Carbon Footprint Assessment of Both a Novel Household Pyrolysis Reactor with Six Series-Connected Condensers and Pyrolysis Oil Derived from Plastic Waste

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Abstract

The greenhouse gas (GHG) emissions assessment for the product life cycle was conducted within a Business–to–Customer (B2C) system boundary, covering all stages from raw material acquisition to end–of–life disposal. The study focused on a pyrolysis reactor and pyrolysis oil, with the functional unit defined as one pyrolysis reactor (302 kg) and 1 kg of pyrolysis oil. Total GHG emissions over the reactor's life cycle reached 3,100.72 kgCO$_2$e, with the usage phase, assuming six years of operation, accounting for the majority at 2,973.24 kgCO$_2$e, mainly due to Liquefied Petroleum Gas (LPG) combustion as the primary fuel. Emissions from raw material acquisition amounted to 125.55 kgCO$_2$e, while the manufacturing phase contributed a minimal 1.10 kgCO$_2$e, primarily from electricity used in component assembly. The life cycle GHG emissions for pyrolysis oil totaled 6.08 kgCO$_2$e. The highest GHG emissions occurred during the usage phase, where pyrolysis oil replaced fuel oil in stationary combustion, contributing 56.13% of total emissions with 3.42 kgCO$_2$e. The second-largest source was raw material preparation, involving compression of polypropylene (PP) waste into densified form, which emitted 33.43% or 2.03 kgCO$_2$e, mainly due to electricity use. The pyrolysis process accounted for 10.44% or 0.63 kgCO$_2$e, primarily from LPG combustion. A small amount of CO$_2$ was also emitted from burning non-condensable combustible gases, which served as supplementary fuel in the process.

Keywords: Carbon footprint of product, Thermal decomposition, Greenhouse gases, Life cycle inventory

1. Introduction

Global population growth and rising living standards have led to increased consumption of energy and materials, resulting in negative impacts such as climate change caused by greenhouse gas (GHG) emissions, environmental degradation from contamination of air, soil, water, and the food chain, and the depletion of fossil fuel reserves [1],[2].

The greenhouse effect is a scientific phenomenon in the Earth's atmosphere driven by solar radiation. The sun emits energy in the form of visible light, ultraviolet rays, and infrared radiation, which penetrate the atmosphere, composed primarily of nitrogen, oxygen, water vapor, and greenhouse gases (GHGs). These gases including carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O), play a crucial role in absorbing and re–emitting thermal radiation, thereby maintaining a stable global temperature. However, human activities have significantly increased the concentration of these gases, leading to excessive heat accumulation, a rise in global temperatures, and the phenomenon of global warming [3]. The greenhouse effect is illustrated in **Figure 1**.

Global warming contributes to climate variability, resulting in extreme weather events, heatwaves, and ecological disruptions such as species extinction and sea-level rise. These impacts pose significant threats to human health, infrastructure, and food security, while exacerbating socio-economic challenges globally. This underscores the urgent necessity for the implementation of effective mitigation strategies [4]. Global GHG emissions in 2023 reached about 35.8 Gt, marking a significant slowdown compared to the sharper increases in 2021 and 2022 [4]. This modest growth was mainly driven by fossil fuel use and cement production, with fossil GHG emissions rising 1.3% from the previous year [5]. The majority of GHG emissions originate from electricity and heat production, as well as transportation. Growing environmental concerns have driven nations to pursue emission reduction strategies. The Paris Agreement, adopted at Conference of the Parties (COP) 21 under the UNFCCC framework, builds upon the Kyoto Protocol with the goal of limiting global temperature rise to below 2 °C, ideally under 1.5 °C above pre-industrial levels. Thailand is a signatory to both the UNFCCC and Kyoto Protocol.

During the 26th UN Climate Change COP26, held in Glasgow, United Kingdom, in 2021, Thailand exhibited heightened awareness and strengthened commitment toward addressing environmental challenges and climate change mitigation. The nation declared ambitious targets, including the achievement of carbon neutrality by 2050, defined as reducing GHG emissions to levels offset by natural absorption, and attaining net–zero GHG emissions by 2065.

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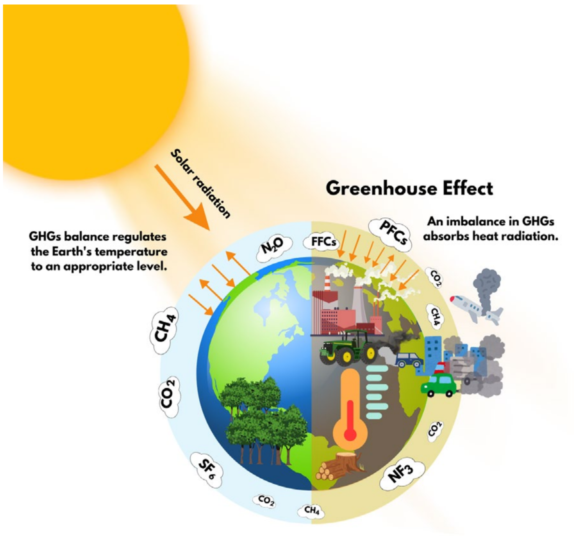

Figure 1 The greenhouse effect.

Additionally, Thailand emphasized the promotion of renewable energy sources including solar, wind, and biomass, as well as the development of energy storage systems and infrastructure to support electric vehicles (EVs).

At COP29, held in Baku, Azerbaijan, in November 2024, Thailand reaffirmed its commitment to its initial targets while also highlighting key initiatives, including the implementation of national greenhouse gas reduction action plans, the establishment of a comprehensive GHG emissions database and reporting system, and the development of mechanisms for mandatory emissions reductions. These efforts align with Thailand's Sustainable Development Goals (SDGs) under the theme of Climate Action, which serves as a critical framework for achieving sustainable national development, with a focus on the phase–out of fossil fuels and a transition toward a bioenergy-based economy.

One approach for countries to achieve carbon neutrality and net–zero greenhouse gas emissions is to assess emissions at both the organizational and product levels, which informs strategies for reducing significant emission sources [6]. The carbon footprint of product (CFP) refers to the total GHG emissions generated throughout a product's lifecycle, including raw material acquisition, production, distribution, usage, disposal, and all associated transportation. CFP is typically expressed in carbon dioxide equivalent (CO_2e) to standardize the measurement of different GHGs. Understanding and managing CFP is essential for industries aiming to mitigate environmental impact and comply with regulatory frameworks. To ensure accurate assessment and effective communication of CFP across supply chains, various methodologies and analytical tools have been developed [7].

