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Original Research

Opportunities and Challenges in Plastic Waste Management Strategies in Boyolali, Indonesia

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Abstract: Plastic waste has become a complex issue in Boyolali district, where much of it is either burned by the community or contributes to environmental pollution. Pyrolysis technology offers a solution by converting plastic waste into renewable and sustainable fuel. This research aims to evaluate the management system of plastic waste and its alternative utilization through pyrolysis technology. The research method for evaluating plastic waste is conducted using a descriptive qualitative approach, while the pyrolysis study is carried out experimentally. Renewable energy-based technologies, such as pyrolysis, are needed to convert plastic waste into high-calorific fuel. The lower heating value (LHV) of Pyrolysis Fuel Oil (PFO) is 9,240 Kcal/kg, with a density of 0.795, giving it high energy potential, making it a suitable candidate for renewable fuel. The pyrolysis process lasts for 7 hours per batch, resulting in a total monthly output of 1,625 liters, which consists of 1,125 liters of diesel, 250 liters of kerosene, and 250 liters of gasoline. To operate this process, four workers are required, with a monthly electricity consumption of 350 kWh. Pyrolysis technology offers a sustainable solution to reduce waste and decrease dependence on fossil fuels.

Key Words	Plastic waste management, Pyrolysis fuel oil, Environmental pollution, Pyrolysis technology, Sustainable fuel, Energy efficiency
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1. INTRODUCTION

Plastic waste consists of long carbon chains that are difficult to degrade naturally. This issue has become increasingly important due to the significant increase in plastic waste in various regions of Indonesia. Integrated waste management has become one of the greatest challenges in efforts to protect the environment from plastic waste pollution (Evode et al. 2021)(de Graaf, Karman, and Janssen 2003) . Despite various recycling management strategies, single-use plastic regulations, and eco-friendly design projects being quite effective in reducing plastic waste, challenges in implementing waste management regulations still exist, such as the lack of alignment between national and local regulations, insufficient public education on plastic waste, difficulty in finding suitable alternatives to plastics, and the complexity of transforming plastic waste into more useful materials (Cornago, Börkey, and Brown 2021)

The Boyolali Environmental Service is the local government agency responsible for environmental management in the region, including waste management at the Final Disposal Site (TPA). The TPA Winong Technical Implementation Unit specifically handles operational tasks related to final waste processing in Boyolali Regency (Wahid and Rizka 2024). According to the Ministry of Environment and Forestry, Indonesia generates more than 42 million tons of urban waste annually, including 7.8 million tons of plastic waste, of which about 4.9 million tons is not managed properly (Supriandi and Rahmawati 2023) Plastic waste comes from human activities in both urban and rural areas. According to data from BPS 2018, Indonesia has 75,436 villages and 8,444 sub-districts, where plastic waste management in rural areas is often inadequate due to the lack of waste management infrastructure (Wijaya 2020)

Boyolali Regency, which has experienced rapid economic growth, consists of 75 urban areas and 192 rural areas (Seruyaningtyas 2019), with a population of 61,032 people generating 287.3 tons of waste per day, Boyolali faces significant waste management challenges, with 20.89% of the total waste being plastic waste (Pemda Boyolali 2021) Waste management practices in Boyolali show that 67% of residents still burn their waste, 7% dispose of it into water bodies, while the rest compost, stockpile, or take their waste to temporary collection sites (Sari et al., 2022). Waste management regulations in Boyolali are governed by Regent Regulation No. 2 of 2021, which includes strategies and policies for reducing household waste and improving its management (Pemda Boyolali 2021)

Waste management in Boyolali needs improvement, particularly in handling plastic waste and reducing the volume of unmanaged waste. While significant efforts have been made in waste reduction and handling, there are still major challenges in achieving fully effective waste management. The increasing amount of waste generated along with the growing population and consumption, coupled with the low percentage of waste management, indicates the need for innovation in waste management policies, improved recycling facilities, and public education to better reduce and manage waste (Raihan, Umrotun, and Musiyam 2024)(Ishartomo et al. 2020)

The success of plastic waste management at TPA Winong heavily depends on the infrastructure, technology, and management practices in place. Proper management is essential to control plastic waste and minimize environmental impacts. Public participation in waste separation before disposal is crucial for effective management. Educational programs and awareness-raising can improve sorting practices and reduce the volume of plastic waste entering the final disposal site (Maskun et al. 2023)

One promising technology for managing plastic waste is pyrolysis, a recycling process that transforms plastic waste into renewable energy. Pyrolysis operates under atmospheric pressure and at around 500°C (Radhakrishnan et al. 2023). This process breaks down plastic waste into several by-products, such as gas (H2, CO, CO2, H2O, and CH4), pyrolytic oil, and charcoal (Armenise et al. 2021). Pyrolysis technology has the potential to reduce waste volume, utilize by-products, and reduce environmental impacts, making it a valuable part of plastic waste management at TPA Winong. However, the success of this technology depends heavily on adequate investment, effective management, and strong legislative support (Eze et al. 2021)

This study aims to evaluate the plastic waste management system in Boyolali and assess the effectiveness of solutions designed to reduce the volume of plastic waste sent to the TPA Winong in Boyolali Regency.

2. MATERIALS AND METHODS

The research on the general description and condition of plastic waste in the Boyolali region was conducted using a qualitative descriptive approach, relying on secondary data. This approach involves utilizing data that has been previously collected by other researchers, such as reports, articles, statistics, and other relevant documents, to analyze and understand the state of plastic waste in the area. Secondary data enables a comprehensive examination of the phenomenon without the need for new primary data collection.

