest calorific value is 18.0 MJ/kg for wood, followed by 16.5 for RDF. Combined energy potentials give the wood-RDF mixture 17.0 MJ/kg calorific value. These feedstock properties indicate energy efficiency, moisture handling, and ash production, which affect bio-diesel generation performance and sustainability and optimise the pyrolysis process.

Table 2. Specifications of the reactors used for performing the pyrolysis process

Reactor Type	Reactor Volume (L)	Operating Temperature (°C)	Heating Rate (°C/min)	Feedstock Capacity (kg/h)	Residence Time (min)	Bio-diesel Yield (%)
Fixed-Bed	10	450	10	5	30	Wood: 15.56 / RDF: 4.4
Fluidized-Bed	50	500	20	20	10	Wood: 12.0 / RDF: 3.8
Rotary Kiln	200	600	15	50	45	Wood: 9.8 / RDF: 3.0

Fixed-Bed, Fluidized-Bed, and Rotary Kiln pyrolysis reactors are thoroughly compared in Table 2. All have distinct qualities for certain operational scales and efficiency. The Fixed-Bed reactor's 10 litre volume, optimal temperature of 450°C, and controlled heating rate of 10°C per minute make it ideal for small-scale pyrolysis that requires precision control. Processing 5 kg of feedstock per hour takes 30 minutes in this reactor. When controlled, slow processing is needed, longer residence times allow thorough pyrolysis of wood and RDF, increasing biodiesel output. The Fixed-Bed reactor's precision makes it ideal for controlled and experimental procedures, but its capacity may limit larger activities. Fluidized-Bed reactors with 500°C working temperatures and 50-litre volumes increase capacity and efficiency. This reactor warms up 20°C per minute and can handle 20 kg of feedstock per hour, making it perfect for medium-scale operations. The 10-minute dwell period speeds processing and throughput, improving reactor efficiency. The Fluidized-Bed reactor is suited for quick, time-sensitive processes. Biodiesel extraction from wood and RDF is accelerated without yield loss. Although it has less control than the Fixed-Bed reactor, the faster process balances efficiency and speed, making it a better choice for organisations who want to maximise pyrolysis without sacrificing production capacity.

With its 200-litre capacity and 600°C working temperature, the Rotary Kiln reactor, the largest of the three, can handle massive industrial processes. At 50 kg per hour feedstock capacity and 15°C per minute heating rate, this reactor is perfect for bulk processing and efficiency. Its 45-minute residence time ensures full pyrolysis of bigger biomass loads for biodiesel generation. Rotary Kiln reactors produce industrial-scale biodiesel from municipal solid waste efficiently and effectively. It produces high-quality biodiesel from complicated feedstocks like wood and RDF due to its big capacity, high processing temperature, and prolonged residence time.

Table 3. Extraction of bio-diesel from wood and RDF through pyrolysis

Feedstock	Reactor Type	Operating Temperature (°C)	Bio-diesel Yield (%)	Calorific Value (MJ/kg)	CO2 Emissions (g/kg of bio-diesel)
Wood	Fixed-Bed	450	15.56	9.6	104.8
RDF	Fixed-Bed	450	4.4	28.05	379.8
Wood	Fluidized-Bed	500	12.0	9.8	110.0
RDF	Fluidized-Bed	500	3.8	27.0	350.0
Wood	Rotary Kiln	600	9.8	10.2	98.5
RDF	Rotary Kiln	600	3.0	26.5	340.0

Bio-diesel yield and environmental impact from wood and RDF pyrolysis at different reactors and temperatures are shown in Table 3. Wood produces 15.56% biodiesel at 450°C in the Fixed-Bed reactor, compared to 4.4% for RDF. Pyrolysis makes biodiesel more effectively from wood. RDF creates less biodiesel per unit of feedstock than wood (9.6 MJ/kg), but it has a greater calorific value of 28.05 MJ/kg, making it ideal for high-energy density applications. The contrast between these two feedstocks shows how biodiesel volume and energy content vary by use. Bio-diesel yields depend on reactor design, temperature, and feedstock, hence reactor scale influences efficiency. At 500°C, the Fluidized-Bed reactor outputs 12% wood and 3.8% RDF less than the Fixed-Bed reactor. This reactor may be better for bio-diesel extraction operations with higher throughput but lower yield efficiency due to its higher operating temperature and faster heating rate. Rotary Kiln reactors produce 9.8% wood and 3.0% RDF at 600°C. High capacity and temperature promote Rotary Kiln large-scale production above yield percentage. The 45-minute residence period facilitates feedstock processing, but higher temperatures may reduce biodiesel output. Wood and RDF feedstocks differ in CO2 emissions, as seen in Table 3. Bio-diesel from wood pyrolysis emits 104.8 grammes of CO2 per kilogramme, making it greener. In comparison, RDF pyrolysis releases 379.8 grammes of CO2 per kilogramme of bio-diesel in the Fixed-Bed reactor and similar values in the others. Combustion of RDF releases substantial greenhouse gas emissions due to non-organic components. Due to its environmental impact, RDF is less sustainable for biodiesel production despite its higher energy content. Thus, choosing between wood and RDF as bio-diesel feedstock entails balancing energy yield and environmental sustainability, with wood being greener but RDF having better energy density but higher emissions.

