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Process Engineering and Techno-Economic Assessment of Plastic Waste Pyrolysis for Liquid Fuel Production in Tourism-Based Geopark Systems

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ABSTRACT

This study presents a process engineering and techno-economic assessment of liquid fuel production from tourism-generated plastic waste using a pyrolysis-based conversion system implemented in geopark environments. The proposed system integrates waste collection and preprocessing, oxygen-limited thermal decomposition, and condensation-based product recovery to transform plastic waste into a usable liquid fuel. The engineering assessment evaluates system operability, feedstock handling, and energy recovery pathways, including the utilization of by-products to enhance overall process efficiency. A techno-economic framework is applied to examine investment feasibility, operational robustness, and long-term financial performance under realistic implementation conditions. The results indicate that plastic waste pyrolysis can function as a viable waste-to-energy solution in tourism-intensive geopark systems when supported by effective operational management and institutional coordination. Beyond economic performance, the system contributes to circular resource utilization, waste reduction, and local energy generation. The proposed approach directly supports the Sustainable Development Goals (SDGs), particularly those related to affordable and clean energy, sustainable communities, responsible consumption and production, and climate action.

1. Introduction

The rapid growth of tourism activities in geopark areas has significantly increased the generation of solid waste, particularly plastic waste, which poses serious environmental and operational challenges due to its persistence, low degradability, and limited end-of-life management options. From a process engineering perspective, tourism-generated plastic waste represents a high-potential secondary feedstock that can be converted into value-added energy products rather than being disposed of through landfilling or open dumping. In tourism-intensive conservation areas,

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unmanaged plastic waste not only degrades environmental quality but also threatens ecosystem integrity and the long-term sustainability of tourism activities.

Among available waste-to-energy technologies, pyrolysis has emerged as a technically viable thermochemical conversion method for transforming plastic waste into liquid fuel, non-condensable gas, and solid char under oxygen-limited conditions. Previous studies have demonstrated that pyrolysis can simultaneously reduce plastic waste volume and recover energy in the form of hydrocarbon-rich liquid products [1-2]. Extensive research has examined the effects of operating temperature, reactor design, catalyst type, and feedstock composition on conversion efficiency and product quality, particularly for polyolefin-based plastics such as polypropylene and polyethylene [3-7]. Recent developments have further explored advanced process configurations, including microwave-assisted pyrolysis and integrated plastic-to-fuel pathways, to improve energy efficiency and operational performance [8-9].

Beyond technical optimization, techno-economic analysis plays a critical role in determining the feasibility of pyrolysis-based systems. Prior studies indicate that profitability is highly sensitive to feedstock availability, production scale, energy utilization, and market conditions [1,10]. However, most existing techno-economic evaluations focus on urban or industrial waste streams, laboratory- or pilot-scale systems, or short-term economic projections. Limited attention has been given to tourism-generated plastic waste, which is characterized by spatial concentration, seasonal variability, and institutional constraints specific to geopark environments. In addition, governance and stakeholder coordination have been identified as important enablers for technology deployment in conservation-oriented tourism areas, although these aspects are rarely integrated with engineering-based feasibility assessments [11-13].

Accordingly, this study aims to conduct an integrated process engineering and techno-economic assessment of liquid fuel production from tourism-generated plastic waste through a pyrolysis-based system implemented in a geopark context. The novelty of this research lies in the combined evaluation of (i) a realistic process engineering design tailored to tourism-derived plastic waste, (ii) a long-term techno-economic assessment using multiple financial indicators, and (iii) the explicit positioning of governance and institutional factors as implementation enablers rather than primary analytical variables. By bridging engineering feasibility with contextual applicability, this study advances scalable waste-to-energy system development that supports circular economy principles and contributes to the Sustainable Development Goals related to clean energy, sustainable communities, responsible production, and climate action.

1.1 Thermochemical Conversion of Plastic Waste via Pyrolysis

The conversion of plastic waste into liquid energy through pyrolysis has gained increasing attention as an effective thermochemical conversion technology for addressing the dual challenges of waste accumulation and sustainable energy supply. Pyrolysis enables the decomposition of long-chain polymer materials under oxygen-limited conditions, producing liquid fuel (pyrolysis oil), non-condensable gases, and solid char, thereby offering a viable pathway for energy recovery from non-biodegradable plastic waste streams [2,14]. From an engineering perspective, this technology is particularly attractive due to its operational flexibility, relatively moderate temperature requirements compared to gasification, and compatibility with heterogeneous plastic feedstocks commonly generated by tourism activities [1,9].