This method provides a clearer picture of the composition and management of plastic waste in Boyolali based on existing information. The article does not specify a particular sample size for waste analysis but focuses on discussing the composition of waste based on secondary data sources (Thorne 2013)

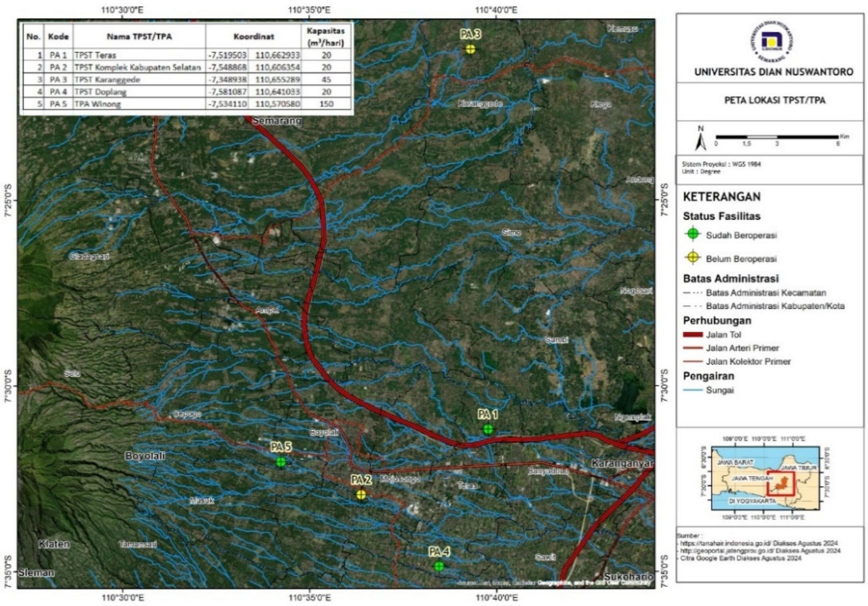


Fig 1. Map of Study Area Boundaries

The problem of plastic waste requires effective management to mitigate its negative impacts on both the environment and public health. One potential solution to this issue is the adoption of pyrolysis technology. This technology allows for the conversion of plastic waste into liquid fuel that can be reused. By transforming plastic waste into an alternative energy source, pyrolysis technology can help reduce the volume of plastic waste while also decreasing reliance on fossil fuels, which are both depleting and environmentally harmful.

The research on the application of pyrolysis technology was carried out with an experimental approach using plastic waste as raw material. In the pyrolysis process, the plastic waste is heated in the absence of oxygen, resulting in a liquid product that can be used as an alternative fuel. This liquid product is then analyzed to determine its physical properties, such as density, viscosity, calorific value, and cetane/octane numbers. The analysis results are compared with conventional diesel fuel to assess its quality and feasibility as an energy source.

Furthermore, to ensure that the pyrolysis process does not have a negative environmental impact, gas emissions such as CO and CO2 produced during the process are also tested. This emission testing aims to evaluate the potential environmental impact of the gases produced, thus helping to determine the extent to which pyrolysis technology is environmentally friendly and sustainable. In this way, pyrolysis technology not only provides a solution for managing plastic waste but also offers a more environmentally friendly energy alternative. All these steps are highly relevant to the efforts in managing plastic waste in Boyolali, contributing to the creation of sustainable solutions for both the environment and the local community (Ascher, Watson, and You 2022)

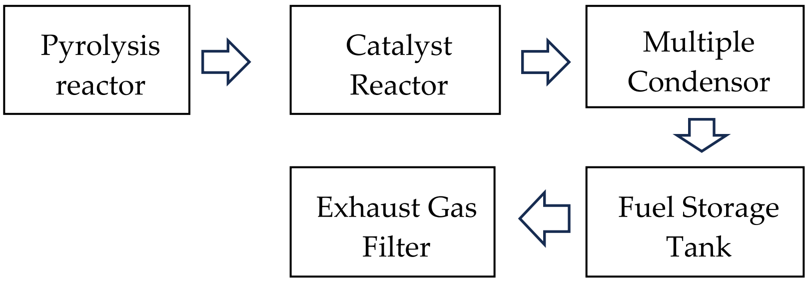


Fig 2. Pyrolisis reactor design
(Lubis, Arifin, and Fitrianingsih 2022)

3. RESULTS OR RESULTS AND DISCUSSIONS

Boyolali is a district located in Central Java Province, covering an area of 1,015.10 km² and having a population of approximately 1,090,131 people. Based on its geographical location, Boyolali is situated between 110° 22' and 110° 50' East Longitude, and between 7° 7' and 7° 36' South Latitude, with an elevation ranging from 75 to 1,500 meters above sea level. The regency consists of 22 sub-districts, characterized by a topography that includes lowland areas as well as hills and mountains (BPS Boyolali 2023). The natural conditions and strategic geographical location of Boyolali Regency support its economic development. The Gross Regional Domestic Product (GRDP) of Boyolali Regency exceeds the national economic growth target and realization, which is around 5-5.5%. (Raihan, Umrotun, and Musiyam 2024). Population plays a significant role in driving economic growth. As the population increases, it contributes to economic expansion by broadening the market, which enhances the level of specialization within the economy. Analyzing population density helps to determine how concentrated the population is in Boyolali District. This information is essential for designing infrastructure, managing resources, and addressing the impacts of economic growth and development. Specifically, it aids in formulating policies related to waste management resulting from development activities. The population density in Boyolali Regency is 1,009 people per km² in 2023 and is projected to increase to 1,074 people per km² in 2024. This places the population density in the moderate category, indicating a relatively balanced population distribution. The population growth rate in Boyolali Regency remains stable at 1%, which falls within the stable growth rate range of 1% to 2%.(Cilluffo and Ruiz 2019) The continuous increase in population and economic growth will indirectly lead to an increase in the amount of waste generated, as a result of anthropogenic activities.