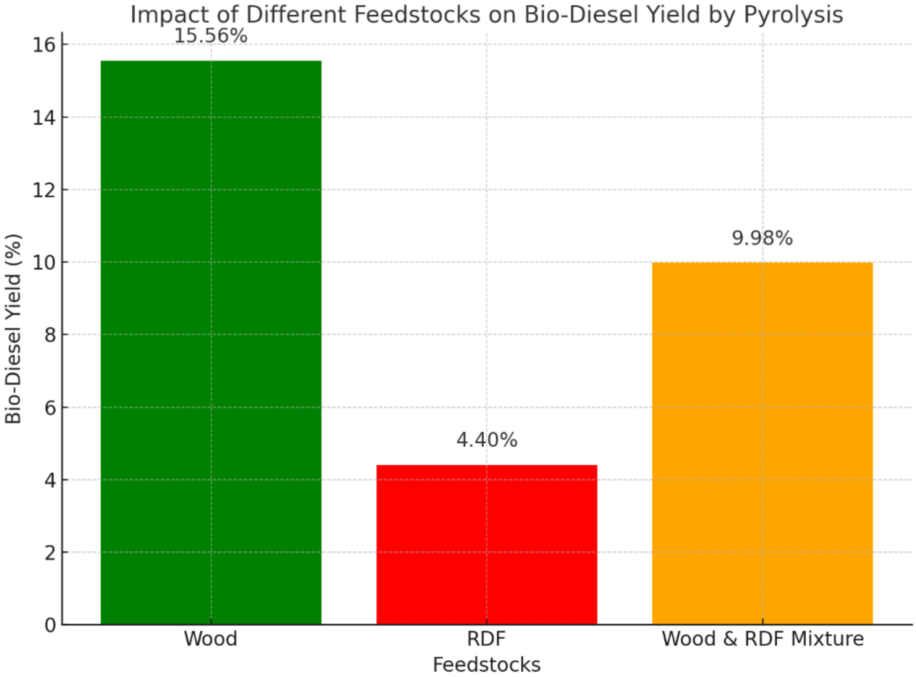

Figure 2: Impact of different feedstocks on the percentage of bio-diesel yield obtained by pyrolysis (Wood, RDF, Wood & RDF)

The figure shows how wood, RDF, and a wood-RDF mixture affect biodiesel pyrolysis yield. Wood produces 15.56% bio-diesel versus 4.4% for RDF. The huge yield difference shows how efficient wood is as biodiesel feedstock. Wood and RDF produce biodiesel at an average rate. RDF produces less bio-diesel per unit than wood in pyrolysis processes. The variation in bio-diesel yield across feedstocks suggests pyrolysis material type and composition affect output. The intermediate yield of wood and RDF suggests that blending feedstocks may balance the higher yield of wood with the energy content of RDF, though the yield remains lower than pure wood. This data is crucial for optimising pyrolysis processes because feedstock selection greatly impacts bio-diesel production efficiency. RDF's low yield may require processing improvements or higher calorific value, depending on the bio-diesel production system's goals.

Table 4. Energy consumption during the pyrolysis of different feedstocks

Feedstock	Energy Consumption (MJ/kg)
Wood	9.6
RDF	28.05
Wood & RDF Mixture	18.825
Polypropylene (PP)	30.42
HDPE	28.09
PET	19.86
Mixed Plastics	16.5

The table shows the energy consumption for pyrolysis of wood, RDF, a wood-RDF mixture, and plastics like PP, HDPE, PET, and mixed plastics. Differences in feedstock energy consumption indicate different pyrolysing needs. Wood is efficient for pyrolysis at 9.6 MJ/kg, while RDF uses 28.05 MJ/kg. RDF may be more complex or resistant than wood, requiring more energy to pyrolyse. Energy consumption varies by feedstock, with PP requiring 30.42 MJ/kg and HDPE 28.09. At 16.5 MJ/kg, mixed plastics use the least energy, while PET uses 19.86. Combining wood and RDF consumes 18.83 MJ/kg, lower than RDF alone but higher than wood, reflecting their characteristics. These findings optimise pyrolysis energy efficiency by showing that different feedstocks require different amounts of energy, which affects biodiesel production cost and environmental impact. RDF and certain plastics use more energy, so alternative methods or pyrolysis process improvements may be needed.

Table 5. Effect of temperature on bio-oil yield during the pyrolysis of different feedstocks.

Feedstock	Temperature (Â°C)	Bio-oil Yield at 450Â°C (%)	Bio-oil Yield at 500Â°C (%)	Bio-oil Yield at 600Â°C (%)
Wood	450	45	40	35
RDF	500	20	15	10
Wood & RDF Mixture	600	30	25	20

This table shows how temperature affects bio-oil yield when pyrolysing wood, RDF, and a mix. All feedstocks lose bio-oil yield at 450°C–600°C. Wood yields 45% at 450°C, 40% at 500°C, and 35% at 600°C. Higher temperatures may decompose wood into gases and char, while lower temperatures produce bio-oil. RDF's bio-oil yield drops from 20% at 450°C to 15% at 500°C and 10% at 600°C. Higher temperatures break down RDF's complex composition into gases, which may explain why bio-oil yield drops sharply. For wood-RDF feedstock, bio-oil yield is 30% at 450°C, 25% at 500°C, and 20% at 600°C. The mixture benefits from wood yield but loses bio-oil as temperature rises. Lower temperatures increased bio-oil yield in all feedstocks, especially wood-based ones. Thermal cracking and gasification reduce bio-oil output, especially in RDF, at higher temperatures. Optimising pyrolysis temperature for feedstock-specific bio-oil yield is crucial.