Extensive studies have examined the process characteristics and performance of plastic waste pyrolysis, focusing on reactor design, operating temperature, heating rate, residence time, and catalyst utilization. Polyolefin-based plastics such as polypropylene (PP), high-density polyethylene

(HDPE), and low-density polyethylene (LDPE) have been reported to yield high fractions of liquid fuel with favorable calorific values when processed at temperatures ranging from 300 to 700 °C [5,15], [16]. The use of catalysts, including natural and synthetic zeolites, has been shown to enhance cracking efficiency, reduce wax formation, and improve fuel quality, although catalyst selection and dosage significantly influence product distribution and operational costs [3,4,6].

Recent advancements in process intensification and reactor innovation have further improved the technical feasibility of plastic pyrolysis systems. Microwave-assisted pyrolysis, for example, has demonstrated enhanced heating uniformity and reduced energy consumption compared to conventional heating methods [8]. Mechanical and thermal redesigns of pyrolysis reactors have also been proposed to improve conversion efficiency, operational stability, and scalability [17,18]. These engineering developments highlight the importance of system-level optimization for reliable, continuous operation, particularly when transitioning from laboratory- or pilot-scale systems to industrial-scale applications.

In addition to technical performance, techno-economic analysis (TEA) has become a critical component in evaluating the feasibility of plastic waste pyrolysis systems. Previous studies have demonstrated that economic viability is highly sensitive to feedstock availability, production capacity, energy efficiency, and market price of pyrolysis oil [1,10]. Long-term economic evaluations indicate that integrating energy recovery from non-condensable gases and optimizing utility consumption can significantly improve project profitability and shorten payback periods [19,20]. However, many existing TEA studies are limited to urban or industrial waste streams, with relatively little attention given to tourism-generated plastic waste, which exhibits distinct characteristics such as seasonal fluctuations and spatial concentration [7,21].

From a sustainability and environmental engineering perspective, pyrolysis contributes directly to circular economy principles by converting waste materials into secondary energy resources, thereby reducing reliance on fossil fuels and minimizing landfill disposal [2,9]. Several studies have highlighted the role of pyrolysis in supporting Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [22-23]. Nevertheless, achieving these sustainability outcomes requires not only technical efficiency but also system integration within local socio-economic and institutional contexts.

In geopark and tourism-based environments, the deployment of waste-to-energy technologies introduces additional considerations related to infrastructure limitations, governance structures, and community participation. Previous studies on tourism and geopark management emphasize that technological interventions must align with local institutional capacity, stakeholder collaboration, and policy frameworks to ensure long-term operational success [24,25,11]. While these studies primarily focus on governance and policy dimensions, they implicitly underscore the need for engineering solutions that are economically robust, operationally simple, and socially acceptable within conservation-oriented tourism areas.

Overall, the existing literature confirms the technical potential and economic promise of plastic waste pyrolysis as a waste-to-energy solution. However, there remains a critical gap in integrated engineering-oriented studies that combine realistic production capacity design, long-term techno-economic evaluation, and context-specific application in tourism-intensive geopark areas. Addressing this gap is essential to translating pyrolysis technology from experimental, isolated implementations into scalable, deployable energy systems that support sustainable tourism development and circular resource management.

1.2 Pyrolysis Technology for Tourism Waste Conversion into Liquid Fuel

Pyrolysis is a thermochemical conversion process that involves the thermal decomposition of organic materials in the absence or near-absence of oxygen, enabling the breakdown of long-chain polymers into smaller hydrocarbon compounds [14]. In engineering applications, pyrolysis is typically conducted at temperatures ranging from 300 to 700 °C, depending on feedstock characteristics, heating rate, residence time, and reactor configuration, such as fixed-bed, fluidized-bed, or rotary kiln reactors (Gabbar & Aboughaly, 2021; Sheldon, 2020). Waste generated from tourism activities, including plastic packaging, disposable utensils, paper waste, and organic residues, represents a heterogeneous feedstock that is technically suitable for pyrolysis due to its high volatile content and energy potential [4,7].