Table 1 presents the population, population growth rate, and waste predictions for the period from 2019 to

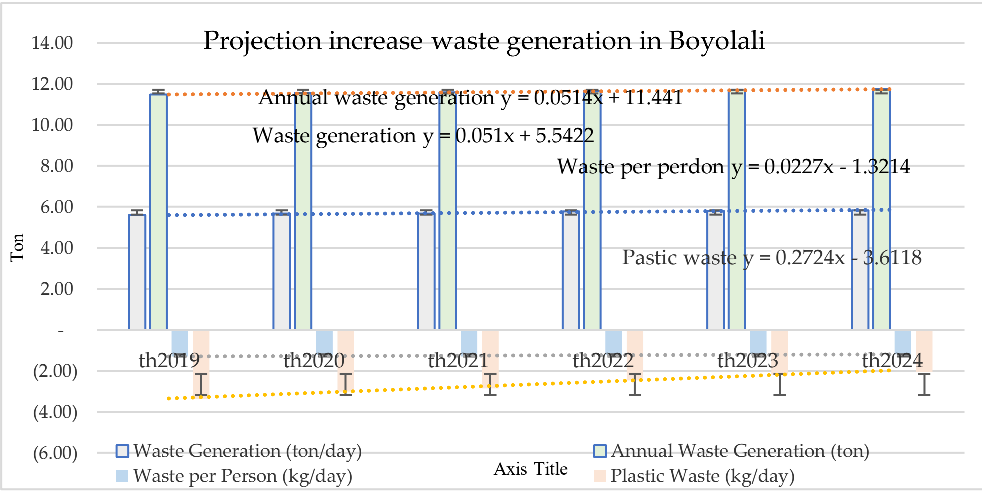
2024, as follows:

Table 1. Projected Increase in Waste Generation in Boyolali District

Period	Population	Growth Rate (%)	Waste Generation (ton/day)	Annual Waste Generation (ton)	Waste per Person (kg/day)	Plastic Waste (kg/day)	Percentage of Plastic (%)
th2019	984,807	1%	266	97,052	0.270	0.034	12.6%
th2020	989,619	1%	288	105,095	0.291	0.049	16.7%
th2021	1,070,247	1%	291	106,159	0.272	0.057	20.9%
th2022	1,079,952	1%	319	116,383	0.295	0.086	29.2%
th2023	1,090,131	1%	330	120,934	0.303	0.114	37.5%
th2024	1,133,245	1%	344	125,485	0.304	0.127	41.6%
Avg	1,058,000	1%	306	111,851	0.290	0.077	26.4%

Prediction of percentage composition of plastic waste $y = 16.58\ x + 4.31$

Table 1 and Graph 1 illustrates that waste generation (tons/day), annual waste generation (tons), waste production per person (kg/day), and plastic waste production (kg/day) in Boyolali Regency are projected to increase each year from 2019 to 2024.



Graph 3. Trends in the Increasing Generation of Waste and Plastic Waste in Boyolali Regency

The predicted increase for 2024 is 344 days per ton, or 125,485 years per ton, while the average waste production per person from 2019 to 2024 is 0.29 kg per day. In comparison, an average Indonesian citizen contributes 0.7 kg of waste per day. (Aprilia 2021) When compared to the waste produced per day in Boyolali District, it is still below the average waste production in Indonesia (0.29 kg/day is less than the average of 0.7 kg/day). The average waste production per district in Indonesia is 883 days per ton, or 38,795,897 years per ton, which accounts for approximately 40% of the district data in Indonesia.

Boyolali Regency, the comparison of waste composition percentages in 2019 revealed that the highest contributors were food waste (53.84%) and plastic (20.89%). Other components included wood and branches (1.8%), paper and cardboard (13.3%), metal (1.1%), cloth (1.57%), rubber and leather (1.05%), glass (0.98%), and others (5.46%). By 2021, the composition had shifted, with food waste contributing 32.18% and plastic rising to

37.47%. The breakdown also included wood and branches (11.85%), paper and cardboard (9.37%), metal (5.39%), cloth (0.67%), rubber and leather (0.70%), glass (0.70%), and others (1.67%) (Table 2).

Table 2. Waste Composition Percentages in Boyolali District and Surrounding Districts.

District	Boyolali		Klaten		Sukoharjo		Wonogiri		Sragen	
Period	2021	2023	2021	2023	2021	2023	2021	2023	2021	2023
Food Waste (%)	53.84	32.18	60.00	35.86	77.1	52.55	22.3	25.00	74.7	74.3
Wood-Twigs (%)	1.8	11.85	5.00	32.92	1.42	0.42	29.48	10.00	0.9	0.8
Paper-Cardboard (%)	13.31	9.37	5.00	3.52	3.12	13.33	19.74	20.00	8.4	8.9
Plastic(%)	20.89	37.47	20.00	35.87	14	23.79	11.81	25.00	11.1	11.2
Metal(%)	1.1	5.39	0.50	2.45	0.21	0.89	6.54	5.00	0.4	0.5
Cloth(%)	1.57	0.67	5.00	2.13	1.39	1.19	0	5.00	2.2	1.8
Rubber-Leather (%)	1.05	0.70	3.00	2.00	0.16	0.33	0	2.50	0.3	0.3
Glass(%)	0.98	0.70	0.50	0.36	0.16	1.03	6.07	5.00	1.7	1.8
Other(%)	5.46	1.67	1.00	0.31	2.4	6.47	4.06	2.50	0.3	0.4

Based on projections, the percentage of plastic waste in Boyolali Regency has been increasing: 12.6% in 2019, 16.7% in 2020, 20.9% in 2021, 29.2% in 2022, 37.23% in 2023, and 37.5% projected for 2024. This increase in plastic waste is also occurring in all surrounding regencies of Boyolali.