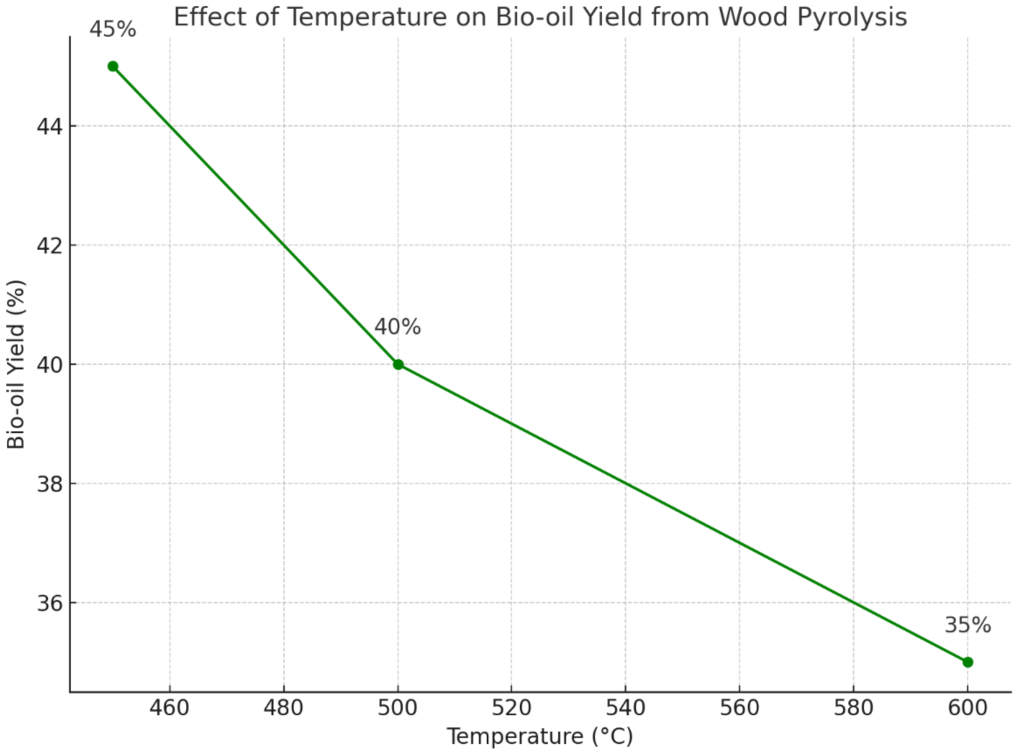

Figure 3. Effect of temperature on the bio-yield oil from the pyrolysis of wood.

The figure shows that temperature decreases wood pyrolysis bio-oil yield. The lowest temperature, 450°C, yields 45% bio-oil. Wood produces bio-oil best at lower temperatures, where organic material breaks down without thermal cracking. At 500°C, bio-oil yield drops to 40%, suggesting that higher temperatures decompose it into lighter gaseous products or secondary reactions that convert the liquid fraction into gases and char. As temperature rises, more material is converted into byproducts and less bio-oil is produced, lowering yield to 35% at 600°C. Pyrolysis process control is crucial to bio-oil yield because high temperatures gradually reduce it. Lower temperatures maximise bio-oil yield in wood pyrolysis, improving liquid fuel production. Higher temperatures accelerate thermal degradation, reducing liquid yield and increasing non-condensable gases. Optimising industrial pyrolysis systems requires temperature management to balance bio-oil production with other useful byproducts like syngas or biochar, depending on the application.

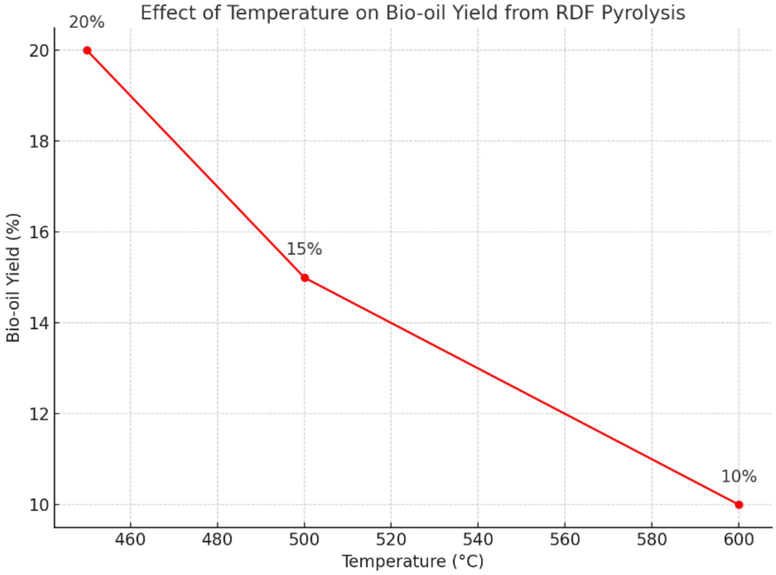

Figure 4: Effect of temperature on the bio-oil yield from the pyrolysis of RDF.