During pyrolysis, tourism waste is converted into three primary products: non-condensable gases (pyrolytic gas), solid residue (biochar), and condensable liquid fractions, commonly referred to as pyrolysis oil. Pyrolytic gas can be internally recycled to provide process heat, thereby improving the overall energy efficiency of the system, while biochar can be used as a soil amendment or as a carbon-rich material for environmental applications [2,26]. The liquid fraction, pyrolysis oil, contains a mixture of aliphatic and aromatic hydrocarbons with a relatively high calorific value, making it a promising alternative liquid fuel after appropriate upgrading or refining [3,5].

From an engineering systems perspective, the application of pyrolysis technology at an industrial or semi-industrial scale in geopark areas offers multiple technical advantages. These include significant reductions in waste volume, energy recovery from non-recyclable waste fractions, and the transformation of tourism waste into economically valuable energy products [6,22]. Several studies have demonstrated that plastic-based pyrolysis systems can achieve favorable energy conversion efficiencies, particularly when optimized through temperature control and catalyst utilization, making them competitive with conventional waste management technologies [8-9].

Beyond its technical merits, the deployment of pyrolysis systems in tourism-intensive geopark areas contributes to the development of a circular economy by closing material and energy loops within the local system. By converting locally generated waste into usable liquid fuel, geopark management can reduce dependency on externally sourced fossil fuels, lower waste transportation and landfill costs, and improve overall resource efficiency [1-2]. From an economic engineering standpoint, this approach creates opportunities for revenue generation, cost savings, and job creation through the operation and maintenance of waste-to-energy facilities, thereby supporting local economic resilience [27-28].

Moreover, the production of liquid fuels through pyrolysis aligns directly with several pillars of the Sustainable Development Goals (SDGs). Specifically, it supports SDG 7 (Affordable and Clean Energy) by providing alternative energy sources, SDG 11 (Sustainable Cities and Communities) through improved waste management systems, SDG 12 (Responsible Consumption and Production) by promoting waste valorization, and SDG 13 (Climate Action) by reducing uncontrolled waste disposal and fossil fuel dependency [29-30]. Consequently, pyrolysis-based waste-to-fuel systems represent not only a technically feasible engineering solution but also a strategic instrument for integrating renewable energy innovation, environmental protection, and sustainable tourism governance in geopark areas.

2. Methodology

This study employed a techno-economic analysis (TEA) framework to evaluate the long-term feasibility of producing liquid fuel from tourism-derived plastic waste via pyrolysis. Detailed information regarding this method is explained elsewhere [20]. TEA is widely applied in engineering studies to assess the technical and economic viability of energy conversion technologies prior to large-scale deployment [1,31,32]. The analysis was conducted over a 20-year operational period, reflecting the typical lifetime of industrial thermochemical processing facilities and enabling comprehensive evaluation of economic sustainability under realistic operating conditions [2,20].

2.1 System Boundary and Process Assumptions

The system boundary encompassed feedstock collection from tourism activities, feedstock preprocessing, pyrolysis conversion, product condensation and separation, and liquid fuel output at the plant gate. This gate-to-gate approach is commonly adopted in waste-to-energy system evaluations to ensure consistency in cost and performance assessment [3,5]. Technical assumptions regarding production capacity, operational days, and conversion efficiency were derived from reported performance ranges of plastic waste pyrolysis systems operating at temperatures between 300 and 700 °C [4,14].

The selling price of the liquid fuel product was determined using market-based benchmarking, referencing average prices of comparable liquid fuel products available on online commercial platforms. This pricing approach has been applied in previous techno-economic studies to capture conservative and up-to-date market conditions in the absence of regulated pricing mechanisms for alternative fuels [27,32].

2.2 Cost Structure and Economic Indicators

The economic evaluation incorporated both capital expenditure (CAPEX) and operational expenditure (OPEX). Fixed costs included investment in pyrolysis reactors, auxiliary equipment, installation, and supporting infrastructure, while variable costs comprised raw material handling, labor, utilities, maintenance, and operational contingencies. This cost classification follows standard engineering economics practice for energy system analysis [20,33].

Financial performance was assessed using multiple economic indicators, including cumulative net present value (CNPV), gross profit margin (GPM), payback period (PBP), breakeven point (BEP), breakeven capacity (BEC), internal rate of return (IRR), return on investment (ROI), and profit index (PI). These indicators are widely used to evaluate investment feasibility and financial robustness of thermochemical conversion technologies [29-30].

