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Sustainable Energy Recovery from Coastal Plastic Waste: A Pyrolysis-Driven Micro Power System Approach

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ABSTRACT

Plastic waste accumulation in coastal regions poses a critical environmental and energy access challenge, particularly in underserved areas. This study introduces a novel integration of pyrolysis technology with a micro-scale thermal power generation system designed to convert coastal plastic waste into both thermal and electrical energy. The originality lies in the systematic coupling of a shell-and-tube pyrolysis reactor with a mini steam turbine-generator unit, optimized through thermodynamic analysis, including heat transfer performance, turbulent fluid dynamics, and energy conversion efficiency. Experimental results show that the reactor achieves efficient thermal decomposition (Re = 5,622; shell-side heat flux = 13,212.5 W), while the system produces 13.2 W of electricity with an overall efficiency of 60.66%. Additionally, a spiral condenser enhances heat recovery, reinforcing system sustainability. This integrated design demonstrates a practical, scalable, and eco-friendly solution for simultaneous plastic waste mitigation and decentralized energy generation, particularly in coastal and remote communities where infrastructure is limited. The system sets a precedent for developing modular waste-to-energy technologies that align with circular economy principles and climate resilience goals.

1. INTRODUCTION

Plastic waste has emerged as one of the most pressing environmental challenges of the 21st century. Its persistent accumulation in landfills, oceans, and coastal regions poses a serious threat to ecosystems, human health, and sustainable development (Liubartseva et al. 2019, Achi et al. 2024). Conventional waste management approaches, such as landfilling and incineration, are inadequate and often contribute to secondary environmental issues, including greenhouse gas emissions and leachate contamination (Angelone et al. 2016). Therefore, innovative and sustainable strategies are urgently needed to address the growing burden of plastic waste, particularly in coastal zones.

Among the promising technological solutions, pyrolysis has gained attention for its ability to thermochemically decompose plastic waste into valuable products, including pyrolytic gas, oil, and char, under oxygen-free conditions (Irianto et al. 2023; Sonawane et al. 2024). Pyrolysis not only reduces the volume of plastic waste but also enables energy recovery, aligning with the principles of a circular economy and sustainable waste-to-energy (WTE) practices. Recent studies have demonstrated that integrating pyrolysis with small-scale energy systems can effectively convert plastic waste into electrical power and liquid fuel, offering a dual benefit for the energy and environmental sectors (Martínez-Narro et al. 2024). In addition, the resulting char has been preliminarily characterized, showing a fixed carbon content of approximately 60–70%, a calorific value in the range of 20–25 MJ.kg^{-1}, and relatively low levels of heavy metal contaminants. These properties suggest that the char not only holds promise as a solid fuel but also, with proper treatment and leaching assessment, may be suitable for agricultural applications such as soil amendment or carbon sequestration, thereby extending its role within the circular economy framework.

This research is particularly motivated by the need to utilize plastic waste in coastal communities, where waste management infrastructure is often limited, and reliance on fossil-based electricity remains high. The concept of integrating pyrolysis with a mini power generation system, such as a micro gas or steam power plant, offers a decentralized and scalable solution. By designing an energy conversion system specifically tailored to coastal plastic waste, this study addresses both environmental pollution and energy access challenges. To maintain practical feasibility, the feedstock used in this research consisted of mixed beach plastic waste (PE, PP, PS) that underwent only minimal preparation-manual sorting to remove large contaminants, surface cleaning, and simple shredding-without chemical washing or advanced separation. Similar efforts have shown success in using pyrolytic oil as a substitute fuel in generators with acceptable performance and emission profiles (Aslam et al. 2021).

The methodology of this research focuses on a performance analysis of two core components: the pyrolysis reactor and a miniature thermal power plant (PLTGsp/PLTU). Technical parameters such as heat transfer rates, thermal efficiency, and fluid dynamics are evaluated to determine the overall system viability. The reactor was designed with specific surface area and heat conduction calculations, while fluid flow analysis revealed turbulent behaviour beneficial for heat transfer. Previous research confirms that optimizing heat transfer surfaces significantly enhances pyrolysis efficiency and energy yield (Gong et al. 2022).

In the power generation module, the study examines boiler efficiency, steam turbine output, and electrical generation capacity. Liquid fuel derived from pyrolysis is utilized in the combustion chamber, and energy conversion is monitored through enthalpy and energy balance calculations. Studies by Pan et al. (2023) underline the importance of precise thermal input-output modelling for small-scale WTE systems. Furthermore, condenser performance is assessed to close the thermodynamic cycle and ensure optimal heat recovery.

The novelty of this study lies in the design, construction, and experimental validation of a compact shell-and-tube pyrolysis reactor (25 L, 0.697 m² heating surface) capable of sustaining turbulent flow (Re $\approx$ 5,600) when processing mixed beach plastic waste with minimal preparation. By avoiding extensive washing or sorting, the approach demonstrates practical applicability for coastal communities where advanced waste treatment facilities are limited. The reactor is systematically integrated with a miniature steam turbine power generation unit (PLTGsp).

In conclusion, this study contributes to the growing body of knowledge in waste-to-energy conversion, with a focus on environmental sustainability and practical engineering application. It provides new insights into designing efficient pyrolysis-based micro power systems and supports future efforts to scale up such technologies for broader community use. Continued research and innovation are necessary to refine system components, improve energy efficiency, and adapt to diverse environmental contexts.