In Boyolali Regency, waste management is regulated by Regional Regulation Number 13 of 2013 and Regent Regulation Number 68 of 2018, which outline the strategies and policies of the local government regarding waste management. This framework emphasizes the reduction and proper handling of waste. Waste is a major environmental issue that significantly impacts society, as every household generates waste daily. Proper management of this waste is essential to ensure that it does not disrupt the comfort of the community.

The final disposal site in Boyolali Regency, with a controlled landfill system, is equipped with waste management facilities such as a waste weighing post, methane gas utilization installation, waste sorting area, waste fermentation area (composting), and liquid fertilizer manufacturing area. In addition to core waste management facilities, learning facilities are also provided for the community in the form of an educational park. The final disposal site in Boyolali Regency, namely the Kuncen Winong Final Disposal Site, covers an area of 3.7 ha with the addition of 0.29 ha of land in 2018 so that the total area of the Kuncen Winong Final Disposal Site is 3.99 ha. The area of the final disposal site that has been utilized as of 2020 is 3.8 ha.

The waste generated by the community in Boyolali Regency continues to increase each year. Table 3 presents the current conditions and forecasts for the Winong Final Disposal Site (TPA) in Boyolali Regency, including the potential for waste accumulation, the amount of waste reduction, the volume of waste processed, and both managed and unmanaged waste. Therefore, there is a need for alternative plastic waste management through sustainable technology.

The potential waste accumulation at Winong TPA indicates a significant increase in waste generation, necessitating effective handling strategies. This includes enhancing waste reduction practices, improving waste sorting and processing methods, and implementing sustainable technologies to manage both managed and unmanaged waste efficiently. The key findings indicate that Boyolali is facing significant challenges in managing the increasing amount of waste, particularly plastic waste. Therefore, a more holistic and sustainable approach is needed to reduce and manage waste in the region, along with the implementation of technologies that can effectively address this issue.

Table 3. Potential waste accumulation and its management at the Winong Final Disposal Site

		Year 2019		Year 2020		Year 2021		Year 2022		Year 2023		Year 2024	
I	Potential Waste Piles (tons/year)	96,262	97,052	104,044	105,095	105,097	106,159	115,219	116,383	119,772	120,934	124,280	125,485
	(Population x 0.29 kg/person/day)												
II	Waste reduction amount	24,417	25,080	26,973	28,319	29,329	29,409	29,543	29,623.44	29,758	29,840	29,976	30,058
	Waste reduction percentage	25	26	27	28	29	30	30	31.02	31	32	31	32
a	Waste generation limitation	18	19	21	22	23	24	22	23.12	21	22	21	22
	Adiwiyata school	18	19	21	22	23	24	22	23.12	21	22	21	22
b	Waste utilized at source	7,073	7,635	8,489	8,816	9,034	9,159	8,678	8,776	8,378	8,459	8,118	8,155
	Waste bank unit	81	84	90	94	97	99	97	98.3	97	98	97	98
	TPS3R	225	352	491	510	457	531	304	352.97	202	235	135	156
	Scavengers of used goods	6,767	7,199	7,908	8,212	8,480	8,529	8,277	8,325	8,079	8,126	7,886	7,932
c	Amount of waste recycled at source	17,325	17,352	18,047	18,741	19,394	19,464	20,096	20,134	20,879	20,899	21,722	21,599
	Composter and Biopore	146	170	201	209	212	218	189	194.15	168	173	150	154
	Composting by TPS3R	76	152	234	243	187	253	97	131.59	51	68	26	36
	Biodigester	17,103	17,030	17,612	18,289	18,995	18,993	19,810	19,808	20,660	20,658	21,546	21,545
III	Waste handling amount	26	25,399	26,684	27,710	28,758	28,776	29,502	29,520	30,264	30,283	31,046	31,065
a	Waste handling percentage	26	26	27	28	29	30	30	31.46	31	33	33	34
b	Processing	0	80	164	170	175	177	180	181.56	185	187	190	192
	Waste processed into raw materials	0	80	164	170	175	177	180	181.56	185	187	190	192
	TPS3R is city-managed	0	80	164	170	175	177	180	181.56	185	187	190	192
c	Final processing	25,090	25,318	26,520	27,540	28,587	28,600	29,419	29,432	30,275	30,288	31,156	31,170
	Waste processed at TPA	25,090	25,319	26,520	27,540	26,943	28,602	27,897	28,405	29,767	29,954	32,048	32,166
	Landfilling TPA	24,411	23,530	23,553	24,459	25,400	25,401	27,365	27,365	29,482	29,482	31,763	31,763
	Composting TPA	460	1,643	2,888	2,999	1,477	3,115	429	905.72	125	263	36	77
	Recovery by scavengers	219	146	79	82	66	86	103	134.39	160	209	249	326
IV	Managed waste (ii + iii)	49,533	50,478	53,390	55,443	57,514	57,576	58,577	58,640.32	59,659	59,724	60,762	60,828
	Percentage of managed waste	51	52	55	57	59	60	60	61	62	63	64	65
V	Unmanaged waste (I - IV)	46,729	46,576	46,389	46,389	48,165	48,174	52,141	52,150.50	56,445	56,455	61,104	61,115