2.3 Scenario and Sensitivity Analysis

To enhance the robustness of the engineering analysis, the techno-economic model was evaluated across multiple operational scenarios. These scenarios included variations in feedstock availability and composition, production capacity utilization, labor conditions, interest rates, and external factors, such as seasonal weather variability, that may affect feedstock supply and plant operations. Scenario-based evaluation and sensitivity analysis are essential tools in engineering decision-making, particularly for waste-to-energy systems subject to uncertainty in supply and market dynamics [2,22].

2.4 Analytical Approach

All calculations were conducted using deterministic mathematical formulations based on mass balance, cost estimation, and discounted cash flow analysis. This approach ensures transparency, reproducibility, and comparability with previous techno-economic studies in renewable energy and waste management [20,32]. The methodology provides a solid engineering basis for assessing the feasibility of pyrolysis-based liquid fuel production systems in geopark tourism contexts.

This study applied techno-economic analysis for two decades. Pricing was based on average product prices on online shopping platforms to find the lowest price with good quality, and to ensure the latest pricing information. All data analysis was done using simple mathematical methods. Some of the parameters used for economic evaluation include CNPV, GPM, PBP, BEP, BEC, IRR, ROI, and PI. This trial evaluated various factors, including variations in raw materials, sales capacity, labor conditions, interest rates, and weather. Complete details for this calculation are explained in other sources [32,20].

The flow diagram of the synthesis route is shown in Figure 1. The diagram illustrates the integrated process flow for converting tourism-generated plastic waste into liquid fuel via a pyrolysis system, from waste collection to final product utilization. From an engineering perspective, the process consists of seven main operational stages, each designed to ensure feedstock quality, process efficiency, and product recovery.

Step 1: Waste Collection from Tourist Locations. The process begins with collecting solid waste from tourism areas, such as visitor centers, food courts, accommodation facilities, and recreational sites. This step is critical to ensure a stable feedstock supply, particularly in geopark environments where waste generation is influenced by tourism intensity and seasonality.

Step 2: Waste Sorting. Collected waste is then manually or mechanically sorted to separate plastic waste (specifically HDPE, LDPE, and PP plastics) from non-plastic materials. Plastic fractions are selected for their high hydrocarbon content and suitability for pyrolysis, while non-plastic waste can be diverted to alternative treatment pathways, such as composting or recycling. Effective sorting improves process reliability and product quality.

Step 3: Washing and Drying. The selected plastic waste undergoes washing to remove contaminants such as dirt, food residues, and labels. Subsequently, the plastics are dried to reduce moisture content. From a process engineering standpoint, this step is essential to minimize energy losses, prevent incomplete thermal decomposition, and enhance overall pyrolysis efficiency.

Step 4: Size Reduction (Shredding). Clean, dry plastics are shredded into smaller, uniform particles using a mechanical shredder. Size reduction improves heat transfer efficiency inside the pyrolysis reactor, ensures uniform thermal decomposition, and facilitates consistent feeding into the reactor system.

Step 5: Pyrolysis Process (Heating without Oxygen). Shredded plastic feedstock is fed into the pyrolysis reactor, where it is heated to 350-500 °C under oxygen-free conditions. Heat is supplied using a burner, and the absence of oxygen prevents combustion, allowing plastics to thermally decompose into smaller hydrocarbon molecules. During this stage, plastics break down into pyrolysis gas, liquid vapor, and solid char through endothermic reactions.

Step 6: Product Separation. The vaporized products exiting the reactor are cooled in a condenser system, where condensable vapors are converted into pyrolysis oil (a liquid fuel). Non-condensable gases are separated and can be recycled as a supplementary heating fuel for the pyrolysis reactor, improving energy self-sufficiency. Solid char is a by-product that can be used as a solid fuel or soil amendment, depending on its properties.

Step 7: Storage and Packaging. The liquid fuel product is filtered to remove impurities and then stored in tanks or drums. At this stage, the product is considered ready for utilization, either for direct energy applications or further refining. Proper storage ensures fuel stability, safety, and readiness for distribution.