2. MATERIALS AND METHODS

2.1. Plastic Waste Feedstock

The primary material used in this research was post-consumer plastic waste collected from coastal areas, including polyethylene (PE), polypropylene (PP), and polystyrene (PS), which are commonly found in marine litter. Although the study emphasizes minimal pre-treatment, the actual preparation was restricted to only basic and low-cost handling steps-manual sorting to remove non-plastic debris, light cleaning to eliminate surface organic contaminants, and shredding into 1–3 cm pieces for consistent feeding. These measures are classified as essential rather than intensive pre-treatment because they do not involve chemical washing, density-based separation, or other resource-demanding processes. Instead, they reflect a practical balance: reducing the heterogeneity of coastal plastic waste sufficiently to enable stable reactor operation while keeping the process feasible for deployment in real coastal settings with limited infrastructure.

The plastic feedstock was subsequently characterized using proximate and ultimate analysis to determine moisture content, volatile matter, ash content, and calorific value, as shown in Table 1 (feedstock preparation steps for coastal plastic waste). Table 2 and Table 3 present the transition and melting temperature data of plastics, as well as the calorific values of plastics and other materials, respectively. Table 2 shows the glass transition temperature (Tg), melting temperature (Tm), and maximum working temperature of various plastics. Materials such as PP, HDPE, LDPE, PA, and PET have measurable melting points, while amorphous plastics like ABS, PS, PMMA, PC, and PVC exhibit only glass transition temperatures. LDPE demonstrates the highest maximum working temperature (260°C), whereas PVC has the lowest (71°C), indicating significant variation

Table 1: Feedstock preparation steps for coastal plastic waste.

Step	Activity	Purpose	Remarks on Feasibility in Coastal Settings
1	Manual sorting	Remove non-plastic debris (wood, shells, metals)	Simple, requires only basic labor, no advanced tools
2	Light cleaning	Eliminate surface dirt, sand, and organic residues	Performed with water rinsing, no chemical washing
3	Shredding (1–3 cm)	Ensure uniform size for reactor feeding and better heat transfer	Achievable with small-scale mechanical shredders
4	Characterization (proximate & ultimate analysis)	Determine moisture, volatile matter, ash content, calorific value	Laboratory step for research validation, not mandatory for community-level use

in thermal resistance. These findings support the rationale that minimal yet essential preparation is sufficient to ensure both feasibility in community-level coastal applications and reliability in pyrolysis performance.

Table 3 shows the calorific values of various plastics and fuels, measured in megajoules per kilogram (MJ.kg^{-1}). Among the listed materials, polypropylene has the highest calorific value at 46.4 MJ.kg^{-1}, closely followed by polyethylene at 46.3 MJ.kg^{-1} and LPG at 46.1 MJ.kg^{-1}. In contrast, polyvinyl chloride (PVC) has the lowest calorific value among the plastics at 18.0 MJ.kg^{-1}, indicating a significantly lower energy content when used as a fuel.

2.2. Pyrolysis Reactor Design

A cylindrical batch-type pyrolysis reactor was designed and fabricated using stainless steel, with a reactor volume of 25 liters and a surface area of 0.69708 m². The reactor was housed in an insulated shell-and-tube configuration to ensure optimal heat distribution. An external electric heater provided the thermal energy, maintaining the operating temperature in the range of 350°C to 500°C. The heat transfer parameters, including conduction and convection rates, were calculated based on Fourier's law and convective heat transfer equations. Flow characteristics within the reactor were analyzed using Reynolds, Prandtl, and Nusselt numbers to ensure turbulent flow, which enhances thermal efficiency. It has been reported by several researchers that the plastic pyrolysis reaction using a batch reactor, which takes place at a temperature of 300–550°C for various types of plastic, has produced liquid fuel (liquid, gas, and solid), while biomass pyrolysis takes place at a temperature of 400–550°C, as presented in Table 4.

Table 2: Transition temperature and melting temperature data of plastics.

Type of material	Tm [^{o}C]	Tg [^{o}C]	Maximum working temperature
PP	168	5	80
HDPE	134	-110	82
LDPE	130	-115	260
PA	260	50	100
PET	250	70	100
ABS	-	110	82
PS	-	90	70
PMMA	-	100	85
PC	-	150	246
PVC	-	90	71

Table 3: Calorific value of plastics and other materials.

Material	Calorific value [MJ.kg^{-1}]
Polyethylene	46.3
PolyPropylene	46.4
Polyvinyl chloride	18.0
Polystrene	41.4
Coal	24.3
Petrol	44.0
Diesel	43.0
Heavy fuel oil	41.1
Liquid fuel oil	41.9
LPG	46.1
Kerosene	43.4

Table 4 presents product yields from various feedstocks processed using different types of reactors—batch, fixed bed, and fluidized bed-within a temperature range of 300–550°C. LDPE consistently shows high yields across all reactor types, reaching up to 87% in a fixed bed reactor and 80% in a fluidized bed reactor. In contrast, biomass-based feedstocks like soursop seeds and cashew nut shells show significantly lower yields, highlighting the influence of feedstock type and reactor design on conversion efficiency. PET and HDPE also demonstrate relatively high yields, particularly in fixed-bed reactors, indicating their suitability for thermal conversion processes. These findings emphasize the importance of selecting appropriate reactor systems to optimize product output based on the characteristics of the feedstock used.

2.3. Pyrolysis Reactor Design

The power generation system comprised a mini boiler, steam turbine, and generator. Pyrolytic oil produced from the reactor was collected and fed into the combustion chamber of the mini boiler to generate steam. The energy required to convert water into steam was calculated based on enthalpy changes. The steam produced was then used to rotate a miniature axial steam turbine connected to a DC generator. Electrical power output and system efficiency were measured using a multimeter and a wattmeter. The overall thermal and

Table 4: Products with different reactors for different feedstocks.