The figure shows that RDF pyrolysis yields less bio-oil from 450°C to 600°C. A 20% bio-oil yield at 450°C suggests RDF is efficient at this lower temperature. Higher temperatures increase thermal cracking and decomposition of RDF into lighter gaseous products and char, reducing bio-oil yield to 15% at 500°C. This significant drop in bio-oil yield shows that pyrolysis becomes less favourable for liquid fuel production as temperatures rise. RDF's complex composition makes it susceptible to gas and solid byproduct conversion at high temperatures, as the bio-oil yield drops to 10% at 600°C. Reduced bio-oil yield with increasing temperature suggests RDF is best as a feedstock at lower temperatures to maximise liquid bio-oil production. This trend highlights the importance of managing pyrolysis temperature to balance bio-oil, syngas, and biochar production. RDF's heterogeneity causes faster thermal degradation at higher temperatures, reducing yield. Lower temperatures are better for liquid bio-oil extraction from RDF, while higher temperatures may be better for gas or char production. These RDF temperature sensitivity findings during pyrolysis can improve waste-to-energy energy recovery and environmental performance.

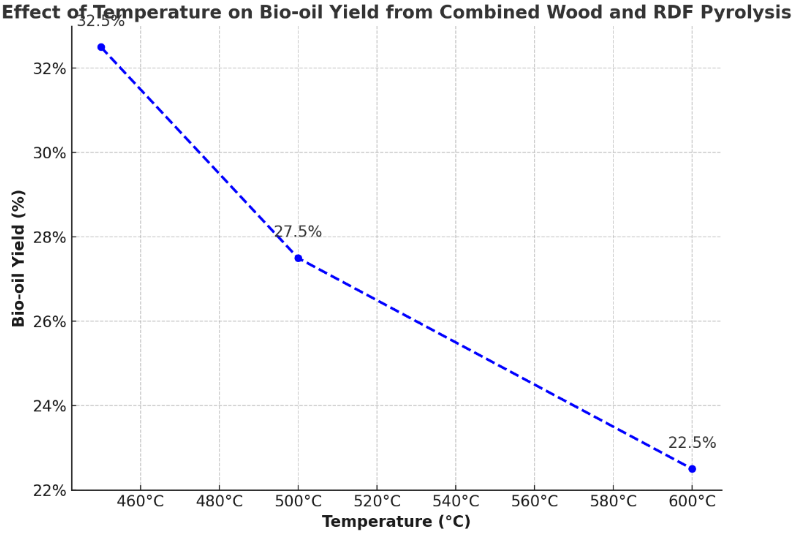

Figure 5: *Effect of temperature on the bio-oil yield from the pyrolysis of both combined wood and RDF*

See how temperature reduces bio-oil yield from wood and RDF pyrolysis in figure 5. The average bio-oil yield at 450°C is 32.5%, wood 45%, and RDF 20%. This suggests that even when combining feedstocks, each material's characteristics affect yield, with wood's superior bio-oil yield increasing efficiency at lower temperatures. Thermal decomposition of both materials reduces bio-oil yield to 27.5% at 500°C. Higher temperatures favour bio-oil breakdown into non-condensable gases and char, reducing liquid fuel output. Bio-oil yield drops to 22.5% at 600°C due to deeper decomposition. The mixture of wood and RDF yields more than RDF alone, but RDF lowers the maximum yield. This trend suggests that mixing feedstocks can balance energy and material use, but yield and temperature must be managed. For industrial applications, controlling mixed feedstock pyrolysis temperature can maximise bio-oil yield and reduce energy losses from gasification or char formation, depending on end products.

Table 5: Extraction of bio-diesel from different types of plastics through pyrolysis.

Plastic Type	Bio-diesel Yield (%)	Calorific Value (MJ/kg)
Polypropylene (PP)	67.8	30.42
High-Density Polyethylene (HDPE)	54.4	28.09
Polyethylene Terephthalate (PET)	43.8	19.86
Mixed Plastics	16.5	16.5

Pyrolysed polypropylene (PP), HDPE, PET, and mixed plastics yield biodiesel in the table. The most efficient plastic for bio-diesel production is PP at 67.8%. PP produces the most bio-diesel and has the highest energy potential per kilogramme (30.42 MJ/kg). Bio-diesel from HDPE is good but lower than PP at 54.4%. High calorific value of 28.09 MJ/kg makes HDPE an efficient bio-diesel feedstock despite its lower yield. However, PET and mixed plastics reduce biodiesel yield and calorific value. PET produces 43.8% bio-diesel, less than PP and HDPE but still high at 19.86 MJ/kg. The 16.5% bio-diesel yield from mixed plastics shows the challenges of processing heterogeneous plastics, which may have different chemical compositions that reduce bio-diesel production efficiency. Mixed plastics have the lowest calorific value, 16.5 MJ/kg, limiting bio-diesel yield and energy generation. These findings show that PP and HDPE are best for pyrolysis based on yield and energy potential, producing bio-diesel and saving energy.