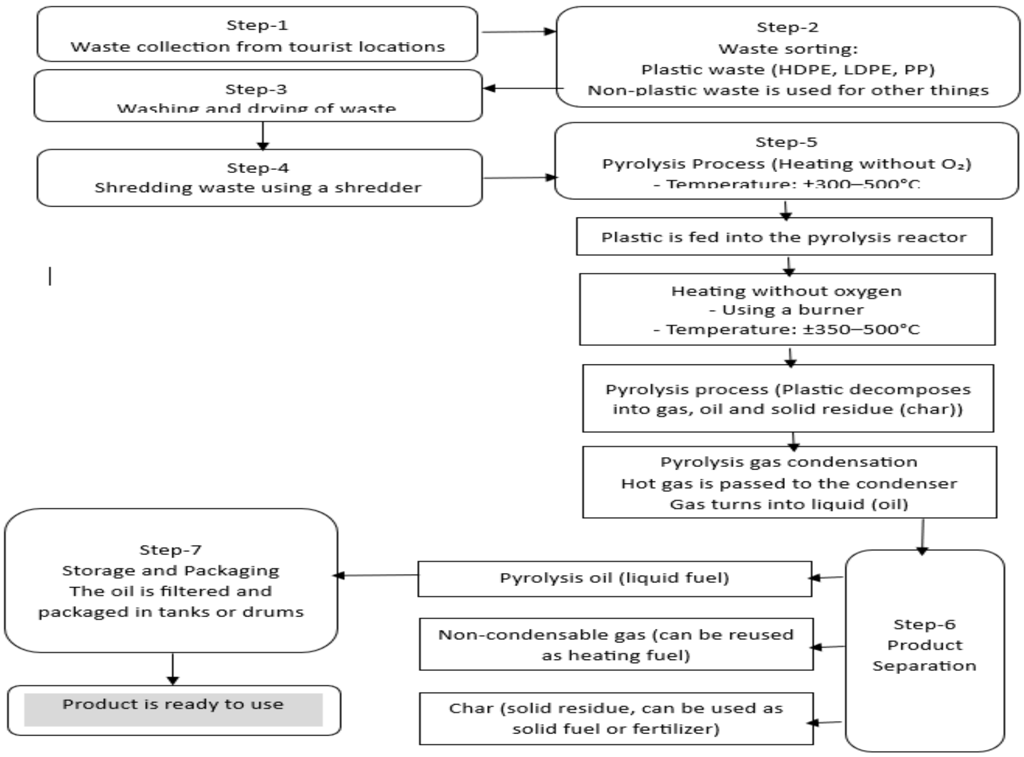

Fig. 1. Flowchart of Liquid Fuel Products from Tourism Waste Through Pyrolysis

The raw materials needed for the production process are Plastic Waste (Polyethylene, Polypropylene), Clean Water, Initial Fuel (Ignition/ LPG), Catalyst (optional, for oil upgrading), Zeolite (ZSM-5, Zeolite Y, Beta Zeolite), Cleaning Chemicals (Industrial Liquid Detergent (Non-ionic / Anionic)). The main product of this pyrolysis process is pyrolysis oil (liquid fuel). However, there are by-products in the form of non-condensation gas (which can be reused as heating fuel) and Char (which can be used for solid fuel or fertilizer). The economic analysis in this study, focusing on liquid fuel, demonstrates the significant potential for cost savings and revenue generation from the pyrolysis process.

From a systems engineering perspective, this process flow demonstrates an integrated waste-to-energy pathway that maximizes resource recovery through material separation, energy recycling, and by-product utilization. The reuse of non-condensable gas as a heating source enhances thermal efficiency, while converting waste into multiple valuable outputs supports circular economy principles. When implemented in geopark areas, this system provides a technically feasible solution to reduce tourism waste, generate alternative energy, and support sustainable development objectives.

3. Results

3.1 Design Basis and Economic Assumptions for Pyrolysis-Based Liquid Fuel Production

A set of technical, economic, and operational assumptions was defined to establish a consistent engineering basis for the techno-economic analysis and to enable realistic performance prediction over the project lifetime. These assumptions are essential for modeling system behavior, cost structures, and financial feasibility under controlled, reproducible conditions.