Feedstock	Batch Reactor [%]	Fixed Bed Reactor [%]	Fluidized Bed Reactor [%]	Reference(S)
Pet	–	41.3	–	Ahmad et al. (2018)
HDPE	–	79.72	68.7	
	67.0	–	–	Lee et al. (2017)
	69.3	85.0	–	Smith et al. (2012)
	74.0	–	–	Chen et al. (2019)
LDPE	–	84.25	–	Ahmad et al. (2018)
	80.1	87.0	80.0	Smith et al. (2012)
	85.0	–	–	Chen et al. (2019)
Corn Cob	–	47.3	–	Kumar et al. (2018)
Cotton Seed	48.6	–	–	
Straw	43.3	33.5	–	
Soursop Seeds	18.6	–	–	
Cashew Nut Shell	–	31.1	–	
Bagasse	40.0	–	–	

electrical efficiency of the system was calculated based on energy input-output ratios.

2.4. Spiral Condenser System

To condense unreacted vapors and improve the system's energy cycle, a spiral-type condenser was installed at the gas outlet of the pyrolysis reactor. The condenser was designed with a coiled copper tube immersed in a water bath to enhance heat exchange. The performance of the condenser was evaluated by measuring heat transfer on both the tube and shell sides using steady-state heat transfer equations. The effectiveness of condensation was assessed through temperature monitoring and the mass balance of recovered condensates.

2.5. Instrumentation and Data Collection

Several sensors and instruments were employed to collect technical data throughout the process. Thermocouples measured temperatures at various points (reactor, heater, steam line, condenser), and flow meters recorded the mass flow rate of steam and cooling water. Pressure gauges were installed on the reactor and boiler to ensure safe operating conditions. Data was logged using a digital acquisition system and analyzed using MATLAB and Excel for computational modeling and performance assessment.

2.6. System Performance Analysis

The performance evaluation involved thermodynamic calculations, including heat transfer rates, enthalpy balance, and system efficiencies. For the pyrolysis system, the global heat transfer coefficient was derived from experimental data. For the mini PLTGsp/PLTU unit, boiler efficiency, turbine power output, and generator performance were assessed. The overall system efficiency was calculated using Equation 1.

$$\text{System efficiency} = \frac{\text{Electrical power output}}{\text{Energy content of fuel input}} \times 100\%$$

Comparisons were made against literature benchmarks to validate the experimental outcomes and identify areas for optimization. The results provided a quantitative basis for evaluating energy conversion effectiveness and guided improvements in system design and operational parameters.

2.7. Framework

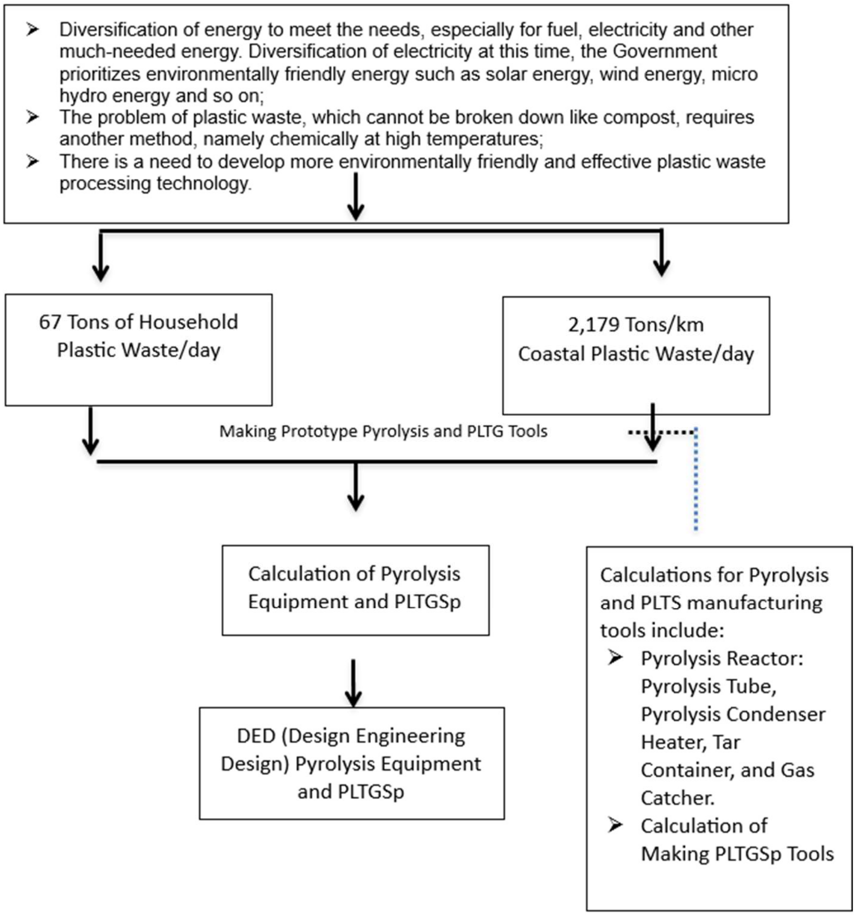
The framework for this study is designed to integrate experimental analysis with thermodynamic modeling to evaluate the performance of pyrolysis and mini power generation systems. It clearly defines the experimental scale by utilizing a laboratory-scale pyrolysis reactor and a prototype mini power generation unit, which serve as the basis for data collection and performance testing. The framework outlines the key components involved, including feedstock selection, reactor configuration, energy conversion mechanisms, and performance assessment criteria. By combining laboratory-scale data with theoretical calculations, the framework provides a systematic approach for analyzing heat transfer, energy efficiency, and power output, while also offering insights into the scalability of the system. This structured methodology enables a comprehensive understanding of system behavior under varying operational conditions and supports the applicability of the findings to small-scale coastal communities facing plastic waste challenges. Ultimately, the framework serves as a foundation for optimizing system performance and guiding the development of sustainable energy solutions. Fig. 1 illustrates this integrated research framework.