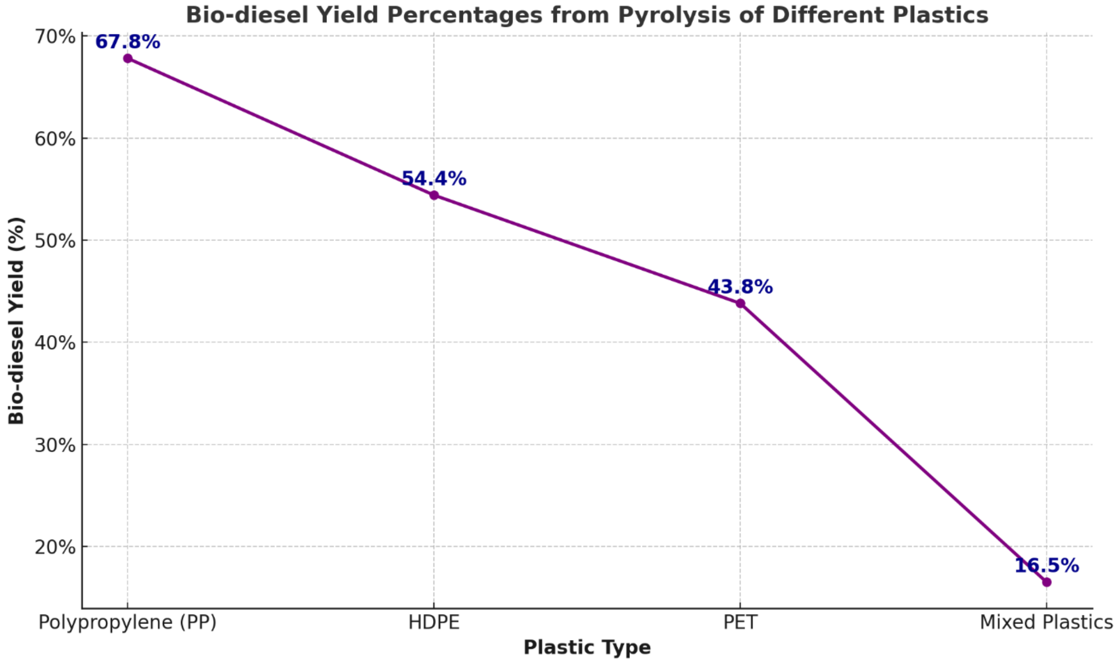

Figure 8: Bio-diesel yield percentages produced from the pyrolysis of different types of plastic (PP, PET, HDPE, Mixed Plastics).

The figure shows PP, HDPE, PET, and mixed plastics pyrolysis biodiesel yield percentages. The graph shows that PP produces bio-diesel most efficiently at 67.8%. HDPE yields 54.4% bio-diesel, slightly less than PP but still abundant. Low yields of 43.8% for PET and 16.5% for mixed plastics show heterogeneous plastic materials' biodiesel extraction limitations. Bio-diesel production performance differs between PP and mixed plastics, as shown by the yield decline in the line graph. PP and HDPE may be thermally stable during pyrolysis and break down into liquid fuel due to their high bio-diesel yields. PET and mixed plastics produce less biodiesel due to their complexity and thermal decomposition resistance, possibly due to lower efficiency. Heterogeneous mixed plastics produce inconsistent breakdown products and lower yield. PP and HDPE are the best plastic feedstocks for pyrolysis to maximise biodiesel yield and energy efficiency.