The use of biofuels instead of fossil fuels resulted in lower emissions, demonstrating a 30–40% reduction in CO_2 emissions. Additionally, fossil fuel usage was reduced by up to 50% compared to gasoline [8],[9]. Furthermore, bio–oil feedstock was produced using whole southern pine trees. Substituting bio-oil for residual fuel oil was estimated to reduce CO_2 emissions by 0.075 kg CO_2/MJ of fuel combustion [10]. Moreover, a comparative GHG emissions analysis of biodiesel production from canola and carinata, relative to petroleum diesel, revealed that biodiesel derived from oilseed crops emitted 21 to 31 g CO_2e/MJ, demonstrating a statistically significant reduction in GHG emissions [11].

GHG emissions from waste plastic have had extensive and profound impacts on environmental health and climate change. Between 1950 and 2020, China's cumulative plastic–related GHG emissions reached 5,544 $MtCO_2e$, with nearly 497 $MtCO_2e$ emitted in 2020 alone [12]. Forecasts suggest that, without intervention, emissions from the plastic sector could peak around 2040, driven primarily by the escalating volume of mismanaged plastic waste. Projections further indicate that, by 2050, these emissions may rise to 3.35 $GtCO_2e$ [13]. Life Cycle Assessment (LCA) has demonstrated that pyrolysis reduces GHG emissions by approximately 28% to 31% compared to incineration, with estimates projecting potential reductions of 39% to 65% by 2030 [14]. Alongside other recycling techniques such as chemical recycling, pyrolysis presents a viable pathway to significantly curb emissions and mitigate the environmental burden associated with plastic waste.

The increasing accumulation of polymer waste poses a critical environmental issue demanding advanced strategies for efficient waste management and resource recovery [15]. One such strategy is the conversion of waste into energy through thermal technology. Pyrolysis is an efficient thermal decomposition process used for municipal solid waste management, particularly for converting plastic waste such as polypropylene (PP), high–density polyethylene (HDPE), and multilayer plastic (ML) into fuel oil, gases, and char. The process operates at a moderate temperature range of 350–500°C for a reaction time of 45 to 90 minutes [16],[17]. As a result, it serves as a potential liquid fuel alternative to petroleum-based fuels. Advancements in pyrolysis–based fuel production are driving significant growth in the industry. Consequently, the commercialization of pyrolysis technology for biofuel production has advanced at an accelerated pace [10].

Assessing GHG emissions is essential for promoting sustainable development. This study aims to assess the carbon footprint of a novel household pyrolysis reactor equipped with six series–connected condensers and its pyrolysis oil derived specifically from densified polypropylene (PP) waste. The scope covers the life cycle from feedstock acquisition to end-of-life disposal, providing a comprehensive environmental impact evaluation of this innovative waste-to-fuel technology. The GHG emissions associated with the use of pyrolysis technology and the production of pyrolysis oil will be quantified based on the collected data. This data can serve as a fundamental database for the development of alternative energy technologies designed to mitigate GHG emissions in the future.

2. Data and Methods

2.1 Conceptual Framework of the Study

The methodology used in this study was based on LCA to analyze the GHG emissions of the product. The LCA methodology consisted of four key phases: 1) goal and scope definition, which involved defining the functional unit, system boundaries, and setting objectives for the analysis; 2) life cycle inventory (LCI), which focused on quantifying the materials, inputs, and outputs of all processes involved; 3) life cycle impact assessment (LCIA), which evaluated the impact potentials of unit flows, specifically in terms of greenhouse gas emissions; and 4) results interpretation, which involved analyzing the outcomes of the assessment [18],[19]. The steps of the life cycle analysis are shown in **Figure 2**.

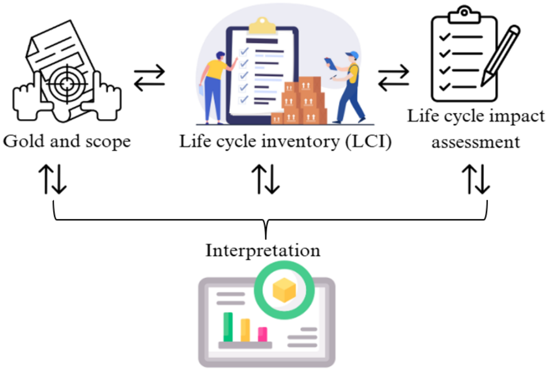

Figure 2 Step of life cycle analysis.

GHG emissions throughout the LCA were considered as part of a cradle–to–grave or Business–to–Customer (B2C) evaluation. The primary objective was to assess the impact across the entire life cycle, including raw material acquisition, manufacturing, transportation, operation and use, secondary use of key components, and end–of–life recycling [20].

This study focused on assessing the GHG emissions of two products and was divided into two main parts. The first part involved evaluating the GHG emissions from a 50–liter household–scale pyrolysis unit used to convert plastic waste into liquid fuel. The second part examined the GHG emissions associated with the pyrolysis oil produced from the pyrolysis process of PP plastic waste. The assessment followed a B2C approach for analyzing the CFP by evaluating GHG emissions across their entire life cycle. This included stages such as material acquisition, production processes, transportation, usage, and waste management (recycling, recovery, and disposal) and transportation associated with each stage. Calculations were performed per functional unit in accordance with ISO 14067:2018, Greenhouse Gases – Carbon Footprint of Products – Requirements and Guidelines for Quantification.

2.2 Scope Definition and System Boundaries

The goal and scope of this research encompassed defining a reference unit, known as the functional unit, to which all inputs and outputs were related. Additionally, the goal and scope outlined the approach for establishing system boundaries [21].

The GHG assessment study involved key processes including goal and scope definition, compiling an inventory through the collection of primary data, and evaluating environmental impacts. The aim of this study was to provide an updated assessment of life cycle GHG emissions associated with a single household–scale pyrolysis unit, as well as the GHG emissions from the liquid fuel produced during the pyrolysis process using PP waste plastic feedstocks. The feedstocks considered in this study were sourced from an open dump site.

The GHGs considered in the calculation included seven types of gases regulated under the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). GHG emissions or global warming potential were calculated by measuring or estimating the actual amount of each GHG emitted and converting it into CO_2e using the global warming potential (GWP) values over a 100–year period, as defined by the IPCC.

The generic system boundary of B2C assessment model encompasses all processes from raw material acquisition to disposal. Within this framework, the GWP values for each type of GHG were applied to convert emissions into CO_2e values, enabling a standardized comparison of the environmental impacts across different gases. The system boundary and GWP values for each gas, as illustrated in **Figure 3**, provide a comprehensive overview of the scope and method used for quantifying the GHG emissions associated with the product throughout its entire life cycle.

