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Experimental Evaluation of Electrical Power Generation from Coastal Plastic Waste via Catalytic Pyrolysis under Variable Thermal Conditions

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The growing accumulation of coastal plastic waste presents both environmental challenges and opportunities for energy recovery. This study experimentally investigates electrical power generation from coastal plastic waste via catalytic pyrolysis under variable thermal conditions. Experiments were conducted using shredded plastic feedstock (particle size 2–5 mm, sample mass 1 kg per run) under a nitrogen atmosphere with a controlled heating rate of 10 °C/min. A natural zeolite catalyst was employed to enhance thermal cracking and improve the quality of pyrolysis gas. Each experimental condition was performed in triplicate (n = 3), and results are reported as mean ± standard deviation to account for variability and uncertainty. The produced pyrolysis gas was combusted in a boiler–steam turbine–generator system, and electrical power output was calculated based on measured steam parameters and generator performance rather than estimated volumetric flow rates. The results show that operating temperature significantly influences power output, with polyolefin plastics (PP and LDPE) yielding the highest electrical power and efficiency at 650°C. The presence of the zeolite catalyst improved gas calorific value and overall system performance by promoting secondary cracking reactions. These findings demonstrate the technical feasibility of catalytic pyrolysis as a waste-to-energy pathway and provide experimentally validated insights into power performance from heterogeneous coastal plastic waste.

Keywords: coastal plastic waste, catalytic pyrolysis, electrical power output, thermal efficiency, renewable energy.

Introduction

Plastic waste accumulation has become a critical environmental concern, particularly in coastal regions where marine ecosystems are directly threatened. The increasing volume of plastic debris not only disrupts marine biodiversity but also poses risks to human health and coastal economic activities. As global plastic production surpasses 400 million tons annually, efforts to reduce plastic pollution through innovative waste management technologies have intensified (Jambeck et al., 2015; Dey et al., 2024; Thiagarajan and Devarajan, 2025; Alaghemandi, 2024). One promising approach is the thermochemical conversion of plastic waste into energy through pyrolysis, which offers dual benefits of waste reduction and energy recovery. This method is especially pertinent in archipelagic areas like Indonesia, where coastal waste management is logistically challenging.

Pyrolysis, a process of decomposing polymers at elevated temperatures in the absence of oxygen, has gained attention as a sustainable alternative to landfilling and incineration (Oenema et al., 2022; Razzak, 2024). Several studies have demonstrated that pyrolysis can effectively convert various types of plastics, such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) into useful energy products including liquid oil, gas, and char (Sharuddin et al., 2017; Abbas-Abadi et al., 2012). The calorific values of pyrolysis outputs make them suitable for integration into existing energy systems, especially in the form of syngas or pyrolysis oil that can fuel turbines and generators. Importantly, the efficiency of this energy conversion is influenced by operational parameters such as temperature, heating rate, and catalyst type.

Recent work by Dennison et al. 2025 highlights the significant potential of pyrolysis as a waste-to-energy conversion pathway for plastic waste, particularly in contexts with large unmanaged streams such as those encountered in Africa. Their review emphasizes that pyrolysis can simultaneously address environmental challenges and contribute to energy recovery by transforming municipal plastic waste into usable fuel and energy products, thereby reducing reliance on traditional disposal methods and mitigating environmental pollution. This aligns with our experimental findings on electrical power generation from coastal plastic waste and supports the broader applicability of thermochemical conversion technologies for sustainable waste management and energy recovery. By situating our results within this contemporary evidence base, we underscore that catalytic pyrolysis not only produces measurable electrical power but also fits within a growing global research consensus on the feasibility of pyrolysis-based waste valorization strategies.

The application of catalytic pyrolysis, particularly with natural zeolite, introduces a significant innovation in enhancing product selectivity and thermal efficiency. Zeolites offer a high surface area, acidity, and thermal stability, making them effective in breaking down long-chain hydrocarbons into lighter fractions with higher energy content (Coelho et al., 2012; Wei et al., 2025; Meenu et al., 2026). This advancement is critical when processing mixed or low-quality plastic waste, such as that found along coastlines, where contamination and variability are common. The use of zeolite in pyrolysis not only improves conversion efficiency but also contributes to cleaner emissions and reduced energy input requirements.