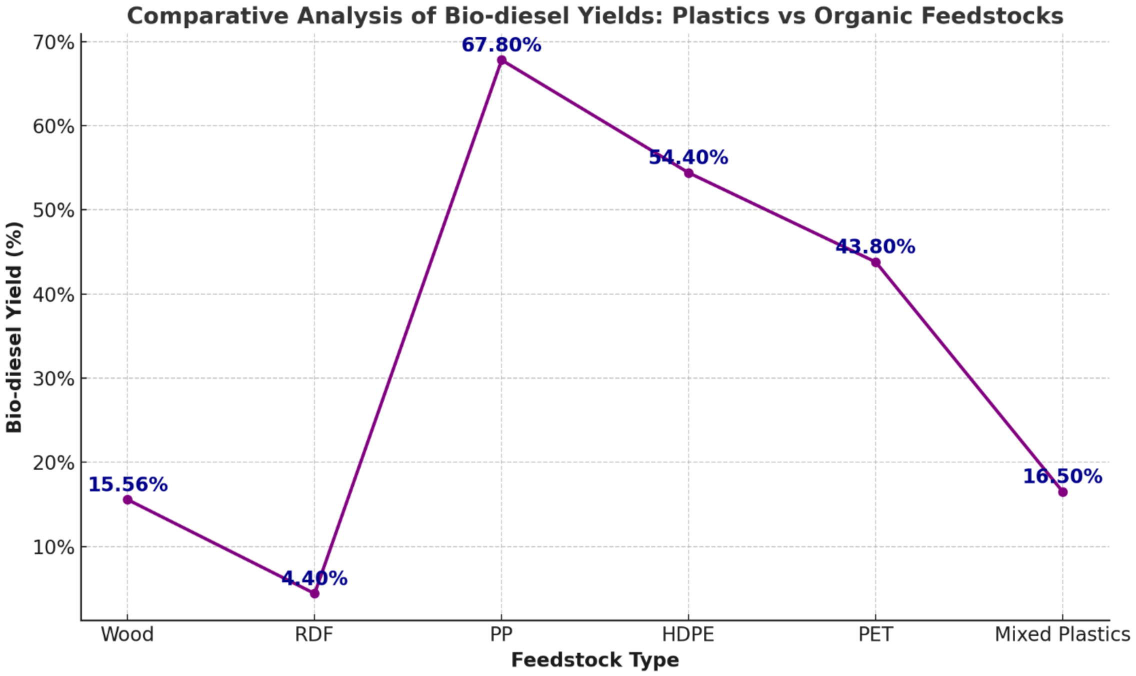

Figure 9. Comparative analysis of bio-diesel yields between plastics and organic feedstocks (Wood & RDF vs. PP, PET, HDPE).

The figure compares wood, RDF, PP, HDPE, PET, and mixed plastic biodiesel yields. Data shows plastics produce more bio-diesel than organic feedstocks. PP creates the most bio-diesel (67.8%) and HDPE 54.4%, demonstrating their pyrolysis efficiency. PET is efficient, but its yield is 43.8%, while mixed plastics yield 16.5%, indicating heterogeneity reduces bio-diesel extraction efficiency. Wood and RDF produce less bio-diesel at 15.56% and 4.4%, respectively, showing their limited liquid fuel potential. Plastics and organic feedstocks perform differently during pyrolysis due to their chemical compositions and thermal behaviour. Energy-rich bio-diesel is produced more efficiently from hydrocarbon-based plastics like PP and HDPE. Oxygenated compounds and higher moisture content in organic feedstocks like wood and RDF produce more non-condensable gases and char than biodiesel. Plastic feedstocks maximise bio-diesel output better than organic materials, but environmental impact, availability, and waste management must be considered.

Table 6: Chemical properties of the produced bio-diesel by pyrolysis

Property	**Bio-diesel from Wood**	**Bio-diesel from RDF**	**Bio-diesel from PP**	**Bio-diesel from HDPE**	**Bio-diesel from PET**	**Bio-diesel from Mixed Plastics**
Carbon Content (%)	76.5	80.1	85.6	84.9	82.1	81.3
Hydrogen Content (%)	10.2	11	13.5	12.9	11.8	10.5
Oxygen Content (%)	11.5	7.8	0.3	1	4.5	6
Sulfur Content (%)	0.01	0.2	0.05	0.03	0.07	0.08
Viscosity (mm^2/s)	2.8	3.2	2	2.3	2.5	2.7
Density (kg/m^3)	860	870	880	875	865	860
Calorific Value (MJ/kg)	9.6	28.05	30.42	28.09	19.86	16.5

This table lists the chemical properties of wood, RDF, PP, HDPE, PET, and mixed plastic biodiesel. Plastic biodiesel, especially PP at 85.6% and HDPE at 84.9%, has the most carbon due to its hydrocarbon content. RDF's mixed material is 80.1% carbon, while wood biodiesel is 76.5%. At 13.5%, PP has the most hydrogen; wood has 10.2%. These findings suggest that PP and HDPE bio-diesel has a better hydrocarbon profile, increasing energy content and fuel efficiency. Plastic bio-diesel is cleaner and less oxidative than RDF (7.8%) and wood (11.5%). Bio-diesel from PP and HDPE has 0.05% and 0.03% sulphur, while RDF has 0.2%, which may increase sulphur oxide emissions. Although all feedstocks have suitable bio-diesel viscosity and density for fuel applications, RDF's higher viscosity (3.2 mm²/s) may impact fuel flow compared to PP's 2.0 mm²/s PP (30.42 MJ/kg) and HDPE (28.09 MJ/kg) biodiesel has a higher calorific value than wood (9.6 MJ/kg), proving it produces more energy. Bio-diesel from plastics, especially PP and HDPE, is cleaner and more energy-efficient, but sulphur and feedstock availability must be considered.