i. All economic calculations were conducted in Indonesian Rupiah (IDR) as the base currency, with conversions to United States Dollar (USD) applied as needed at a fixed exchange rate of 1 USD = IDR 16,500.00, ensuring consistency in financial reporting and international comparability.
ii. Product selling prices and raw material costs were determined based on prevailing market prices at the time of analysis. This market-referenced pricing approach reflects realistic economic conditions and minimizes bias in revenue and cost estimation.
iii. Equipment costs and process operating conditions were specified based on commercially available pyrolysis systems and auxiliary units currently offered in the market, as summarized in Table 1. This assumption ensures that the evaluated system represents a technologically mature, deployable configuration rather than a laboratory-scale prototype.
iv. Production costs were assumed to be predictable from the initial project phase and allowed to vary systematically over the operational period to account for changes in operational intensity and maintenance requirements;
v. Asset depreciation was calculated using a direct (straight-line) depreciation method, which is commonly applied in engineering economic evaluations of process equipment due to its simplicity and transparency [34];
vi. From an operational engineering perspective, one washing cycle required 1 hour, while the conversion of plastic waste into liquid fuel using a diesel-assisted pyrolysis reactor required 3 hours per reactor per batch. The plant was assumed to operate for 20 days per month, resulting in 240 operational days per year. Under these conditions, the maximum annual production capacity was estimated at 5,040,000 L/year, representing the system's design throughput;
vii. Electrical energy was utilized to operate the shredder motor, pumps, control panel, and cooling fan, with an estimated consumption of 4 kWh per hour. To simplify utility analysis, all utility requirements were expressed in electrical energy units (kWh), in accordance with standard engineering practice (Ulrich & Vasudevan, 2006). Electricity consumption was then converted into operating costs using a unit electricity price of IDR 5,000.00 per kWh;
viii. Total annual labor costs were estimated at IDR 102,000,000.00 for non-operational staff. When operator personnel were included, the total annual labor cost increased to IDR 270,000,000.00, reflecting realistic manpower requirements for continuous plant operation.
ix. The financial model applied an annual interest rate of 4.5%, representing prevailing financing conditions for industrial projects;
x. Corporate income tax was assumed to be 20% per year, in accordance with applicable taxation regulations;
xi. The project operational lifetime was set at 20 years, consistent with the expected service life of industrial pyrolysis equipment and infrastructure;
xii. A discount rate of 15% was applied to discounted cash flow calculations to account for investment risk and opportunity cost in energy-related infrastructure projects.

3.2 Economic evaluation Framework

The economic evaluation was conducted to quantify the financial feasibility of the pyrolysis-based liquid fuel production system by systematically accounting for capital investment requirements and operational cost structures. Capital investment was allocated over the initial two years of project implementation to reflect staged construction and commissioning of the processing facility. The required investment in the first year amounted to IDR 7,642,492,941,176, followed by an additional IDR 5,094,995,294,118 in the second year, representing expenditures for land acquisition, equipment procurement, installation, and supporting infrastructure.

Table 1 presents a detailed breakdown of the total cost components, categorized into fixed costs and variable costs, in accordance with standard engineering economic practice. Fixed costs consist primarily of capital-related expenditures and equipment depreciation, which remain constant regardless of production volume. In contrast, variable costs are directly influenced by operational intensity and production throughput. These include raw material costs, utility consumption, operating labor (OL), labor-related costs, and sales-related costs. This cost classification enables a clear distinction between capital recovery obligations and operational expenditures, forming the basis for subsequent financial performance indicators and sensitivity analyses.

Table 1
Cost Details of The Project To Make Liquid Fuel From Plastic Waste Using The Pyrolysis Process

No	Component	Amount (Rp)	Description
A	**Fixed Cost**		
1	Capital Related Cost	12,639,914,100.00	Costs related to initial capital include purchasing machinery, buildings, etc.
2	Depreciation	1,082,686,500.00	Depreciation of fixed assets per year
	Total Fixed Cost	13,722,600,600.00	Fixed costs incurred each year
B	**Variable Cost**		
1	Raw Material	46,922,250,000.00	Costs for plastic raw materials/derivatives
2	Utilities	60,000,000.00	Electricity, water, gas, etc.
3	Operational Labor (OL)	102,000,000.00	Daily operator salary
4	Labor Related Costs	30,600,000.00	Allowances, social security, etc.
5	Sales Related Cost	5,292,000,000.00	Promotion, distribution, etc.
	Total Variable Cost	52,406,850,000.00	Costs that change according to production volume

3.2.1 Revenue and Profit Analysis

Revenue and profit performance of the pyrolysis-based liquid fuel production system are summarized in Table 2. Based on the economic calculations, the system generates an annual sales revenue of IDR 75,600,000,000.00, derived from the projected production capacity and prevailing market price of the liquid fuel product. The total manufacturing cost, which includes both fixed and variable operating expenses, amounts to IDR 65,046,764,100.00 per year. The total capital investment required for the system is IDR 11,604,915,000.00.