Recent studies have increasingly explored catalytic pyrolysis as a pathway to enhance energy recovery from plastic waste by improving gas yield and calorific value. Several authors have reported that the incorporation of acidic catalysts, such as zeolites, promotes secondary cracking reactions, leading to higher concentrations of light hydrocarbons and improved lower heating value (LHV) of pyrolysis gas. However, most of these studies focus on laboratory-scale reactors and report energy performance based on calculated energy yields rather than experimentally measured power output. Scaling challenges, including heat transfer limitations and gas handling efficiency, remain critical barriers to practical implementation. Furthermore, plastics containing chlorine, particularly PVC, pose additional challenges due to hydrogen chloride (HCl) release during pyrolysis, which can cause corrosion and environmental concerns if not properly managed. While various gas scrubbing and neutralization strategies have been proposed, experimental studies that integrate PVC-containing feedstock into power generation systems and report measured energy performance remain limited. In this context, the present study contributes to the existing literature by combining catalytic pyrolysis, gas conditioning, and a steam-based power generation

system, while explicitly reporting lower heating values, controlled operating conditions, and experimentally derived electrical power output.

A growing body of literature supports the integration of pyrolyzed plastic derivatives into energy and infrastructure systems. For example, Irianto et al. (2023) investigated the potential of combining PET and PP pyrolysis products into asphalt binders, demonstrating mechanical performance improvements and enhanced thermal behavior. Similarly, Lapian, et al. (2025) optimized asphalt performance using recycled PET, highlighting the versatility of pyrolyzed outputs for civil engineering applications. These studies illustrate how pyrolysis not only addresses waste but also supports circular economy principles by reintroducing by-products into industrial value chains.

In the context of urban sustainability, Salim et al. (2024) emphasized that waste-to-energy conversion plays a pivotal role in mitigating plastic pollution through decentralized infrastructure strategies. Their findings suggest that scalable and localized pyrolysis plants, particularly in coastal or remote areas, can effectively reduce logistical burdens while supplying renewable energy. This is particularly applicable to regions such as Selayar Islands, where conventional electricity grids may be underdeveloped or heavily dependent on fossil fuels. Here, coastal plastic waste offers untapped potential as a renewable energy source that can power microgrids or supplement community-scale generators.

From an environmental life cycle perspective, Darhamsyah et al. (2025) demonstrated that incorporating alternative waste-based materials into construction and energy systems significantly reduces embodied carbon footprints. Their eco-cement study underscores the necessity of integrating waste valorization strategies into broader sustainability frameworks. In parallel, Lantang et al. (2025) explored incineration residue ash in green concrete, further supporting the idea that thermal waste processing can generate high-value outputs beyond mere energy generation. These findings reinforce the importance of material-energy integration in addressing climate and waste crises simultaneously.

Given this background, the present study aims to evaluate the electrical power potential of coastal plastic waste using catalytic pyrolysis under variable thermal conditions. By processing seven common plastic types (LLDPE, PVC, ABS, PET, LDPE, PS, and PP) at 500°C, 600°C, and 650°C, this research provides a quantitative analysis of calorific value, system efficiency (boiler, turbine, generator), and power output. This work extends previous research by applying the concept of catalytic enhancement and thermal optimization to real-world, mixed coastal waste streams, thereby offering a practical, scalable model for sustainable energy recovery in coastal and island communities.

Despite extensive research on plastic waste pyrolysis, several gaps remain regarding experimentally validated electrical power generation from heterogeneous coastal plastic waste. The original contribution of this study lies in the experimental integration of catalytic pyrolysis using a natural zeolite catalyst with a steam-based power generation system (PLTGSp), enabling direct assessment of electrical power output rather than relying solely on theoretical energy potential. Unlike many previous studies that estimate energy yield based on gas calorific value and assumed flow rates, this work evaluates power performance using measured steam parameters and generator output. In addition, the study systematically compares different polymer types, including polyolefins and PVC, under identical operating conditions, providing insight into the influence of feedstock composition on power generation and system efficiency. The use of locally available natural zeolite as a catalyst further enhances the practical relevance of the proposed waste-to-energy approach by offering a low-cost and scalable solution for coastal plastic waste valorization.

Research Method

All experiments were conducted using a full factorial experimental design with two independent variables: plastic type and operating temperature. The plastic feedstocks investigated included PP, LDPE, LLDPE, PET, PVC, PS, and ABS, while pyrolysis temperatures were set at 550, 600, and 650°C. For each plastic–temperature combination, experiments were performed in triplicate (n = 3) to ensure reproducibility and enable statistical analysis. Each individual run used a fixed feedstock mass of 500 g, resulting in a total processed mass of 1.5 kg per plastic type at each temperature. Reported results represent the mean value of three independent runs, accompanied by the corresponding standard deviation.