Description: TPA : Final Waste Disposal Site, TPS3R : Waste Management Place for Reuse, Reduce, and Recycle. Adiwiyata School is an environmental education program focused on promoting a healthy, clean, and beautiful environment. (BPS Boyolali 2023)

Table 4. Potential waste accumulatio n and its management at the Winong final disposal site

A	B	C	D	E	F	G	H	I	J	K	L
Th2019	984,807	97,052	49,533	46,576	96,109	961	1.0%	0.13	0.067	0.063	0.130
Th2020	989,619	105,095	53,390	46,389	99,779	5,089	5.1%	0.17	0.091	0.079	0.170
Th2021	1,070,247	106,159	57,514	48,174	105,688	423	0.4%	0.21	0.114	0.096	0.210
Th2022	1,079,952	116,383	58,577	52,151	110,728	5,426	4.9%	0.29	0.153	0.137	0.290
Th2023	1,090,131	120,934	59,659	56,455	116,114	4,645	4.0%	0.38	0.195	0.185	0.380
Th2024	1,133,245	125,485	60,762	61,115	121,877	3,534	2.9%	0.42	0.209	0.211	0.420
Average	1,058,000	111,851	56,573	51,810	108,382	3,346	3.1%	0.27	0.139	0.127	0.267

Source: Boyolali Regency Environmental Service, 2019.

Information:

A Period (Year)
B Population (Number of inhabitants)
C Waste Production / year / ton
D Amount of managed waste
E Amount of unmanaged waste
F Total waste is the sum of unmanaged + managed waste
G Unknown/lost waste
H Percentage of unknown/lost waste

I Percentage composition of plastic waste (%)
J Managed plastic waste (tons/day)
K Unmanaged plastic waste (tons/day)
L Total amount of plastic waste (managed and unmanaged)

On average, this amounts to approximately 0.08 tons per day per person. Divided by the number of residents, this translates to about 0.29 kg (Table 1) of plastic waste per person per day. This figure varies depending on the region and individuals' consumption habits.

Based on Table 4, the predicted average population from 2019 to 2024 is 1,058,000, with waste production amounting to 111,851 tons per year. Of this, 56,573 tons (51%) is managed in landfills, while 51,810 tons per year remains unmanaged (46%). Additionally, approximately 3.1% of waste, estimated at 3,468 tons per year, is lost, possibly due to transportation activities or being utilized by the community (scavengers) before reaching the landfill. The average daily production of plastic waste is 0.267 tons, with 0.137 tons per day managed and 0.127 tons per day being unmanaged. The percentage of unmanaged plastic waste in Boyolali Regency is estimated to be around 46% of the total plastic waste generated. This indicates that a significant amount of plastic waste accumulates and ends up in landfills or the environment, without going through proper recycling or management processes. This figure highlights the substantial challenges faced in plastic waste management and underscores the importance of improving recycling systems and raising community awareness about reducing plastic usage. (Dai et al. 2022). Therefore, more intensive management is needed, specifically through alternative technologies based on renewable and sustainable energy, as well as reducing dependence on fossil fuels by utilizing waste, particularly plastic waste (Achi et al. 2024). Pyrolysis technology is a process that breaks down polymer chains into simpler compounds through thermal processes (heating) while utilizing minimal oxygen. Plastic waste can be decomposed and converted into fuel with a high calorific value through pyrolysis. (Jahari and Saputra 2021).

Fast Catalytic Pyrolysis Technology

Catalytic pyrolysis technology is a process for recycling plastic by converting it into new plastic materials. The pyrolysis process yields three types of products: solids (char), gas (fuel gas), and bio-oil. The pyrolysis tool series consists of a pyrolysis reactor equipped with an induction heater and a condenser. The reactor generates steam, which is then transformed into liquid through the condenser, resulting in pyrolysis oil (Fink 2021). Fast pyrolysis is a sustainable method, as it can convert non-biodegradable plastic waste into useful energy sources, reducing dependence on fossil fuels. The resulting pyrolysis oil can be utilized as fuel for engines or as a substitute for fossil fuels in various industrial applications. The fast pyrolysis technology for plastic waste has the potential to become an innovative solution for waste management and renewable energy provision, while also reducing the environmental impact of plastic waste (Sonawane, Shindikar, and Khaladkar 2024) In this study, pyrolysis technology was implemented on a small scale (less than 10 tons) to consider low initial investment, more efficient construction costs, flexibility, and simpler operations According to Sakthipriya (2022), the design of a plastic processing system using a pyrolysis device with a capacity of 5 tons per batch consists of 5 units, allowing for a plastic input of 25 tons per day. The estimated products produced from this system are 16.25 tons of oil per day, 6.25 tons of gas per day, and 2.5 tons of char per day (Sakthipriya 2022) The technical and economic analysis conducted on the feasibility of implementing a pyrolysis plant for producing fuel oil (FO) from plastic fractions of Municipal Solid Waste (MSW) indicates a promising opportunity for resource recovery. The catalytic pyrolysis process employs a fixed bed reactor with a capacity of 4 m³, which processes crushed and dried plastic waste at specific temperatures to achieve optimal yields. Additionally, the costs of managing MSW in the municipality can be reduced by up to 54.75%.(Hauschild et al. 2022) The mass balance analysis of the pyrolysis process indicates that 35-40% of the output comprises liquid products (30-35% bio-oil and 5-10% water and other by-products), 40-45% consists of gas products, and 15-25% is char. The average yield of bio-oil from the studies ranges from 50-75%. This demonstrates that a small-scale biomass pyrolysis industry, with a capacity of 20-30 dm³ of bio-oil per day, can yield promising economic benefits

(Jaroenkhasemmeesuk and Tippayawong 2015). Table 5, presents the economic analysis of the pyrolysis plant using various types of fuels, including Liquefied Petroleum Gas (LPG), waste lube oil, and Refuse-Derived Fuel (RDF). (Mani et al. 2020).