From these values, the gross profit margin, defined as the ratio of net profit to manufacturing cost, was calculated to be 0.14 (14%), indicating that the system generates a positive operating surplus relative to its production cost. In addition, the profit-to-investment ratio, which represents the proportion of annual profit relative to total capital investment, reached 0.91 (91%), indicating strong capital recovery potential and high investment attractiveness. These results demonstrate that the pyrolysis-based liquid fuel production system is economically viable and capable of generating substantial returns under the assumed operational and market conditions.

Table 2
Revenue and Profit

No	Component	Amount (Rp)	Description
1	Sales	75,600,000,000.00	Calculated from production capacity of 5,040,000 liters/year × selling price of Rp15,000/liter
2	Manufacturing Cost	65,046,764,100.00	Total production cost = Fixed + Variable
3	Initial Investment	11,604,915,000.00	Total initial investment of the project
4	Net Profit	14% of manufacturing cost	Gross profit margin (GPM)
5	Return on Investment	91% of total investment	ROI (Return on Investment) of 0.91 or 91%

3.2.2 Break-Even and Financial Feasibility Analysis

Table 3 presents the BEP and key financial feasibility indicators of the pyrolysis-based liquid fuel production project. The BEP analysis indicates that the system begins to generate positive net profits at an annual production of approximately 3 million L, corresponding to about 59% of the designed maximum production capacity. This result demonstrates that the system does not require full-capacity operation to achieve financial sustainability, indicating a relatively robust economic structure under partial load conditions. In addition to the BEP, several profitability indicators were evaluated to assess overall investment performance. The profit-to-sales ratio was 0.1396 (13.96%), indicating a stable operating margin relative to annual revenue. The ROI reached 0.9747 (97.47%), indicating that the annual net profit nearly equals the total capital investment, which suggests strong capital efficiency. Furthermore, the pay-out time (POT), also known as the payback period, was estimated at 0.93 years, confirming that the initial investment can be recovered within 1 year of operation. Overall, the BEP and financial feasibility results demonstrate that the pyrolysis-based liquid fuel production system is economically attractive, resilient to production variability, and suitable for industrial-scale implementation, particularly in tourism-driven geopark environments where feedstock availability may fluctuate.

Table 3
Break-even point and financial feasibility analysis of the project to make liquid fuel from plastic waste through pyrolysis.

No	**Component**	**Amount (Rp)**
1	Annual Production Capacity	5,040,000 liters
2	Selling Price per Liter	Rp15,000.00
3	Total Revenue	Rp75,600,000,000.00
4	Fixed Cost	Rp13,722,600,600.00
5	Variable Cost per Liter	Rp10,400.00
6	BEP (Break Even Point)	2,981,997 liter/tahun
7	Percentage of BEP to full capacity	59%

3.2.3 Cumulative Net Present Value (CNPV) Analysis

Figure 2 presents the CNPV/TIC profile of liquid fuel production from plastic waste via pyrolysis over a 20-year operational period. The x-axis represents project time (years), while the y-axis shows the CNPV/TIC. The curve indicates negative CNPV/TIC values during years 0–5, reflecting the dominance of capital and operating costs in the early project phase. The BEP is reached around the 6th year, when CNPV/TIC crosses zero, indicating that cumulative discounted revenues equal total investment costs. After this point, CNPV/TIC increases steadily, with faster growth during years 6–10, followed by a more gradual increase until year 20. At the end of the project lifetime, the CNPV/TIC reaches approximately 60,000, demonstrating the strong long-term financial viability of the pyrolysis-based liquid fuel production system.