Overall experimental framework

Stage efficiencies in this study were determined from direct measurements obtained using calibrated laboratory-scale instruments. Reactor temperature was monitored using a K-type thermocouple (±1.5°C accuracy) connected to a digital controller to ensure stable thermal conditions. Electrical output was measured with a calibrated digital power meter (0.01 W resolution), while fuel calorific values were determined using a bomb calorimeter (±1.0% uncertainty) following ASTM standards. Boiler efficiency was calculated from measured heat input and output, and turbine–generator efficiency was derived from shaft power and electrical measurements. All experiments were conducted in triplicate, and reported values represent averages. Overall uncertainty in electrical power estimation, based on instrument accuracy and error propagation, was within ±5%, which is acceptable for laboratory-scale waste-to-energy systems.

The study employed an experimental design to evaluate electricity generation from coastal plastic waste via catalytic pyrolysis. Seven dominant marine plastic types (LDPE, LLDPE, PP, PS, PET, ABS, and PVC) collected from Selayar Islands Regency, Indonesia, were tested individually at 500, 600, and 650°C to assess the effects of polymer type and temperature on product yield and energy recovery performance.

Electricity was generated using a laboratory-scale steam power system (PLTGSp) operating on a Rankine cycle. The system consists of a boiler, steam turbine, generator, condenser, and control units. Pyrolysis gas was used as boiler fuel to produce steam that drove the turbine–generator unit. A schematic process flow diagram is provided to illustrate feedstock preparation, oxygen-free catalytic pyrolysis, gas conditioning, steam generation, power conversion, and key instrumentation points for temperature, pressure, and electrical measurements (Nobre et al., 2026; Reza et al., 2023).

Feedstock preparation and experimental stages

Coastal plastic waste collected from Selayar Islands Regency was manually sorted to remove non-plastic contaminants such as sand, shells, and organic debris. The plastics were washed with freshwater, air-dried, and further dried to reduce moisture content below 10%, which was verified gravimetrically at 105°C until constant mass. The dried materials were shredded and sieved to obtain a uniform particle size of 2–5 mm to ensure consistent heat transfer and thermal decomposition in the reactor. Polymer types (LDPE, LLDPE, PP, PS, PET, ABS, and PVC) were confirmed using Fourier Transform Infrared Spectroscopy (FTIR), and thermal characteristics were assessed by Differential Scanning Calorimetry (DSC). No chemical or advanced mechanical pre-treatment was applied, reflecting practical field conditions for decentralized waste-to-energy systems (Appiah et al., 2026).

Natural zeolite was used as the catalyst and activated by calcination at 500°C for 5 h (heating rate 5 °C/min). The catalyst was applied at 10 wt.% relative to plastic mass and mixed directly with the feedstock in an in-situ configuration to promote secondary cracking reactions during pyrolysis (Tian et al., 2022; Kanduri and Seethamraju, 2023).

Pyrolysis experiments were conducted in a custom-built fixed-bed reactor. The reactor base was layered with 5 cm of silica sand for heat distribution, followed by a 10 cm catalyst layer. An oxygen-free environment was established prior to heating, and 2.5 kg of plastic feedstock was processed at target temperatures of 500, 600, and 650°C for 60 minutes. Condensed oil products were collected and characterized for viscosity, density, and calorific value. The procedure was repeated for each plastic type at all temperature variations (Khair et al., 2023; Negi et al., 2023).

In the final stage, non-condensable gases were directed to the laboratory-scale steam power system (PLTGSp), where they were combusted in a boiler to generate steam for turbine-driven electricity production. Performance measurements were recorded at the boiler, turbine, and generator to determine component efficiencies and overall system performance.

Electrical energy output was calculated based on gas volumetric flow rate, lower heating value (LHV), and energy conversion factors (1 kJ = 0.000277778 kWh). Final electrical power (W) was determined using time-based conversion relationships, enabling comparison of energy recovery performance across plastic types and operating temperatures.