Table 5. Economic Analysis of the Pyrolysis Plant Based on Fuel Type (Rajca et al. 2020)

Fuel Type	LPG	Waste Lube Oil	RDF	Economic (Profit/Loss) IDR
Case - 1	100%	0	0%	+ 32.5 Million/Year
Case - 2	0%	100%	0%	+ 54.1 Million/Year
Case - 3	0%	0%	100%	+ 81.8 Million/Year

Liquefied Petroleum Gas, is a flammable mixture of hydrocarbons, primarily consisting of propane, butane, and propylene (Thompson et al. 2021) Waste lube oil is oil that has been used to lubricate engines or equipment and has lost its quality and ability to function effectively (Sharma, Gupta, and Agrawal 2020). Refuse-Derived Fuel (RDF) is fuel produced from waste or solid refuse after undergoing specific processing. (Shehata et al. 2022). Pyrolysis Fuel Oil (PFO) is a liquid product obtained from the pyrolysis of organic materials, such as biomass or plastic waste (Kumar and Kumar 2024). Table 5, case 3, indicates that RDF is the most profitable option, yielding the highest profit of 81.8 million per year, followed by waste lube oil and then LPG. RDF demonstrates strong performance in terms of calorific value and could be a better choice when considering applicable environmental policies (Sarquah et al. 2022)

Table 6. Lower Heating Value (LHV) of Various Fuel Types

LHV - MSW (Municipal Solid Waste)	2.973 Kcal/Kg
LHV – LPG (Liquefied Petroleum Gas)	11.080 Kcal/Kg
LHV – PFO (Pyrolysis Fuel Oil)	9.240 Kcal/Kg
LHV - Gasoline	11.055 Kcal/Kg
LHV - Kerosene	10.270 Kcal/Kg
LHV - Diesel Oil	10.175 Kcal/Kg
LHV – NG (Natural Gas)	9.850 Kcal/Kg

Table 6 shows the Lower Heating Values (LHV) of various types of fuels. The Lower Heating Value (LHV) is the amount of energy that can be obtained from a fuel during combustion, excluding the energy contained in the water vapor produced. LPG (Liquefied Petroleum Gas) has the highest LHV at 11,080 Kcal/Kg, making it the best type of fuel. The LHV of Pyrolysis Fuel Oil (PFO) is 9,240 Kcal/Kg (Crespo et al. 2023), indicating that its energy efficiency as a fuel is quite good, comparable to commercial fuels such as gasoline, kerosene, and diesel oil. PFO serves as a sustainable energy source that can reduce dependence on fossil fuels and help address pollution caused by plastic waste

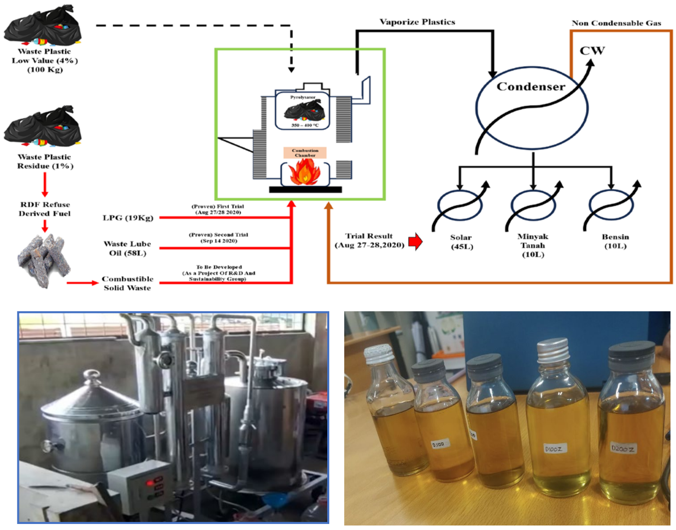


Fig 5. Process and Schematic of Plastic Waste Pyrolysis

Table 6. Product Yield Calculation and Operating Conditions for Plastic Pyrolysis

1	Pyrolysis Capacity	= 100 Kg/Batch
2	Pyrolysis Yield	
	a) Solar Plast (Diesel Oil)	= 45 Liters
	b) Minyak Tanah Plast (Carosene)	= 10 Liters
	c) Bensin Plast (Gasoline)	= 10 Liters
3	Running Hours Per Batch	= 7 Hours
4	Operation Day	One Batch/Day
5	Monthly Total Production (Every day Running, Except Sunday)	= 25 Batches
6	Total Man Power Requirement	= 4 Person
	a) Operation Manager	1
	b) Supervisor	1
	c) Operator	2
7	Electricity Consumption 2 Kw For 7 Hours Of Pyrolysis Proces	

Figure 5 and table 6 illustrates the process and schematic of plastic waste pyrolysis. Based on the results of the pyrolysis process using approximately 100 kg of plastic, a total fuel volume of 65 liters can be produced, with a distribution of 45 liters equivalent to diesel, 10 liters equivalent to kerosene, and 10 liters equivalent to gasoline. The pyrolysis process lasts for 7 hours per batch, with an operating frequency of 1 batch per day, resulting in a total monthly production of 25 batches (assuming one day off, such as Sunday). The total monthly production is as follows: Plastic Diesel: 25 batches × 45 liters = 1,125 liters, Plastic Kerosene: 25 batches × 10 liters = 250 liters and Plastic Gasoline: 25 batches × 10 liters = 250 liters. The overall total monthly yield is 1,625 liters. The total workforce required is 4 people, consisting of 1 Operations Manager, 1 Supervisor, and 2 Operators. The electricity consumption for each batch is 2 kW over 7 hours, resulting in daily consumption of 2 kW × 7 hours = 14 kWh. Therefore, the monthly consumption is 14 kWh × 25 batches = 350 kWh.