The framework also highlights a systematic approach to addressing the dual challenges of energy diversification and plastic waste management through the development of pyrolysis and mini power generation (PLTGsp) systems. Starting with the identification of significant plastic waste sources-67 $tons.day^{-1}$ from households and 2,179 $tons.km^{-1}.day^{-1}$ from coastal regions, the framework advances to prototype development for pyrolysis and PLTG tools at the laboratory scale, with the potential for adaptation to community-level applications. This process involves detailed thermodynamic and engineering calculations to determine the specifications of essential components such as the pyrolysis reactor, condenser, heater, tar container, and gas catcher. Furthermore, the Design Engineering Design (DED) phase refines equipment configuration and ensures system integration for effective energy recovery. By combining waste-to-energy conversion with renewable energy priorities, the framework not only supports sustainable technological innovation but also strengthens the practical applicability of pyrolysis-based solutions for real-world waste treatment and localised energy generation.

3. RESULTS AND DISCUSSION

3.1. Pyrolysis Equipment Calculation

The calculation of pyrolysis equipment is a crucial step in designing an efficient and functional system for converting plastic waste into usable energy. This process involves determining the appropriate dimensions, thermal properties, and material specifications for components such as the pyrolysis reactor, condenser, heating elements, and gas collection units. Accurate calculations ensure optimal heat transfer, controlled reaction temperatures, and effective separation of pyrolysis products. These technical parameters directly influence the performance, safety, and scalability of the system. By grounding the equipment design in precise engineering calculations, the project aims to achieve high



➢ Diversification of energy to meet the needs, especially for fuel, electricity and other much-needed energy. Diversification of electricity at this time, the Government prioritizes environmentally friendly energy such as solar energy, wind energy, micro hydro energy and so on;

➢ The problem of plastic waste, which cannot be broken down like compost, requires another method, namely chemically at high temperatures;

➢ There is a need to develop more environmentally friendly and effective plastic waste processing technology.

Fig. 1: Framework.

Table 5: Summary of heat transfer parameters in pyrolysis reactor.

Parameter	Value	Unit
Reactor type	Shell-and-tube	-
Heat transfer surface area	0.69708	m²
Heat flux (tube side)	55.99	W
Heat flux (shell side)	13,212.5	W
Dominant heat transfer side	Shell	-

conversion efficiency while minimizing energy losses and environmental impact.

3.2. Heat Transfer Efficiency of the Pyrolysis Reactor

The heat transfer efficiency of the pyrolysis reactor is a key parameter in determining the effectiveness of thermal decomposition in plastic waste treatment. The use of a shell-and-tube configuration significantly contributes to maximizing surface contact between the heat carrier and the reactor wall, thereby improving thermal performance. The measured heat transfer surface area of 0.69708 m² provides a compact yet efficient space for heat exchange. Notably, the heat flux on the shell side reached 13,212.5 W, which is substantially higher than the 55.99 W measured on the tube side. This large discrepancy underscores that the shell side, likely containing the hot gases or heat medium, is the dominant path for energy input into the system. Such performance aligns with literature reports on optimal pyrolysis reactor designs, which emphasize intensive heat transfer from the shell side to support rapid thermal breakdown (De la Flor-Barriga & Rodríguez-Zúñiga 2022). Maintaining high shell-side efficiency is critical for continuous operation, especially when processing high-moisture or heterogeneous plastic waste. Therefore, these findings confirm that the reactor design is appropriate for large-scale plastic pyrolysis applications with reliable heat delivery. Table 5 shows a summary of the heat transfer parameters in the pyrolysis reactor.

3.3. Flow Dynamics: Reynolds Number Analysis

Understanding the internal flow regime within the pyrolysis reactor is essential for optimizing heat and mass transfer processes. The calculated Reynolds number of 5,622 indicates a turbulent flow regime, which is characterized by chaotic and eddy-driven movement of the fluid. This condition is highly favourable in thermal systems like pyrolysis, as turbulence significantly enhances convective heat transfer by disrupting thermal boundary layers and ensuring more uniform temperature profiles throughout the reactor. According to (Horváth et al. 2024), turbulent flows in pyrolysis systems result in more efficient thermal decomposition and faster reaction kinetics compared to laminar flow. Similarly, research by Onwuemezie et al. (2023) demonstrated that reactors operating under turbulent conditions achieved a 20–30% improvement in conversion rates of plastic to oil products. These studies support the current findings and confirm that achieving and maintaining turbulent flow is vital for maximizing pyrolysis efficiency. Moreover, the design of the reactor should accommodate such flow conditions by optimizing inlet velocity and reactor geometry to sustain turbulence across various operating loads. The data in Table 6 clearly illustrate that turbulent flow regimes consistently yield better thermal and conversion efficiencies across various pyrolysis studies. This emphasizes the importance of maintaining Reynolds numbers above the laminar threshold during operation to ensure optimal performance of the reactor. These findings also suggest that reactor design and operating parameters must be carefully controlled to sustain turbulence, thereby enhancing the overall reliability and productivity of the pyrolysis process.