The study assessed GHG emissions across the life cycles of two products: the pyrolysis reactor and the pyrolysis oil. For the pyrolysis reactor, the life cycle included: 1) raw material acquisition, which involved procuring and transporting materials; 2) production, covering the assembly of reactor components; 3) usage, during which the reactor operated to convert plastic waste into pyrolysis oil; and 4) waste management, which entailed disassembly and recycling.

The life cycle of the pyrolysis oil included: 1) raw material acquisition, which involved the transportation and preparation of plastic waste for compaction before processing; 2) pyrolysis oil production, which encompassed the pyrolysis process; and 3) usage, referring to the application of pyrolysis oil as an alternative fuel in industrial boilers for combustion processes. The system boundary for the life cycle of the pyrolysis reactor is illustrated in **Figure 4**, while the system boundary for the life cycle of the pyrolysis oil is shown in **Figure 5**. For this analysis, a functional unit of 1 kg of pyrolysis oil and one pyrolysis reactor was defined to represent the two production processes.

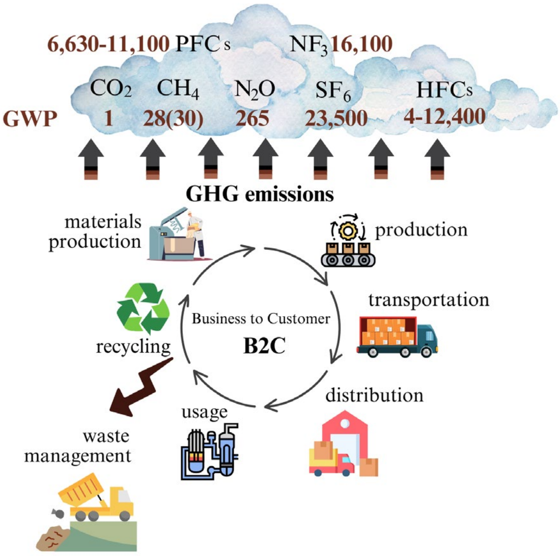

Figure 3 Generic system boundary of the B2C assessment model and the GWP values for each type of gas.

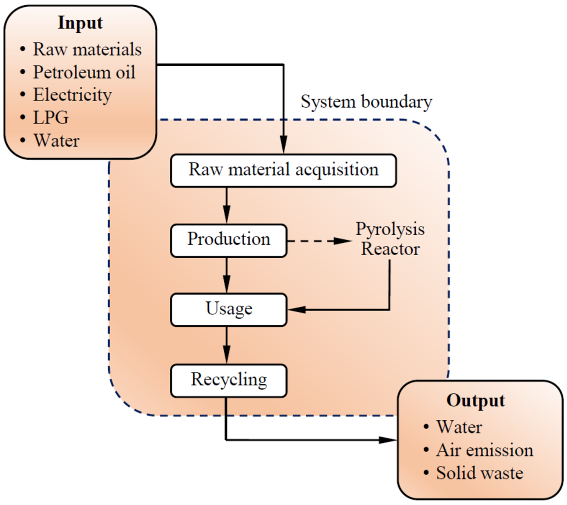

Figure 4 System boundary for the life cycle of the pyrolysis reactor.

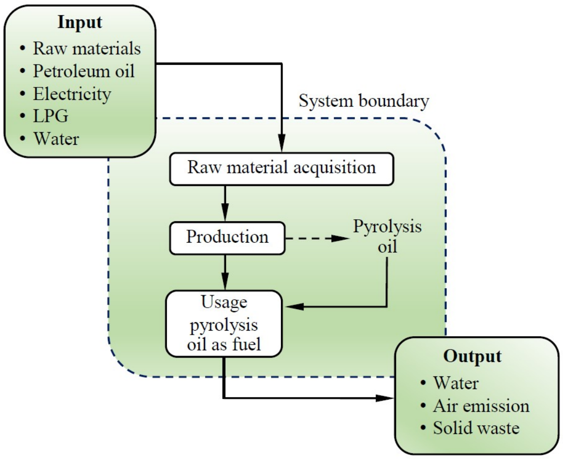

Figure 5 System boundary for the life cycle of the pyrolysis oil.

2.3 Basic Information on Pyrolysis Reactor Technology

The household–scale 50–liter batch pyrolysis unit consisted of four main components: the fuel feeding chamber, the reactor chamber, the condensation unit, and the pyrolysis vapor filtration system. The fuel feeding chamber was made of low carbon steel, with an inside diameter of 8.4 cm and a length of 65 cm. The reactor chamber, a fixed–bed reactor with a 50 L capacity, was also constructed from low carbon steel, with an inside diameter of 34 cm and a length of 58 cm. The reactor was sealed with a top cover and insulated with ceramic fiberglass to enhance thermal efficiency. The external structure, constructed from steel, was rectangular with dimensions of 60 × 120 × 100 cm [17].

The condensation unit consisted of six parallel pipes arranged in three rows, with two pipes per row. Each pipe had a diameter of 10 cm and a length of 70 cm. The system used LPG as the primary fuel source for heating, in combination with a recirculating non–condensable pyrolysis gas system that redirected uncondensed vapors back into the burner to improve combustion efficiency.

The pyrolysis vapor filtration system consisted of low carbon steel pipes with a diameter of 10.8 cm and a length of 50 cm. Water was used as the filtering medium. Additionally, a vacuum pump was integrated into the system to regulate and maintain internal atmospheric conditions, ensuring optimal operational efficiency. The pyrolysis machine is shown in **Figure 6**.