Table 7 presents the results of the analysis of the physical and thermal characteristics of various fuel samples obtained from the pyrolysis process. It highlights the variations and advantages of each sample in terms of sustainability and reducing dependence on fossil fuels

Table 7 . Physical and Thermal Characteristics of Various Fuel Samples (Capareda 2023) (Misna and BTBRD-BPPT n.d.)

Sampel	Specific gravity at 60 F	Standard specific gravity	Density at 15 s C (kg/m3)	Standard density	Kinematic viscosity at 40 C (mm2/sec)	Standard kinematic viscosity	Flash point (C)	Standard flash point	Heating value (BTU/lb)	Standard heating value
D-100	0.795	0.880-0.895	794(kg/m3)	830-860	2.25 (mm2/sec)	4.0-6.0	<25(C)	48-55°C	19929	18,500
D-100-1	0.794	0.860-0.880	793(kg/m3)	830-860	2.43 (mm2/sec)	4.0-6.1	31 (C)	48-55°C	19936	17,500-18,000
D-100-1-50	0.827	0.850-0.870	826(kg/m3)	860-890	2.78 (mm2/sec)	3.5-5.5	24 (C)	48-55°C	19734	17,000-17,500
D-100-2-50	0.813	0.850-0.870	812(kg/m3)	850-880	2.55 (mm2/sec)	3.5-5.5	24 (C)	48-55°C	19817	17,000- 7,500
Solar Fuel	0.831	0.820-0.870	837(kg/m3)	820-860	4.55 (mm2/sec)	2.0-4.5	52 (C)	52 to 60°C	19300	18,500

Notes: Method American Standard Testing and Material (ASTM)

The D-100 has a specific gravity of 0.795 and a density of 794 kg/m³, indicating that this sample can be considered a light liquid among fuels. Specific gravity is the ratio of a substance's density to the density of water at a specific temperature (4°C), allowing it to be categorized as a light liquid. Light liquids have the advantage of quick evaporation, which aids in the combustion process in engines, enhancing efficiency. With a high calorific value, they can produce more energy per unit volume, leading to a more efficient combustion process and lower emissions compared to heavier liquids. (Larionov et al. 2022). The kinematic viscosity of 2.25 mm²/s at 40°C indicates that this sample has relatively good flow characteristics. With a boiling point and flash point below 25°C, this sample is classified as a flammable material. The heating value of 19,929 BTU/lb demonstrates that this fuel has a high energy potential, making it a suitable candidate for fuel applications. Overall, this sample possesses characteristics that are well-suited for use as a fuel, though it has flammable properties. despite its flammable nature, because it has a flash point <25⁰C.

The D-100-1 data reveals several important characteristics. Its specific gravity at 60°F is 0.794, which is lower than the standard range of 0.860 - 0.880, indicating that this sample is lighter than other reference materials. The density at 15°C is 793 kg/m³, also below the standard range of 830 - 860 kg/m³, further confirming its lighter nature. The kinematic viscosity at 40°C is 2.43 mm²/sec, which is lower than the standard range of 4.0 - 6.1 mm²/sec. This lower viscosity suggests that D-100-1 flows more easily at this temperature. The flash point of 31°C, while higher than that of materials with lower flash points, is still below the standard range of 48 - 55°C, indicating that D-100-1 poses some fire risk. However, the higher heating value of 19,936 BTU/lb exceeds the standard value of 17,500 - 18,000 BTU/lb, suggesting good combustion efficiency and making it an effective energy source. D-100-1 is a lighter fuel with low viscosity and high combustion efficiency (Khan et al. 2016) While it offers increased safety compared to materials with lower flash points, it is important to remain aware of the fire risk due to its flash point being below the ideal standard.(Gao 2010)

The D-100-1-50 data presents several key characteristics. Its specific gravity at 60°F is 0.827, which is lower than the standard range of 0.850 - 0.870, indicating that this sample is lighter than reference materials but heavier than both D-100 and D-100-1. The density at 15°C is 826 kg/m³, also below the standard range of 860 - 890 kg/m³. The kinematic viscosity at 40°C is 2.78 mm²/sec, which falls below the standard range of 3.5 - 5.5 mm²/sec. This suggests that while the viscosity is higher compared to D-100 and D-100-1, D-100-1-50 still has a lower viscosity than the ideal value. The flash point of 24°C indicates a higher fire risk, as it is significantly below the recommended standard range of 60 - 100°C, making D-100-1-50 quite flammable. On the other hand, the heating value of 19,734 BTU/lb exceeds the standard value of 17,000 - 17,500 BTU/lb, indicating good energy efficiency despite the fire risk. In summary, D-100-1-50 exhibits characteristics that make it heavier and with higher viscosity compared to D-100 and D-100-1. While it has a favorable heating value, the low flash point signifies a heightened fire risk. Therefore, careful consideration of safety precautions is essential when using