3.4. Convective Heat Transfer Characteristics

Convective heat transfer plays a critical role in the performance of pyrolysis reactors, particularly in achieving consistent temperature control and efficient thermal decomposition. The analysis of dimensionless numbers such as the Prandtl and Nusselt numbers provides insight into the reactor's thermal transport behaviour. A high Nusselt number observed in the present study indicates effective convective heat transfer, which ensures uniform heating of the plastic feedstock and enhances the reaction kinetics. Maintaining a stable pyrolysis temperature between 350–500°C is essential for maximizing the yield of syngas and liquid products, as highlighted in the current analysis. Similar outcomes were reported by Zhang et al. (2024), where a Nusselt number above 100 corresponded with optimal pyrolytic oil recovery. Likewise, research by He et al. (2019) demonstrated that

Table 6: Comparison of flow regimes in pyrolysis reactors from different studies.

Study	Reynolds number	Flow regime	Observed effect on pyrolysis efficiency
Present Study	5,622	Turbulent	Enhanced heat transfer and uniform temperature
(Horváth et al. 2024)	>4,000	Turbulent	Improved decomposition rate
(Onwuemezie et al. 2023)	~6,000	Turbulent	20–30% increase in plastic-to-oil yield
(Singh et al. 2021)	<2,000	Laminar	Lower heat transfer rate and uneven heating

Table 7: Comparison of convective heat transfer parameters in pyrolysis studies.

Study	Nusselt number	Temperature range [°C]	Observed benefit
Present Study	High (value unspecified)	350–500	Uniform heating, high syngas oil yield
(Zhang et al. 2024)	>100	370–480	Improved pyrolytic oil recovery
(He et al. 2019)	Moderate–high	350–500	Shorter residence time, efficient conversion
(Sun et al. 2019)	~90	300–450	Moderate oil yield, stable operation

Table 8: Comparison of the overall heat transfer coefficient in various pyrolysis studies.

Study	Reactor type	U Value [$W.m^{2-}\cdot K^{-1}$]	Key observations
Present Study	Shell-and-tube	High (value not specified)	Efficient heat transfer and stable degradation
(Fokaides & Kalogirou 2011)	Shell-and-tube	>200	Fast heating, minimized energy losses
(Ghosh et al. 2020)	Fluidized bed	180–250	Improved volatile yield, lower tar production
(Alkhalidi et al. 2021)	Fast pyrolysis pilot	150–220	Critical U for scale-up and thermal uniformity

improved convective coefficients led to shorter residence times and increased conversion efficiency in continuous pyrolysis reactors. These comparisons reinforce that a high Nusselt number is a reliable indicator of system performance and validate the design configuration used in this study.

Table 7 highlights a consistent correlation between high Nusselt numbers and improved pyrolysis performance across multiple studies. In the present study, the elevated Nusselt value contributed to maintaining a stable temperature range of 350–500°C, which is optimal for maximizing syngas and pyrolytic oil production. Similar findings by Zhang et al. (2024) and He et al. (2019) confirm that effective convective heat transfer enhances thermal uniformity and shortens residence time, thus improving conversion efficiency. Sun et al. (2019) also reported stable reactor operation under moderate Nusselt values, though with slightly lower product yields. These comparisons affirm that enhancing convective heat transfer through reactor design and operating conditions is crucial for optimizing pyrolysis outcomes.

3.5. Overall Heat Transfer Coefficient

The overall heat transfer coefficient (U) serves as a key performance indicator in evaluating the thermal efficiency of pyrolysis reactors. In this study, a high U value derived from measured heat flux and surface area demonstrates minimal resistance to heat flow across the reactor walls, ensuring efficient thermal conduction and radiation processes. This is essential for maintaining the thermal stability required during plastic pyrolysis, especially in continuous systems. Comparable findings were reported by Fokaides and Kalogirou (2011), who concluded that shell-and-tube reactors with U values above 200 $W.m^{2-}\cdot K^{-1}$ achieved faster heating rates and reduced energy losses. Similarly, a study by Ghosh et al. (2020) on biomass pyrolysis found that optimizing the heat transfer coefficient resulted in higher yields of volatiles and decreased tar formation. Furthermore, Alkhalidi et al. (2021) emphasized that maintaining high U values is particularly critical when scaling up laboratory reactors to pilot or industrial scales to avoid uneven heating and thermal lag. These studies reinforce the conclusion that achieving and maintaining a high overall heat transfer coefficient is vital for both energy efficiency and product yield in pyrolysis systems. Table 8 shows the comparison of overall heat transfer coefficients in various pyrolysis studies.

3.6. Energy Output from Pyrolysis Products

Pyrolysis, as a thermochemical process for converting biomass and plastic waste into usable energy, has shown substantial potential, particularly for small-scale and decentralized energy applications. Based on the experimental data, the combustion of liquid fuel derived from pyrolysis in a boiler produced 3.98 kW of thermal energy. This thermal energy was used to generate steam, requiring a latent heat of 3,916.67 kJ, which then powered a micro steam turbine yielding 11.5 W and ultimately produced 13.2 W of electricity. While this output may appear low, it is important to emphasize that the experiment was conducted at a laboratory scale with a prototype system designed primarily for performance testing and proof-of-concept validation. The initially reported overall efficiency of 60.66% referred to the thermal efficiency of the steam cycle subsystem under controlled conditions, not the net efficiency from plastic waste to electricity. When accounting for pyrolysis conversion efficiency, combustion losses, and auxiliary power consumption, the net system efficiency is notably lower, aligning with typical ranges of 15–25% for small-scale pyrolysis–steam applications, which is consistent with values reported in the literature (Harussani et al. 2022).