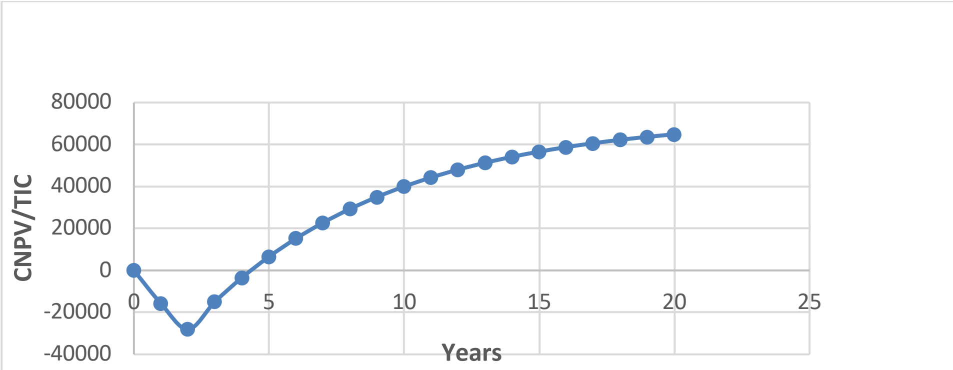

Fig. 2. CNPV economic evaluation for liquid fuel production by pyrolysis process

3.3 Sociological Impact

This study demonstrates a significant sociological and institutional impact of government involvement, particularly in governance structures, community participation, multi-stakeholder collaboration, and the strengthening of local institutions within geopark areas [35-36]. The implementation of pyrolysis technology for converting tourism waste into liquid fuel [37] has increased community engagement in environmental management while simultaneously improving local economic welfare through job creation and additional income streams. A direct economic benefit for local communities is generated through the supply of plastic waste as raw material, with a daily demand of approximately 300 tons (300,000 kg). At a purchasing price of IDR 3,500 per kg, this activity generates a daily community income of approximately IDR 1,050,000,000.

3.4 Contribution to the Sustainable Development Goals (SDGs)

The successful deployment of green technologies, such as plastic waste pyrolysis, is not determined solely by technical performance or economic feasibility but is strongly influenced by social acceptance and effective governance [23]. In tourism-based geopark environments, synergistic collaboration among geopark managers, local governments, local communities, and other stakeholders plays a critical role in enabling the integration of waste-to-energy systems into existing management structures. Such collaborative governance facilitates community participation in decision-making, resource management, and technology adoption, thereby strengthening the institutional foundation required for sustainable development at the local level.

Within this governance framework, the application of plastic waste pyrolysis contributes directly to multiple SDGs by integrating waste management and energy recovery within a circular economy approach. This supports current issues in SDGs, as reported elsewhere [38-42]. The conversion of tourism-generated plastic waste into liquid fuel supports SDG 7 (Affordable and Clean Energy) by enabling localized energy production and improving resource efficiency through the utilization of process by-products. Reducing unmanaged plastic waste and landfill dependency aligns with SDG 11 (Sustainable Cities and Communities) by enhancing environmental quality in conservation-oriented tourism areas. In addition, waste valorization through pyrolysis promotes SDG 12 (Responsible Consumption and Production) by extending material life cycles and minimizing waste leakage into natural ecosystems. By reducing uncontrolled disposal and associated emissions, the system also contributes to SDG 13 (Climate Action). Overall, pyrolysis-based waste-to-energy systems represent a practical engineering pathway for advancing sustainable tourism development while supporting the achievement of the SDGs in geopark contexts.

4. Conclusions

This study demonstrates that the conversion of tourism-generated plastic waste into liquid fuel through a pyrolysis-based system is technically feasible and economically viable within geopark environments. The integrated process engineering and techno-economic assessment confirms that pyrolysis can function as an effective waste-to-energy solution when supported by appropriate operational design and long-term financial evaluation. Beyond technical and economic performance, the results highlight the importance of governance structures, stakeholder collaboration, and community participation in enabling sustainable implementation. By integrating waste management, energy recovery, and circular resource utilization, the proposed system contributes to the achievement of the SDGs, particularly those related to clean energy, sustainable communities, responsible production, and climate action, while supporting sustainable tourism development in geopark areas.

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Conflict of Interest Statement
The authors declare that there is no conflict of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions Statement
Rita Rahmawati conceptualized and designed the study. Martin Roestamy supervised the project. Sri Harini reviewed the manuscript. Faisal Tri Ramdani conducted the experiments. Irma Purnamasari data analysis. Awa Awa and Warizal Warizal contributed to data interpretation. Ginung Pratidina wrote the initial draft of the manuscript. All authors contributed to manuscript revision, read, and approved the final version.

Data Availability Statement
All data generated or analyzed during this study are included in this published article. Additional datasets are available from the corresponding author upon reasonable request.

Ethics Statement
This study was conducted in accordance with the ethical standards of the institutional and/or national research committee.

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