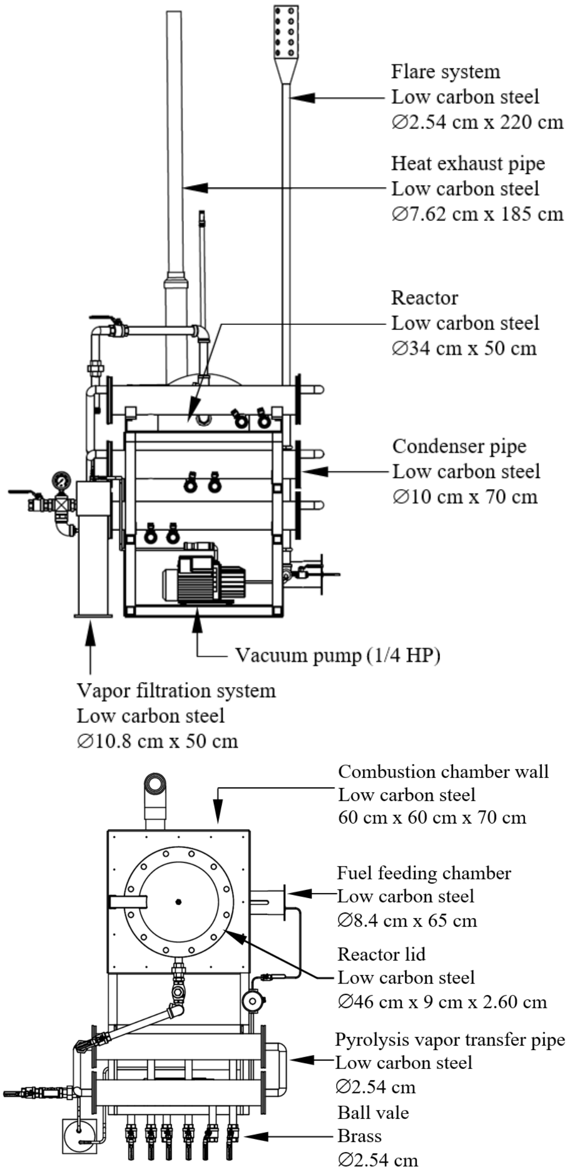

Figure 6 Side and top view of the pyrolysis reactor.

2.4 Basic Information on Pyrolysis Oil Conversion

Pyrolysis oil production required plastic waste, which was collected from an open dump site. In open drum landfill sites, municipal solid waste including plastics, was disposed of without any compaction. Waste deposition typically occurs every 2 to 3 days. The plastic waste underwent a pyrolysis reaction in this study. After size reduction (**Figure 7**), the PP plastic feedstock was compacted and molded into a cylindrical shape using a hydraulic machine. The final product had a diameter of 8 cm, a length of 4 cm (**Figure 7**), and a density of 0.6 g/cm^3. A total of 5 kg of densified plastic was placed into the reactor chamber, with LPG used as the heating fuel. The pyrolysis process was carried out at a temperature range of 250–450°C under vacuum conditions, maintained by a vacuum pump, with a heating rate of 5–15°C/min and a reaction time of 60 min.

The energy in the pyrolysis reactor exit gas contained non–condensable gases, which were combustible components that served as an energy source for the pyrolysis process. The syngas produced (comprising 25% by weight) and these gases were directed to a burner, where they were combusted together with LPG to supply process heat and serve as supplementary fuel.

The pyrolysis procedure comprised two primary stages. Initially, the plastic waste was subjected to heating to convert it into hot vapor. Subsequently, this vapor was directed to the condenser, where it underwent condensation to form pyrolysis oil. Prior to entering the fuel feeding chamber, the vapor was passed through a filtration column containing water to remove impurities. The physicochemical properties of the resulting oils were subsequently analyzed.

Figure 7 The shredded and densified plastic derived from PP waste.

2.5 Life Cycle Inventory Data

The LCI phase involved collecting primary data, calculating inputs and outputs within the product system boundary, and performing allocation. The inventory results were then used as inputs for the LCIA phase. The environmental inventory compilation included analyzing and recording data on raw material consumption, energy use, and waste emissions throughout the life cycle of producing one pyrolysis reactor and 1 kg of pyrolysis oil. This study, conducted under the principles of LCA, systematically and comprehensively analyzed environmental impacts across all production stages. To ensure accuracy and alignment with actual production conditions, all data were gathered from primary processes. The GHG emission calculation method was selected to accurately quantify emissions by using activity data from raw material acquisition through to product waste disposal.

This study was conducted in accordance with ISO 14067:2018 standards [22], which define and report GHG emissions in products. It focused on calculating, monitoring, and reporting emissions from various organizational activities to support effective emission management and reduction. The study also assessed the CFP by evaluating GHG emissions throughout their life cycle, from raw material acquisition to disposal or recycling. Mass balance output data were utilized to estimate environmental impacts, including emissions, fossil fuel consumption, resource use, and contributions to global warming.

2.5.1 Pyrolysis Reactor Data Collection

The process for evaluating the GHG emissions of the pyrolysis reactor consisted of four stages: 1) acquisition of equipment components, 2) component assembly, 3) usage, and 4) waste management. Distance data for transporting the equipment components were collected using a 4–wheel pickup truck powered by diesel fuel, with a 7–ton maximum payload. Fuel consumption rate data helped determine the quantity of fuel consumed. Components were cut to size using an electric–powered metal cutting machine and assembled using an electric welding machine, with welding electrodes as the medium. Data on the weight of the components, electricity consumption, and quantity of welding electrodes used were gathered to calculate GHG emissions.

For usage, the pyrolysis reactor had a 6–year lifespan and consumed 700 kg of LPG for the pyrolysis of 7 tons of plastic waste. The vacuum pump consumed 322 kWh of electricity annually. Waste management included recycling components and sending general waste to a landfill, with transportation fuel consumption calculated based on a 4–wheel pickup truck running on diesel fuel. The flowchart of the pyrolysis reactor was shown in **Figure 8**, and the inventory data was presented in **Table 1**, which did not include transportation data for the various processes.

Electricity consumption was calculated by multiplying the power rating of electrical equipment or machinery by the duration of its usage. The power ratings were obtained from the specification documents of the respective equipment or machinery.

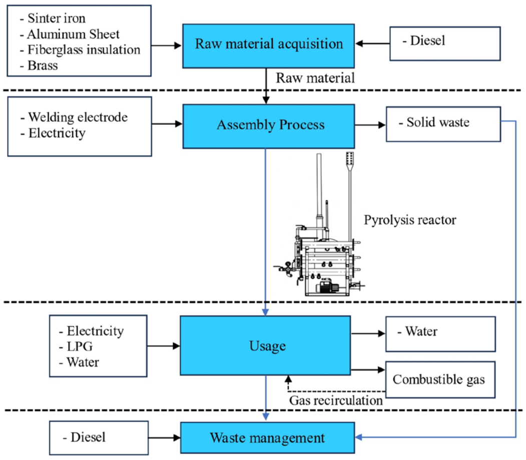

Figure 8 Flowchart of pyrolysis reactor.

Table 1 Inventory data of pyrolysis reactor product.