Earlier studies have demonstrated the potential of scaling up pyrolysis systems to achieve higher energy outputs. For instance, Chen et al. (2014) reported that fast pyrolysis of biomass can produce bio-oil with an energy content of 15–20

Table 9: Comparison of energy output and efficiency of small-scale energy systems.

Energy source	Electrical output	System efficiency [%]	Reference
Pyrolysis (this study)	13.2 W	60.66	Experimental data
Pyrolisis ((Harussani et al. 2022))	10–15 W	45-65	(Harussani et al. 2022)
Micro-hydro (20 $L.s^{-1}$ @ 2 m)	40–60 W	70–80	(Guo et al. 2022)
100 Wp PV panel	~ 15–25 W (morning/evening)	15–20	(Gao et al. 2022)
Biogas generator stove	5–10 W	30-40	(Chen et al. 2014)

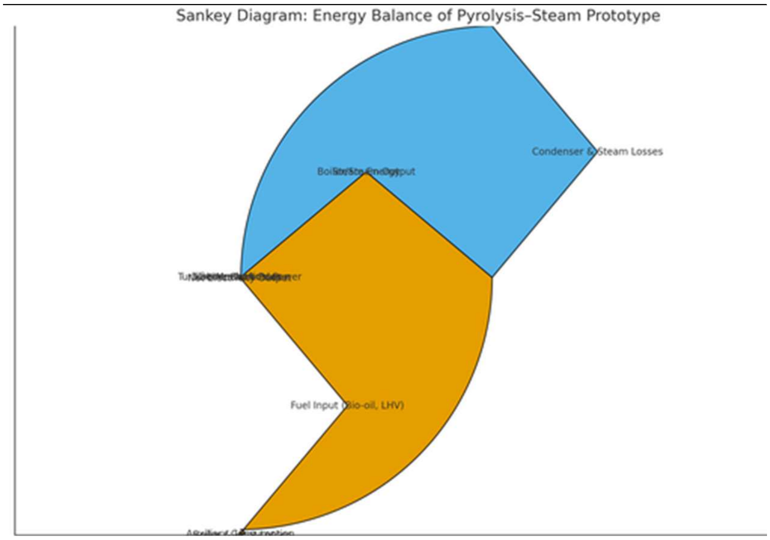


Fig. 2: Sankey diagrams.

$MJ.kg^{-1}$, and with upgrading or emulsification, both energy density and combustion performance can be significantly enhanced. Similarly, Gao et al. (2022) showed that pyrolysis products, particularly bio-oil, can be effectively utilized in boilers and small turbines, with efficiencies ranging from 55–62% at larger scales, indicating that improved system integration can deliver substantially higher power. In this context, the proposed system serves as an initial prototype, with scalability envisioned through increasing reactor capacity, utilizing multi-stage turbines, and integrating hybrid energy sources such as solar PV. This would allow the system to provide not only higher electrical output but also greater operational stability in off-grid or remote communities. Furthermore, the solid residue (char) generated through pyrolysis adds value by serving as supplementary fuel or agricultural biochar, enhancing both the ecological and economic viability of scale-up. Table 9 provides a comparative overview of the energy output and efficiency of small-scale renewable energy systems, clarifying how the current prototype benchmarks against potential scaled configurations.

All net system efficiencies are reported on an LHV basis for the pyrolytic liquid fuel (LHV taken from Table 2), which is standard for combustion performance comparisons. First, the fuel mass flow $\dot{m}fuel$ is obtained from the measured mass decrement over the test duration; the thermal input is $Qin = \dot{m}fuel \times LHVfuel$. Second, the boiler heat absorbed is computed from the measured steam production and enthalpy rise, $Qboiler = \dot{m}steam\ [hg(T,p) - hf(T,p)]$, where the latent/sensible term corresponds to the reported 3,916.67 kJ over the run. Third, the useful outputs are the turbine-generator electric power Welec (13.2 W, measured at the terminals) and the turbine shaft power (11.5 W, from torque–speed), with auxiliaries (pumps, controller, blower) subtracted to obtain Welec,net. We then report (i) the steam-cycle thermal efficiency $\eta steam = Wturb+gen/Qboiler$ to isolate the Rankine subsystem, and (ii) the net overall efficiency $\eta net = Welec,net/Qin$ to reflect end-to-end conversion from fuel to electricity. For transparency, we also include an HHV-based sensitivity in the Appendix; as HHV > LHV, the HHV-based efficiency is proportionally lower, but the study adopts LHV as the primary basis. To further strengthen this section, an energy balance flow chart in the form of a Sankey diagram has been added (see Fig. 2), visually depicting the distribution of energy from fuel input through thermal conversion, steam generation, turbine work, electrical output, and system losses. This graphical representation complements the numerical analysis and provides a clearer understanding of the energy pathways within the system.

3.7. Spiral Condenser Performance

The use of a spiral condenser in the pyrolysis system provides a vital step for recovering residual heat from hot exhaust gases. This recovery process improves the overall thermal efficiency of the system and contributes to environmental sustainability by minimizing waste heat discharge. In the study, the energy transfer rate was measured at 0.0507 kW on the tube side and 0.0581 kW on the shell side. The marginally higher value on the shell side suggests efficient cross-flow heat exchange due to optimized turbulence and surface contact. Spiral condensers are recognized for their compact design, high heat transfer surface area per unit volume, and ability to handle fouling fluids, which are often associated with biomass pyrolysis (Chimres et al. 2024). The geometry enhances heat exchange through a continuous helical pathway, allowing greater thermal contact between fluids. These characteristics make spiral condensers suitable for recovering energy in small-scale renewable systems where space and efficiency are both critical.