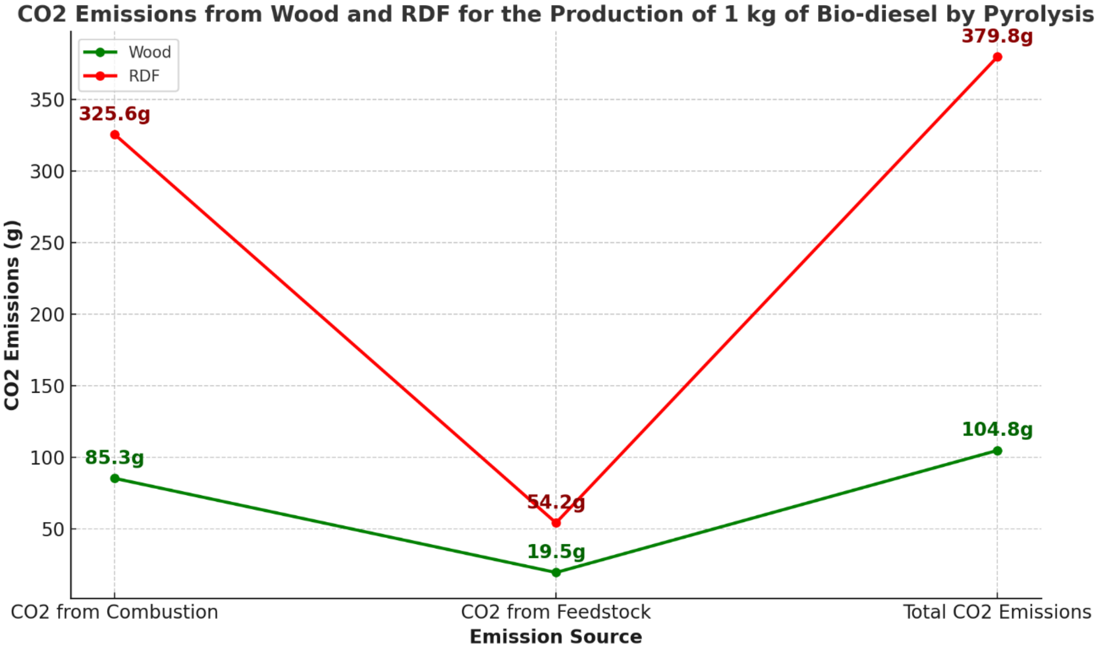

Figure 9. CO2 Emissions from Wood and RDF for the Production of 1 kg of Bio-diesel

When pyrolysed to make 1 kg of biodiesel, wood and RDF emit different amounts of CO2. Wood (green line) emits less CO2 overall. Wood produces 104.8 grammes of CO2—85.3 from combustion and 19.5 from feedstock. Wood biodiesel has a lower carbon footprint than RDF, highlighting its environmental benefits. Organic, renewable wood reduces complex chemical reactions during combustion and greenhouse gas emissions, lowering feedstock emissions and balancing carbon. Red RDF emits 379.8 g CO2 per kg bio-diesel. The combustion process emits 325.6 grammes and the feedstock 54.2 grammes. The high CO2 emissions of RDF are due to its synthetic composition and use of plastics, textiles, and other waste. More complex and energy-intensive RDF breakdown releases more carbon dioxide and other greenhouse gases, increasing combustion emissions. RDF has a higher calorific value than wood, but its carbon emissions make it unsustainable biodiesel feedstock. The figure emphasises environmental impact when choosing biodiesel feedstocks.

Table 7. Environmental impact comparison between different pyrolysis feedstocks (Wood, RDF, Plastics).

Feedstock	CO2 Emissions (g/kg of bio-diesel)	Bio-diesel Yield (%)	Calorific Value (MJ/kg)
Wood	104.8	15.56	9.6
RDF	379.8	4.4	28.05
Polypropylene (PP)	85.3	67.8	30.42
HDPE	54.2	54.4	28.09
PET	43.8	43.8	19.86
Mixed Plastics	16.5	16.5	16.5

The figure compares CO2 emissions from pyrolysis of wood, RDF, PP, HDPE, PET, and mixed plastics. The figure shows that RDF emits 379.8 grammes of CO2 per kilogramme of bio-diesel, more than any other feedstock. Due to RDF's heterogeneous composition, which includes plastics and textiles, combustion is more complicated and greenhouse gas emissions are high. Although wood is an organic feedstock, it produces moderate CO2 emissions of 104.8 grammes per kilogramme of bio-diesel, making it a more balanced environmental impact than RDF. Polypropylene (PP) and HDPE have lower CO2 emissions than other plastics. At 54.2 grammes per kilogramme of bio-diesel, HDPE emits less CO2 than PP at 85.3 grammes. Since their chemical structure is efficient during pyrolysis, these plastics emit less than RDF and wood. While PET and mixed plastics yield less bio-diesel, they emit less CO2 with 43.8 grammes and 16.5 grammes per kilogramme, respectively. This comparison shows that plastics, especially PP and HDPE, have a lower environmental footprint than RDF and wood, making them better for bio-diesel production that aims to reduce carbon emissions.