LCI stage	Carbon footprint inventory	Unit	Value	EF (CO_2e/ unit)
Raw material acquisition				
Input	Sinter iron	kg	303	0.3493
	Aluminum Sheet	kg	0.4	0.2231
	Fiberglass insulation	kg	5.0	2.5612
	Synthetic rubber	kg	0.24	3.5138
	Brass	kg	2.2	2.4528
Output	Sinter iron (recycling)	kg	10.0	0
Production				
Assembly Process				
Input	Electricity	kwh	1.1	0.5986
	Welding electrode	kg	1.16	0.3493
Output	Pyrolysis reactor	kg	302	–
Usage (6–year period)				
Input	Pyrolysis reactor	kg	302	–
	Electricity	kwh	322	0.5986
	LPG (Stationary combustion)	kg	700	3.1134
	LPG	kg	700	0.8582
	water	m^3	0.2	0.541
Output	Water (recycling)	m^3	0.2	0
	Pyrolysis reactor	kg	302	–
Waste management by recycling				
Input	Pyrolysis reactor (recycling)	kg	302	0

2.5.2 Pyrolysis Oil Data Collection

The process of collecting GHG emissions data for pyrolysis oil began with sourcing raw materials. The transportation of PP plastic waste was carried out using a motorcycle with a sidecar, fueled by gasoline. After transportation, the plastic waste underwent a washing process with water before being compressed to increase its density. It was then processed through pyrolysis, utilizing LPG and non–condensable pyrolysis gases as supplementary fuels. Data collection throughout the entire process, from raw material acquisition to pyrolysis oil production, included fuel consumption for transportation, water usage, LPG consumption, and electricity used for vacuum system operations. In the usage phase, the pyrolysis oil was combusted as a substitute for fuel oil in an industrial boiler.

GHG emissions released into the environment from combustion were recorded and calculated using standardized methods. A functional unit of 1 kg was used to demonstrate the environmental assessment. A detailed process flowchart for pyrolysis oil production and emission assessment was illustrated in **Figure 9**. The inventory data for the pyrolysis oil product and the emission factor of densified PP waste were presented in **Table 2** and **Table 3**, which did not include transportation data for the various processes.

Emissions associated with the combustion of pyrolysis oil in boilers were not available. Therefore, the GHG emissions for the pyrolysis oil usage process in boilers were calculated using Eq. (1):

$$EF_{\text{combustion}} = \sum(\mathrm{DF_i} \times \mathrm{CV} \times 10^{-6} \times \mathrm{GWP_i}) \qquad (1)$$

Where:

$\mathrm{EF_{combustion}}$	refers to the Emission Factors associated with the combustion of pyrolysis oil ($\mathrm{kgCO_2e/kg}$).
$\mathrm{DF_i}$	refers to the default emission factor for stationary combustion in the energy industries for GHGs(CO_2, CH_4, and N_2O) (kg/TJ).
$\mathrm{GWP_i}$	refers to the global warming potential of each GHGs. CV refers to the calorific value of pyrolysis oil (MJ/kg).

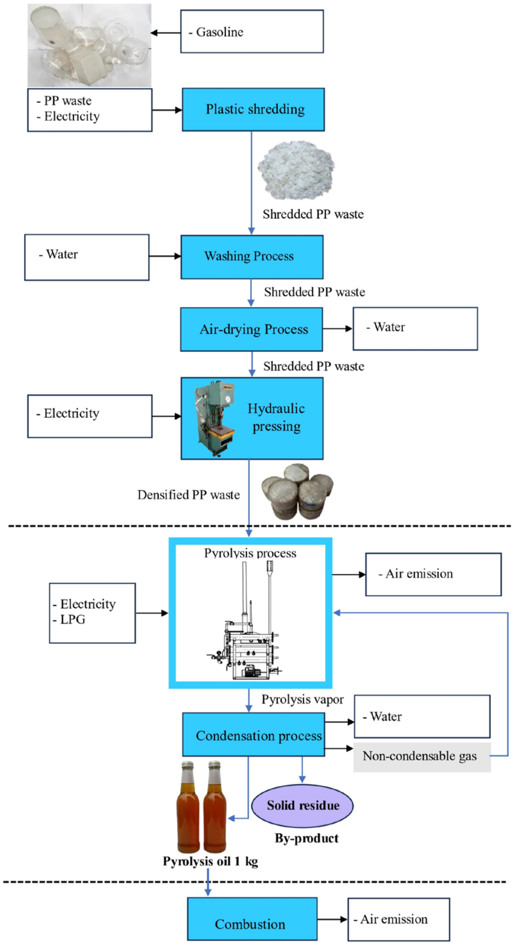

Figure 9 Flowchart of plastic waste conversion into 1 kg of pyrolysis oil.

The default emission factor was assumed to be from the combustion of residual fuel oil, with CO_2 77,400 kg CO_2/TJ, CH_4 3 kg CH_4/TJ, and N_2O 0.6 kg N_2O/TJ. The GWP values were CO_2 1, CH_4 30, and N_2O 265. The calorific value of pyrolysis oil was 44 MJ/kg.

Based on the calculation using Eq. (1), the Emission Factor from the stationary combustion of pyrolysis oil was determined to be 3.4166 $\mathrm{kgCO_2e/kg}$.

Possible uncertainties in the input data resulted from the GHG emissions associated with the combustion of pyrolysis oil used as fuel in the steam boiler. Direct measurements of CO_2, CH_4, and N_2O emissions from combustion were not conducted. Instead, default emission factors based on residual fuel oil combustion were applied, which likely resulted in an overestimation of GHG emissions for this stage.

Table 2 Inventory data of pyrolysis oil product.

LCI stage	Carbon footprint inventory	Unit	Value	EF (CO_2e/ unit)
Raw material acquisition				
Input	Densified PP waste	kg	1.3514	1.5056
Production				
Pyrolysis process				
Input	Electricity	kwh	0.0622	0.5986
	LPG	kg	0.1351	0.8582
	LPG (Stationary combustion)	kg	0.1351	3.1134
	Water	m^3	0.0008	0.5410
Output	Pyrolysis oil	kg	1	**product**
	Solid residue (By–product)	kg	0.0081	0
	Non–condensable gases (Recirculation)	kg	0.3432	
	CO_2 emission	kg	0.0609 Considering the CO_2 generated from the re–combustion process	
	Water (recycling)	m^3	0.0008	0
Usage				
Combustion process				
Input	Pyrolysis oil (Product)	kg	1	–
Output	GHG emissions from stationary combustion	kg	1	3.4166

Table 3 Calculation data for determining the Emission Factor of densified PP waste in the raw material acquisition stage.