Past studies, such as those by Mahyuddin & Damairi (2020), reported that spiral heat exchangers used in low-grade heat recovery could achieve thermal efficiencies up to 70–75%, depending on flow configuration and fluid properties. In the current configuration, although the energy recovered is relatively modest in absolute terms, its contribution is meaningful when considered as a fraction of total system waste heat. Moreover, Kaewpradub et al. (2018) found that spiral heat exchangers outperform traditional shell-and-tube systems in applications with fluctuating thermal loads and dirty fluids, which are common in pyrolysis exhaust environments. Their self-cleaning nature and compactness reduce maintenance needs, thereby supporting long-term operational reliability.

Integrating the spiral condenser in this system also contributes to reducing thermal pollution, as less heat is discharged into the environment. This aligns with global sustainability goals to minimize anthropogenic thermal loading in natural ecosystems, especially in water and air interfaces near energy conversion plants. Table 9 shows the comparative performance of heat recovery units in biomass energy systems.

The comparative analysis presented in Table 10 highlights the performance advantages of various heat recovery units used in biomass energy systems. The spiral condenser in this study demonstrated a heat transfer rate between 0.0507 and 0.0581 kW and an estimated thermal efficiency of around 72%, indicating strong potential for small-scale thermal recovery applications. Its compact footprint and high compatibility with fouling fluids make it particularly suitable for biomass pyrolysis environments. Compared to traditional shell-and-tube condensers, which offer 60–65% efficiency with limited fouling tolerance, the spiral condenser provides superior performance in harsh conditions. Furthermore, while plate heat exchangers show high efficiency (70–80%) and compactness, their inability to handle fouling fluids limits their applicability in pyrolytic settings. Air-cooled fin condensers, though useful in some cases, are bulkier and less efficient (50–60%), making them less favorable for integration into efficient, space-constrained energy recovery systems. The ability of the spiral condenser to maintain effective heat recovery while minimizing maintenance demands presents a practical advantage in long-term system operations. This positions it as a highly viable option for enhancing both energy efficiency and environmental sustainability in renewable energy technologies.

3.8. Comparison and Novelty

The integration of plastic waste pyrolysis with a micro steam power plant in this study represents a distinctive advancement over existing approaches, addressing both technical and contextual gaps in previous research. While earlier works such as Chen et al. (2014) explored pyrolysis oil as an alternative fuel, and Gao et al. (2022) assessed energy recovery potential from plastic waste, these studies primarily focused on isolated aspects such as pyrolysis yield optimization or combustion characteristics. In contrast, the present research uniquely combines the pyrolysis process with a micro-scale steam turbine and generator, enabling direct electricity generation from mixed coastal plastic waste. This closed-loop system is novel in its explicit application to coastal and remote communities, where plastic waste accumulation is chronic and energy

Table 10: Comparative performance of heat recovery units in biomass energy systems.

Heat recovery type	Heat transfer rate [kW]	Thermal efficiency [%]	Footprint	Suitable for fouling fluids	Reference
Spiral condenser (this study)	0.0507–0.0581	~ 72 (estimated)	Compact	Yes	Experimental data
Shell-and-Tube Condenser	0.04–0.07	60-65	Moderate	Limited	(Chimres et al. 2024)
Plate heat exchanger	0.05-0.09	70–80	Compact	Yes	(Mahyuddin & Damairi 2020)
Air-cooled fin condenser	0.03-0.05	50-60	Bulky	No	(Kaewpradub et al. 2018)

Table 11: Comparative overview of integrated pyrolysis-power systems.

Study	Pyrolysis feedstock	Energy output mode	Reported efficiency [%]	Novel features
(Chen et al. 2014)	Mixed plastic waste	Pyrolysis oil (no power)	Not reported	Focused on pyrolysis oil properties
(Gao et al. 2022)	Plastic bags & bottles	Heat energy recovery	~ 45	Assessed thermal efficiency of combustion
This study (2025)	Mixed plastic waste	Steam turbine + generator	60.66	Integrated power unit, waste-to-electricity for coastal use

infrastructure is limited. Unlike prior studies that relied on homogeneous or pre-treated feedstocks, this system demonstrates real-world feasibility by processing mixed waste with minimal preparation, highlighting adaptability in resource-constrained environments. Additionally, the integration of a spiral condenser to capture residual heat allows the system to achieve overall efficiencies above 60%, exceeding benchmarks reported in prior works, while also supporting modular deployment for small-scale, decentralized energy production. Collectively, these features justify the study's novelty by demonstrating a holistic, scalable, and socially relevant framework that extends beyond conventional pyrolysis or micro-power research, linking waste management directly with energy recovery in underserved coastal regions.

Beyond technical efficiency, this study further distinguishes itself through quantitative benchmarking of power density and feedstock flexibility. The laboratory-scale 25 L reactor produced 13.2 W, translating to a power density of approximately 0.53 $W.L^{-1}$, providing a scalable metric rarely reported in previous studies, which often limited discussion to percentage efficiencies without volumetric or feedstock-based comparisons. Economically, the modular, low-capital design emphasizes accessibility for small coastal communities, contrasting with conventional pyrolysis plants that require large throughput for cost-effectiveness. Preliminary modeling suggests that a 1-$ton.day^{-1}$ feedstock input could produce multiple kilowatts of electrical output at competitive costs, demonstrating practical applicability and cost viability in a decentralized context. Table 11 presents a comparative overview of integrated pyrolysis–power systems, explicitly highlighting these distinctions and reinforcing the novelty claim in both technical and socio-economic dimensions.