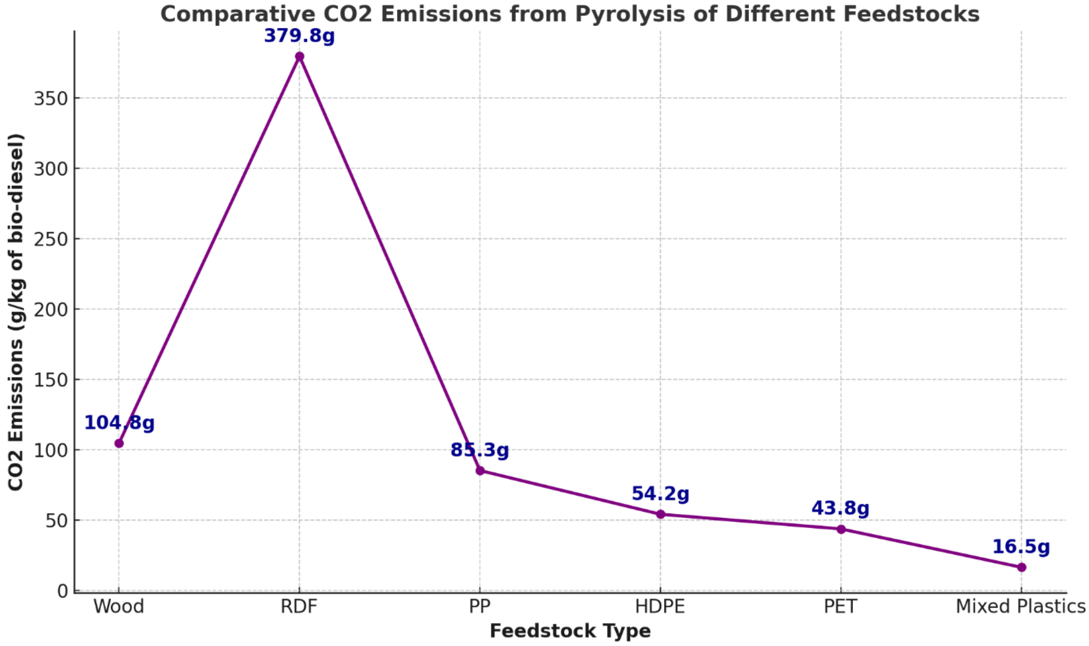

Figure 10. Comparative CO2 emissions from the pyrolysis of different feedstocks (Wood, RDF, Plastics).

Pyrolysis of organic and plastic feedstocks emits significantly different CO2. Wood-based biodiesel emits 104.8 grammes of CO2 per kilogramme. Wood releases less CO2 per kilogramme of bio-diesel than RDF (379.8 grammes), but more than most plastic-based feedstocks. RDF contains non-biodegradable materials like plastics, textiles, and waste, which increases combustion and greenhouse gas emissions. However, pyrolysis of PP and HDPE emits less CO2. They are environmentally friendly because PP emits 85.3 grammes of CO2 per kilogramme of bio-diesel and HDPE 54.2 grammes. PET and mixed plastics produce less bio-diesel than RDF and wood, but emit less CO2 at 16.5 grammes per kilogramme. PP and HDPE feedstocks have lower emissions and a better environmental impact, so they should be prioritised in carbon-reducing bio-diesel production.

Conclusion

In conclusion, pyrolysis can efficiently convert feedstocks including plastics, RDF (Refuse-Derived Fuel), wood, and their combinations into bio-diesel, making it a sustainable and environmentally acceptable approach. Wood produced the greatest bio-diesel at 15.56%, while RDF, despite its higher calorific content, produced the least at 4.4%. Biodiesel yield was higher from plastics like PP and HDPE than organic sources. The chemical properties of bio-diesel, such as calorific values, viscosities, and densities, vary substantially depending on the feedstock, confirming the premise that input material composition greatly affects quality and efficiency. Wood pyrolysis produced 104 grammes of CO2 per kilogramme of bio-diesel, but RDF pyrolysis emitted 379 grammes due to its more complex feedstock, which contains plastics and textiles. PP and HDPE shed 85.3 and 54.2 grammes of CO2 per kilogramme of bio-diesel, respectively, proving that plastics are better for the environment than wood and RDF. These data show that while plastics produce bio-diesel more efficiently and with fewer emissions, pyrolysis of non-organic waste may not be environmentally viable.

The study also examined the wider implications of using different feedstocks for bio-diesel production, finding that while organic materials like wood have a lower life cycle and carbon footprint than plastics like PP and HDPE, their lower bio-diesel yield and energy content make them less efficient for large-scale production. RDF is a less desirable feedstock because it produces less bio-diesel and emits a lot of greenhouse gases. Further study is needed to optimise the pyrolysis process for complicated materials or create waste management methods that balance energy output and environmental sustainability. To optimise MSW-to-biodiesel conversion, pyrolysis research and technological advances are needed to improve yield efficiency, reduce greenhouse gas emissions, and minimise environmental impact, especially when processing complex or mixed waste streams like RDF. The results show that pyrolysis of plastics like PP and HDPE has potential for large-scale bio-diesel production with lower environmental costs, but more innovations are needed to improve organic material and RDF efficiency and better manage bio-diesel yield, energy consumption, and emissions to make it a more viable and environmentally sustainable waste-to-energy conversion solution.

Recommendations

Based on this research, pyrolysis sustainability and efficiency recommendations may increase biodiesel production. Pyrolysis must be tuned to maximise biodiesel production from RDF and mixed polymers. Explore alternative pyrolysis methods, adjust temperature and residence time, or build hybrid systems to break down complex materials. Second, wood, PP, and HDPE emit less CO2 than RDF, hence they should be utilised to lessen environmental impact. Adding carbon capture or other emission reduction methods to pyrolysis could reduce greenhouse emissions and green the process. Third, bio-diesel must improve pyrolysis energy efficiency to remain a fossil fuel alternative. Reusing non-condensable gases and using heat for cogeneration and power production can boost system efficiency and minimise energy demand. Finally, research should increase bio-diesel's compatibility with transportation infrastructure and engines to satisfy industry standards and reduce fossil fuel use. This will lessen climate change risks and accelerate renewable energy adoption.

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