LCI stage	Carbon footprint inventory	Unit	value	EF (CO_2e/ unit)
Raw material acquisition				
Plastic shredding				
Input	PP plastic waste	kg	1	–
	Gasoline (Transportation)	L	0.45	2.2719
	Electricity	kwh	0.06	0.5986
Output	Shredded PP waste	kg	1	–
Washing process				
Input	Water	m^3	0.0014	0.5410
Output	Shredded PP waste	kg	1	–
Air–drying Process				
Input	Shredded PP waste	kg	1	–
Output	Water (recycling)	m^3	0.0014	0
Hydraulic pressing process				
Input	Electricity	kwh	0.746	0.5986
Output	Densified PP waste	kg	1	–
Emission Factor of densified plastic 1 kg				**1.5056**

The non–condensable gases from the pyrolysis process were utilized as fuel within the same process. The composition of these non–condensable gases, which contained combustible components, was shown in **Table 4**, as referenced from the study by Pan et al. [23], which investigated the pyrolysis of PP plastic waste. During the combustion of these combustible gases, CO_2 was produced and released through the exhaust. These data were used to calculate the GHG emissions, with the combustion of the non–condensable gases resulting in a CO_2 emission of 0.0609 kg per kilogram of pyrolysis oil.

Table 4 Composition of gases generated from the pyrolysis of PP waste plastic.

Composition	Value (%w)	Reference
H_2	0.09	Pan et al. (2021) [18].
CH_4	2.01	
C_2H_6	4.24	
C_2H_4	0.90	
C_3H_8	7.36	
C_3H_6	29.06	
C_4H_{10}	0.23	
C_4H_8	1.48	
CO_2	0	

The transportation of raw materials for the production of the pyrolysis reactor (10 km), LPG (2 km), and waste to a recycling site (15 km) was carried out using a small 4–wheel pickup truck operating under normal conditions, with a maximum payload capacity of 7 tons. For the outbound trip, with 100% loading, the Emission Factor was 0.1411 kgCO$_2$e/unit, while for the return trip, with 0% loading, the Emission Factor was 0.3131 kgCO$_2$e/unit. The outbound load was determined by multiplying the weight by the transportation distance. For the return load, the outbound load value was divided by the maximum payload capacity, as shown in Eqs. (2)–(3).

$$\text{Outbound load (tkm)} = \frac{\text{Weight (kg)} \times \text{Distance (km)}}{1000} \quad (2)$$

$$\text{Return load (km)} = \frac{\text{Outbound load (tkm)}}{\text{Maximum payload capacity (ton)}} \quad (3)$$

2.6 Life Cycle Impact Assessment

The impact assessment involved evaluating the environmental effects of the overall product system under study [9], with a focus on GHG emissions. The assessment relied on activity data, including resource and energy consumption as well as GHG released from processes. GHG emissions were calculated using the GWP and Emission Factors. When the dataset included different GHG types, each type was multiplied by its GWP value according to IPCC 2006, as shown in Eq. (4). For data related to resource or energy consumption, emissions were determined by multiplying the values by the Emission Factor, as shown in Eq. (5). The Emission Factors were sourced from the Thai National LCI Database and IPCC AR5, with quantity units adjusted to align with the Emission Factors for conversion into CO$_2$e units. To ensure transparency and traceability, the calculation of GHG emissions required clear documentation of the sources for both the calculation methods and emission factor references.

$$\text{CFP} = \text{GHG} \times \text{GWP} \quad (4)$$

$$\text{CFP} = \text{Activity data} \times \text{Emission Factor} \quad (5)$$

Where:

CFP	refers to the life cycle GHG emissions of product (kgCO$_2$e).
Activity data	refers to activities that result in GHG emissions or removals.
GWP100	quantifies a greenhouse gas's warming effect relative to CO$_2$ over 100 years.
GHG	refers to the seven types of GHGs under the Kyoto Protocol.
Emission Factor	is the amount of GHG emitted or removed per unit of activity (kgCO$_2$e/unit).

3. Results and Discussion

3.1 Pyrolysis Product

The pyrolysis process of PP plastic waste for pyrolysis oil production was studied to utilize the obtained data for assessing the GHG emissions of the product. The experiment was conducted using a 50–liter pyrolysis reactor with 5 kg of PP plastic waste as feedstock. The process conditions included a temperature range of 250–450°C, a heating rate of 5–15°C/min, and a reaction time of 60 min. The results indicated that pyrolysis oil was the main product, with a yield of 3.7 kg, followed by non–condensable gases at 1.27 kg and solid residue at 0.03 kg. The pyrolysis oil and solid residue products are shown in **Figure 10**. The color of the pyrolysis oil was light brownish–yellow with slight turbidity, which was consistent with the color of pyrolysis oil from plastic reported in the study by Khair et al. [24].

The analysis of the pyrolysis oil properties revealed that its density ranged from 0.7 to 0.8 g/cm^3, which was consistent with the findings of Khair et al. [24], who produced pyrolysis oil from PP plastic waste at 350°C and reported a density of 0.78 g/cm^3. Furthermore, the thermal property analysis indicated that the calorific value of the obtained pyrolysis oil was 10,524 cal/g, closely matching the value reported by Khair et al. [24] at 10,340 cal/g. Solid residue was a by–product generated from the pyrolysis process. It exhibited a glossy black appearance, as illustrated in **Figure 10**, and was subsequently utilized for further applications.

The calorific value of the pyrolysis oil served as a fundamental parameter for assessing GHG emissions resulting from its combustion. This was particularly relevant to stationary combustion systems that employed burners as an alternative to conventional fuel oil.

Figure 10 Sample of pyrolysis oil (left) and solid residue (right).

3.2 Life Cycle GHG Emissions from The Production of a Pyrolysis Reactor

This study evaluated the life cycle (B2C) GHG emissions of a pyrolysis reactor used for plastic pyrolysis, with the functional unit defined as a single reactor weighing 302 kg. The life cycle GHG emissions associated with the reactor's production are presented in **Table 5**. The assessment covered the entire life cycle, from raw material acquisition to end–of–life disposal, and was categorized into four main phases: 1) raw material acquisition, 2) manufacturing and assembly, 3) operation, and 4) end–of–life disposal.

The total carbon footprint of the pyrolysis reactor was found to be 3,100.72 kgCO$_2$e. The operation phase contributed the highest GHG emissions, totaling 2,973.24 kgCO$_2$e, primarily due to electricity and LPG consumption over the reactor's six–year operational period. Specifically, 2,179.38 kgCO$_2$e resulted from stationary LPG combustion, while 600.74 $kgCO_2e$ was attributed to LPG production. Additionally, electricity consumption contributed 192.75 $kgCO_2e$, whereas water usage had a negligible impact, accounting for only, accounting for only 0.11 $kgCO_2e$.

The raw material acquisition phase was identified as the second–largest contributor to GHG emissions, primarily due to the significant use of sinter iron as the main material for the reactor. This phase, including the transportation of raw materials, was responsible for 125.55 $kgCO_2e$.

The end–of–life disposal phase generated the lowest GHG emissions, as the reactor was fully recycled. However, minor emissions were still emitted from the transportation of the dismantled reactor to the recycling facility.