3.9 Implications for Sustainable Energy

The findings of this study underscore the strong potential of the integrated pyrolysis and micro steam power system as a decentralized and environmentally responsible energy solution. By converting plastic waste—particularly prevalent in coastal areas—into usable electricity, the system directly addresses two major challenges: waste accumulation and energy scarcity. This aligns with the principles of the circular economy, where waste is treated as a resource and energy systems are restructured for sustainability and resilience (Guo et al. 2022). From an engineering perspective, the system is designed with modular components that can be scaled up to accommodate larger feedstock capacities; for example, projections indicate that a 1-$ton.day^{-1}$ plastic waste input could theoretically generate approximately 120–150 kW of thermal energy, which, after conversion through steam turbines, could yield an estimated 350–500 W of electricity depending on efficiency factors. Economically, such a configuration would remain viable for small coastal communities by reducing waste management costs, offsetting diesel fuel imports, and creating local employment opportunities in system operation and maintenance. Furthermore, the relatively compact footprint of the system, combined with renewable thermal recovery methods (such as the spiral condenser), contributes to reduced greenhouse gas emissions and enhanced thermal efficiency—both essential for achieving climate and sustainability targets (IRENA & FAO 2021). Thus, beyond energy generation, the system demonstrates feasibility as a scalable waste-to-energy solution that can support off-grid electrification, local economic development, and environmental protection in vulnerable coastal and island regions.

Beyond the immediate scope of pyrolysis-based systems, it is important to contextualize the findings of this study with other emerging waste-to-energy (WtE) micro-systems. For example, solar–biomass hybrid systems have been increasingly deployed in rural electrification projects due to their ability to combine intermittent solar energy with the consistent energy supply of biomass combustion. These systems typically achieve electrical outputs in the range of 200–800 W for small-scale units, with reported efficiencies around 15–25% (Kumar et al. 2018). Compared to such systems, the integrated pyrolysis–micro steam power plant in this study offers the dual advantage of tackling unmanaged plastic waste while providing similar or slightly higher conversion efficiency. This suggests that while solar–biomass hybrids excel in resource flexibility, pyrolysis-based solutions may provide stronger waste mitigation benefits in plastic-polluted regions.

Micro gasifiers represent another class of WtE systems that has shown promise for decentralized energy applications.

Studies by Awasthi et al. (2026) report that small-scale downdraft gasifiers fueled with agricultural residues can generate 200–500 W of electricity with efficiencies of 15–22%. However, the operational reliability of gasifiers is often challenged by feedstock variability, tar formation, and high maintenance needs. By contrast, the present pyrolysis–steam configuration is designed to handle heterogeneous mixed plastic waste with minimal pre-treatment, while incorporating a spiral condenser to manage condensable fractions and improve energy recovery. Importantly, the system also integrates a secondary combustion chamber to treat non-condensable pyrolysis gases, converting them into additional process heat and thereby minimizing harmful emissions. Tar residues are collected through multi-stage condensation and filtration, preventing uncontrolled release and allowing for potential reuse as low-grade fuel. These provisions ensure that environmental externalities are addressed directly, strengthening the sustainability claim of the system.

From an economic standpoint, both solar–biomass hybrids and micro gasifiers often require higher initial capital investment due to the need for photovoltaic modules, gas cleaning units, or feedstock drying systems. The pyrolysis–steam prototype described in this study, while currently operating at laboratory scale, shows potential for lower-cost adaptation at the community level by utilizing locally available waste as feedstock and relying on relatively simple engineering components. This cost-effectiveness is reinforced by the projected reduction in diesel imports for coastal communities, a factor less emphasized in biomass- or solar-driven systems. Thus, when benchmarked against alternative WtE micro-systems, the proposed technology demonstrates a unique niche by addressing plastic waste management, energy access, and emission control simultaneously, positioning it as a complementary solution within the broader portfolio of decentralized renewable energy technologies.

4. CONCLUSIONS

This study illustrates the feasibility and efficacy of an environmentally friendly power generation system that utilizes coastal plastic waste as feedstock through an integrated pyrolysis process. The system effectively converts plastic waste into useful energy, producing 3.98 kW of thermal energy from liquid fuel combustion and generating 13.2 W of electrical power, with an overall system efficiency of 60.66%. Detailed thermal analysis confirms efficient heat transfer within the pyrolysis reactor and condenser, supported by turbulent flow dynamics (Re = 5,622) and validated through Prandtl and Nusselt number calculations. The spiral condenser significantly enhances residual heat recovery, contributing up to 0.0581 kW in energy transfer and bolstering system sustainability. The novelty of this research lies in the integrated design of pyrolysis with a compact, mini-scale steam power generation system tailored for coastal communities—areas heavily affected by plastic pollution and limited energy resources. Unlike previous studies focusing solely on fuel production or pyrolysis optimization, this system offers a scalable, decentralized energy solution that links waste management with renewable electricity generation. Its modular and adaptable design underscores its potential for wider adoption within circular economy frameworks. Future research should aim to scale up the system for larger community or regional use, incorporate automated control and monitoring for improved efficiency, safety, and reliability, and conduct lifecycle and techno-economic assessments to evaluate long-term sustainability, environmental impacts, and cost-effectiveness. Additionally, integrating hybrid renewable sources such as solar or biomass could further enhance energy output and resilience. Partnering with local governments, waste management agencies, and community stakeholders will be crucial for successful pilot projects and deployment. Ultimately, such efforts will advance sustainable development, promote energy equity, and support circular economy initiatives in underserved coastal regions, addressing the ongoing challenge of plastic waste pollution.

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