D-100-2-50 data highlights several important characteristics. Its specific gravity at 60°F is 0.813, which is below the standard range of 0.850 - 0.870, indicating that this sample is lighter than other reference materials. The density at 15°C is 812 kg/m³, also lower than the standard range of 850 - 880 kg/m³. The kinematic viscosity at 40°C is 2.55 mm²/sec, falling below the standard range of 3.5 - 5.5 mm²/sec. This low viscosity suggests that D-100-2-50 flows more easily. The flash point of 24°C indicates a high fire risk, as it is significantly below the recommended standard range of 60 - 100°C, making the sample highly flammable. Conversely, the heating value of 19,817 BTU/lb exceeds the standard value of 17,000 - 17,500 BTU/lb, indicating good combustion efficiency and making it an effective energy source despite the associated fire risk. D-100-2-50 exhibits characteristics that make it lighter with low viscosity and good energy efficiency. However, the high fire risk due to its low flash point is a significant concern. As indicated by the analysis of the flash point of fuel derived from pirolysis of plastic waste, it is crucial to exercise caution regarding workplace safety due to its flammability.

Solar Fuel has been Specific Gravity at 60°F: 0.831 (within the standard range of 0.820 - 0.870), Density at 15°C: 837 kg/m³ (within the standard range of 820 - 860 kg/m³), Kinematic Viscosity at 40°C: 4.55 mm²/sec (within the standard range of 2.0 - 4.5 mm²/sec), Flash Point: 52°C (at the upper end of the standard range of 52 - 60°C), Heating Value: 19,300 BTU/lb (above the standard value of 18,500 BTU/lb). The solar fuel sample meets or exceeds standard values for specific gravity, density, and heating value, while its kinematic viscosity is within acceptable limits. The flash point indicates a moderate fire risk, necessitating careful handling

Low-density and low-viscosity fuels such as D-100 are more efficient in the combustion process, leading to reduced emissions and offering greater benefits as an environmentally friendly energy source. This results in cleaner and more efficient combustion, which, in turn, reduces emissions and pollution while maximizing the energy potential generated. However, fuels with a low flash point (like D-100) increase the risk of fire, whereas fuels like Solar Fuel, with a higher flash point, are more stable and safer for storage and transportation. Fuels with high calorific value, such as D-100 and Solar Fuel, allow for more efficient combustion, reducing environmental impacts as they require less fuel to produce the same amount of energy (Praveenkumar, Velusamy, and Balamoorthy 2022) The use of tightly sealed containers for fuel, protected from high temperatures, is crucial to prevent fuel evaporation and avoid uncontrolled fires. Strict handling policies for fuels with a low flash point must be implemented by trained personnel, following stringent procedures to prevent fires and explosions. This includes the use of appropriate fire extinguishing equipment and personal protective gear (Nolan 2014) (Santos et al. 2020)

Catalytic pyrolysis technology for plastics can have significant environmental impacts, with several key benefits and challenges as follows: a) Plastic Waste Reduction: Pyrolysis transforms plastic into valuable products such as fuel (Pyrolysis Fuel Oil/PFO), gas, and char, which helps reduce plastic waste in landfills and the environment, addressing plastic pollution. b) Fossil Fuel Replacement: The PFO produced has a calorific value nearly equivalent to fossil fuels like gasoline and diesel, potentially reducing dependence on fossil fuels and carbon emissions. c) Energy Efficiency: PFO and other fuels produced through pyrolysis have high energy efficiency, with a calorific value similar to conventional fuels, making them suitable for meeting energy needs in a more environmentally friendly manner. d) Air Pollution and Emissions: Pyrolysis can generate harmful gas emissions (VOCs, CO, hydrocarbons) if not properly managed. The treatment of pyrolysis gases is critical to reduce air pollution. Fire Risks: Pyrolysis products have a low flash point, increasing the risk of fire. Therefore, handling and storing these fuels must be done with strict safety procedures. e) Char Management: Char, a by-product of pyrolysis, can be used beneficially, but if not properly managed, it could become an environmental burden. f) Environmental Policies: This technology aligns with policies that support waste-to-energy conversion, but it requires regulations to monitor emissions and fuel quality..(Qureshi et al. 2020)(Saxena 2024). However, overall, catalytic pyrolysis of plastics can reduce the environmental impact of plastic waste, replace fossil fuels, and generate efficient energy, but it requires careful management to address emissions and potential fire risks..

4. CONCLUSION

The average population from 2019 to 2024 is estimated to reach 1,058,000, with an annual waste production of 111,851 tons. Of this amount, 51% is managed in landfills, while 46% remains unmanaged, and approximately 3.1% is lost before reaching disposal sites. The average daily production of plastic waste is 0.267 tons, with 0.137 tons managed and 0.127 tons unmanaged, highlighting significant challenges in plastic waste management. There is a need for improved management through renewable energy-based technologies, such as pyrolysis, which converts plastic waste into fuel with a high calorific value. The LHV of Pyrolysis Fuel Oil (PFO) is 9,240 Kcal/Kg, indicating good energy efficiency, comparable to commercial fuels like gasoline and diesel. The pyrolysis process lasts for 7 hours per batch, producing a total monthly output of 1,625 liters, consisting of 1,125 liters of diesel, 250 liters of kerosene, and 250 liters of gasoline. To operate this process, 4 workers are required, with a monthly electricity consumption of 350 kWh. Sample D-100 has a specific gravity of 0.795 and high energy potential, making it a suitable candidate for fuel. Pyrolysis technology offers a sustainable solution to reduce waste and dependence on fossil fuels.

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