These findings demonstrated that energy consumption during the operation phase was the dominant factor contributing to GHG emissions. Therefore, improving energy efficiency or adopting alternative energy sources were identified as key strategies for reducing the environmental impact of pyrolysis reactor usage in the future.

However, when the GHG emissions within the B2B system boundary were considered, from raw material acquisition to the production process, excluding the usage and end–of–life disposal phases, the total GHG emissions amounted to only 126.65 $kgCO_2e$.

Table 5 Life cycle GHG emissions from the production of a pyrolysis reactor.

Life cycle stage		**$kgCO_2e$**
1. Raw material acquisition		
Transportation of raw materials, energy, and resources		0.58
Input	Sinter iron	105.84
	Aluminum Sheet	0.09
	Fiberglass insulation	12.81
	Synthetic rubber	0.84
	Brass	5.39
GHG emissions		**125.55**
2. Production		
Transportation of raw materials, energy, and resources		0.03
Assembly Process		
Input	Electricity	0.66
	Welding electrode	0.40
Output	Sinter iron (recycling)	0.00
	Pyrolysis reactor	**Product**
GHG emissions		**1.10**
3. Usage (6–year period)		
Transportation of raw materials, energy, and resources		0.26
Input	Electricity	192.75
	LPG (Stationary combustion)	2,179.38
	LPG	600.74
	water	0.11
Output	Water (recycling)	0
GHG emissions		**2,973.24**
4. Waste management		
Transportation of raw materials, energy, and resources		0.84
Pyrolysis reactor (recycling)		0
GHG emissions		**0.84**
Total GHG emissions		**3,100.72**

The consideration of GHG emissions based on the ratio revealed that product usage accounted for the highest proportion, at 95.89%. This was followed by 4.05%, 0.04%, and 0.03%, attributed to raw material acquisition, production, and waste management, respectively, as shown in **Figure 11**. The life cycle mass flow diagram is presented in **Figure 12**.

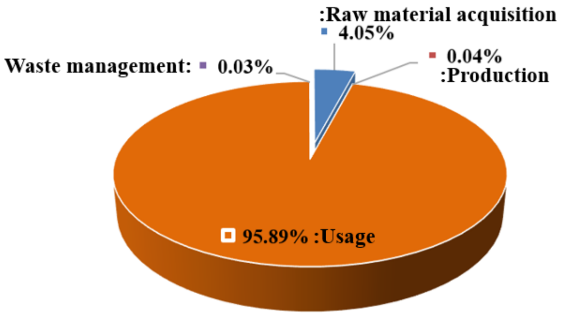

Figure 11 The proportion of GHG emissions at each stage throughout the life cycle of the pyrolysis reactor.

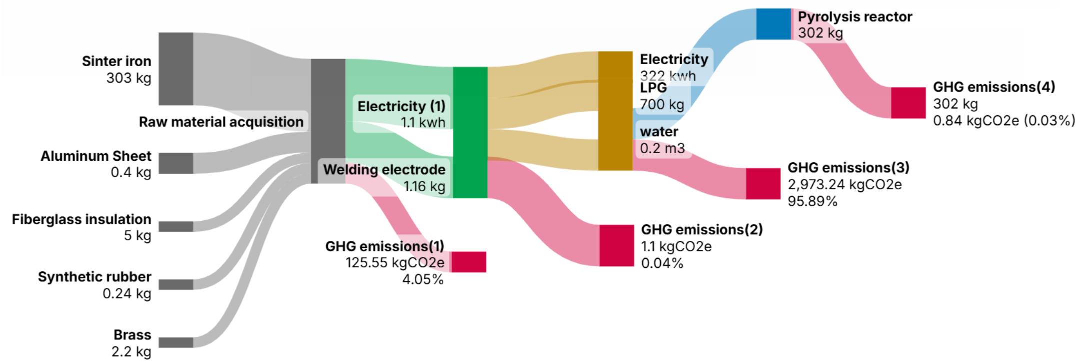

Figure 12 Pyrolysis reactor life cycle flow diagram.

3.3 Life Cycle GHG Emissions from The Production of Pyrolysis Oil

The life cycle assessment of GHG emissions from 1 kg of pyrolysis oil indicated a total emission of 6.08 kgCO$_2$e, as shown in **Table 6**.

The assessment encompassed raw material acquisition, production, usage, and disposal. However, since pyrolysis oil was entirely consumed, no emissions were attributed to the disposal phase.

The experimental findings demonstrated that the highest GHG emissions were associated with the usage phase, with 3.42 kgCO$_2$e emitted from replacing fuel oil with pyrolysis oil. Considering the case GHG emissions from the combustion of pyrolysis oil, which had a density of 0.7 g/cm^3, in boilers compared to Fuel Oil C for an equivalent volume of 1 L, it was observed that emissions from pyrolysis oil were approximately 26.42% lower than those from Fuel Oil C.

Table 6 Life cycle GHG emissions from producing 1 kg pyrolysis oil.

Life cycle stage		**kgCO$_2$e**
1. Raw material acquisition		
Densified PP plastic		2.03
GHG emissions		**2.03**
2. Production		
Transportation of raw materials, energy, and resources		0.0001
Input	Electricity	0.03
	LPG (Stationary combustion)	0.42
	LPG	0.12
	Water	0.0004
Output	Water (recycling)	0
	CO$_2$ emission	0.06
	Pyrolysis oil	**Product**
GHG emissions		**0.63**
3. Usage as fuel oil		
Pyrolysis oil (combustion)		3.42
GHG emissions		**3.42**
Total GHG emissions		**6.08**

The second–highest emissions, totaling 2.03 $kgCO_2e$, were associated with raw material acquisition, which involved the production of densified PP waste. This process included the transportation of PP plastic waste from open dump sites using gasoline–powered transportation, resulting in emissions of 1.02 $kgCO_2e$. In line with the experiments conducted by Tapanadilok et al. [25], which evaluated GHG emissions from plastic oil production via pyrolysis, it was determined that the raw material acquisition stage contributed the majority of the emissions, primarily due to electricity consumption.

The raw material preparation phase focused on producing densified PP waste, which entailed several subprocesses. The shredding process required electricity, resulting in emissions of approximately 0.04 $kgCO_2e$. The washing process contributed 0.0007 $kgCO_2e$ due to tap water usage. The air–drying process did not generate emissions, as it relied solely on natural evaporation to reduce the plastic's moisture content. The hydraulic pressing process, which shaped the plastic into compacted forms, generated the highest emissions within this phase, reaching 0.45 $kgCO_2e$ due to electricity consumption.

The pyrolysis oil production phase generated the lowest GHG emissions, totaling 0.63 $kgCO_2e$. This was primarily due to the combustion of LPG, which resulted in 0.42 $kgCO_2e$. The acquisition of LPG further contributed 0.12 $kgCO_2e$. Next, GHG emissions from CO_2 released during the combustion of non–condensable gases used as fuel amounted to 0.06 $kgCO_2e$, while electricity consumption for operating the vacuum pump added another 0.03 $kgCO_2e$. Minor emissions were also recorded from tap water usage (0.0004 $kgCO_2e$) and the transportation of LPG (0.0001 $kgCO_2e$). The experimental results were consistent with those reported by Tapanadilok et al. [24], in which LPG was used as the fuel in the pyrolysis process. The study confirmed that the majority of greenhouse gas emissions were attributable to fuel combustion.

The GHG emissions from the pyrolysis oil production process were consistent with the findings of Khair et al. [24]. When considering only the production phase, this study reported lower GHG emissions at the same functional unit. However, when accounting for the feedstock preparation stage, the total emissions were higher. This was due to the fact that in the study by Khair et al. [24], plastic waste was directly fed into the pyrolysis process without undergoing pre–compaction, whereas this study included an additional preparation step, resulting in increased GHG emissions.

However, when considering a B2B assessment, which accounted for emissions from raw material acquisition to the production of 1 kg of pyrolysis oil, the total GHG emissions were estimated 2.6 $kgCO_2e$.

The results of the GHG emissions ratio analysis from the life cycle of 1 kg of pyrolysis oil, as shown in **Figure 13**, indicated that the highest proportion, 56.13%, was associated with the usage phase of pyrolysis oil. This was followed by the raw material acquisition phase, which accounted for 33.43% of the total GHG emissions. The production phase contributed the least, with only 10.44% of the total GHG emissions over the life cycle. The life cycle mass flow diagram is presented in **Figure 14**.

The management of the product after its end–of–life did not result in GHG emissions, as the pyrolysis oil was entirely consumed. GHG emissions occurred exclusively during the usage phase. These findings underscored the significance of the usage and raw material acquisition phases as the primary contributors to GHG emissions throughout the life cycle of pyrolysis oil.

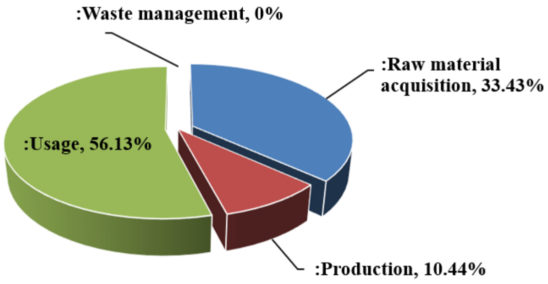

Figure 13 The proportion of GHG emissions at each stage throughout the life cycle of pyrolysis oil.

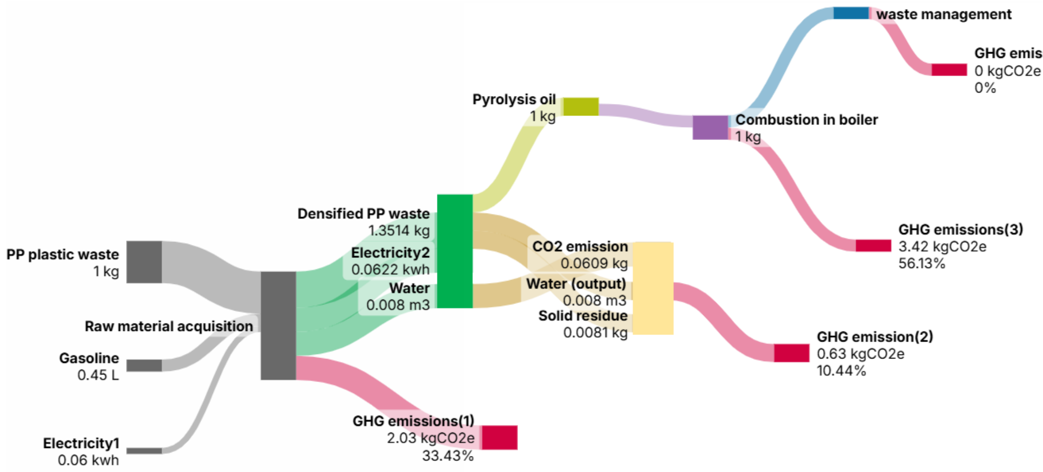

Figure 14 Pyrolysis oil life cycle flow diagram

4. Conclusion

This study evaluated the carbon footprint of two key products: the pyrolysis reactor and pyrolysis oil. The assessment encompassed the GHG emissions across their entire life cycle from raw material acquisition to end–of–life disposal. The system boundary was defined based on two functional units: a single pyrolysis reactor weighing 302 kg and 1 kg of pyrolysis oil. The life cycle was divided into four main stages: 1) raw material acquisition, including transportation and material preparation; 2) product manufacturing to meet the defined functional unit; 3) product usage–where the reactor operated over a six–year period and the pyrolysis oil served as an alternative to conventional fuel oil; and 4) end–of–life disposal, covering waste management at the conclusion of product use.

The assessment revealed that the pyrolysis reactor generated a total of 3,100.72 kgCO_2e over its life cycle, with the majority of emissions attributed to LPG combustion during the six–year operational phase. The second-largest contributor was raw material acquisition (125.55 kgCO_2e), driven mainly by the embodied emissions of materials used in reactor construction. Emissions from the manufacturing stage were minimal (1.10 kgCO_2e), primarily due to electricity consumption. The end–of–life disposal phase resulted in only minor emissions from transporting the dismantled reactor to a recycling facility.

For pyrolysis oil, the total life cycle GHG emissions per kilogram were calculated at 6.08 kgCO_2e. The usage phase was the dominant contributor (3.42 kgCO_2e), resulting from stationary combustion as a replacement for fuel oil. The second-highest emissions source was raw material preparation, particularly the compaction of densified PP waste (2.03 kgCO_2e), which involved significant electricity consumption. Emissions from the production phase were comparatively low, primarily stemming from LPG combustion used to thermally decompose plastic into vapors, later condensed into pyrolysis oil.

Overall, the findings underscored that the operational phase of the pyrolysis reactor and the usage phase of the pyrolysis oil were the primary contributors to their respective carbon footprints. Enhancing fuel efficiency and adopting alternative or renewable energy sources are key strategies to mitigate the environmental impacts of these technologies. Future research should focus on energy optimization and integrating renewable inputs to improve the sustainability of the pyrolysis process.

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