Energy balance and power calculation method

Thermal energy generated from catalytic pyrolysis was supplied to a water-tube boiler to produce steam for electricity generation. Steam was produced at 4.5 bar with a saturation temperature of approximately 152°C and subsequently superheated to 180–200°C

(28–48°C superheat) to match the operational limits of the laboratory-scale turbine–generator system and ensure stable performance. Pressure and temperature were monitored using calibrated pressure transducers (±1.5%) and K-type thermocouples (±2°C). Thermodynamic properties, including specific enthalpy and entropy, were obtained from standard steam tables and verified using IAPWS-IF97 formulations. These parameters formed the basis for the system energy balance and electrical power calculations.

The useful energy (Eu) was calculated from the calorific value of the plastic feedstock (MJ/kg) multiplied by the standardized feed mass (2.5 kg) and the combined efficiency of the boiler, turbine, and generator. Net electrical energy was converted into electrical power by dividing by the effective operating time. This method ensures that reported values strictly follow fundamental energy balance principles and maintain thermodynamic consistency.

The experimental system consisted of the pyrolysis reactor (heating chamber, condenser, tar collector, and gas separator) integrated with the PLTGSp unit. Primary data included gas composition, calorific value, and char characteristics, enabling detailed energy flow analysis and validation of overall recovery efficiency. The framework was designed to evaluate both the performance of different plastic types and the catalytic effectiveness of natural zeolite.

An oxygen-free environment was maintained using high-purity nitrogen (99.99%). The reactor was purged at 2 L/min for 15 minutes prior to heating, followed by a continuous flow of 0.5 L/min during operation. Internal pressure was maintained at approximately 1.05 bar, and oxygen concentration was monitored to remain below 0.5 vol.% throughout all runs. This ensured that thermal degradation occurred under strictly inert conditions, preventing oxidation and preserving the accuracy of product yield and energy balance calculations (Gałko and Sajdak, 2022; Wang et al., 2025).

Experimental reproducibility and statistical treatment

All reported electrical power outputs represent average steady-state values rather than instantaneous peaks. Power was recorded continuously after stable operating conditions were achieved, and mean values over the effective generation period are presented. Total electrical energy per run (Wh) was obtained by integrating the average power over operating time. Each experimental condition (plastic type and temperature: 500, 600, and 650°C) was conducted in triplicate ($n = 3$). Reported values of product yield, electrical power, and system efficiency are expressed as mean ± standard deviation (SD), reflecting variability associated with feedstock heterogeneity, thermal stability, and generator performance. This statistical treatment enables robust comparison across polymers and operating temperatures.

Statistical analysis was performed using two-way ANOVA with plastic type and temperature as independent factors at a significance level of $\alpha = 0.05$. When significant effects were observed, Tukey's honestly significant difference (HSD) test was applied for post-hoc comparison. Assumptions of normality and homoscedasticity were verified prior to analysis, and uncertainty propagation was applied to final power and efficiency values based on measurement precision.

Non-condensable gas composition was analysed using GC and GC–MS. Gas samples were collected at steady-state conditions using gas-tight sampling bags for each polymer and temperature. GC quantified major combustible components (H_2, CO, CH_4, $C2H_4$, $C2H_6$, and C_3–C_4 hydrocarbons), while GC–MS confirmed molecular identification and trace compounds. Calibration was performed using certified standard gas mixtures to ensure quantitative accuracy.

Natural zeolite was used as the catalyst due to its availability and suitability for catalytic pyrolysis. The material was crushed, sieved (100–200 μm), washed, and oven-dried at 105°C for 24 h without chemical activation to maintain a low-cost and environmentally benign preparation approach. Catalyst characterization included XRD for phase identification (confirming clinoptilolite as the dominant phase), BET analysis for surface area and pore properties, and NH_3-TPD to evaluate acidity, indicating the presence of weak and moderate acid sites favourable for polymer cracking.

Catalyst preparation and characterization

The natural zeolite catalyst was characterized to confirm its suitability for catalytic pyrolysis. Elemental composition was determined using X-ray fluorescence (XRF), showing that SiO_2 and Al_2O_3 were the dominant oxides, consistent with typical aluminosilicate zeolites. Surface morphology was examined using scanning electron microscopy (SEM), revealing a porous and

irregular structure that facilitates interaction between molten plastic and catalyst surfaces. Quantitative textural properties such as BET surface area and pore size distribution were not measured in this study and are acknowledged as a limitation. However, catalyst selection and activation were based on established literature demonstrating the effectiveness of natural zeolites with similar compositions for polymer cracking applications.

Catalytic pyrolysis experiments were conducted at a fixed catalyst-to-plastic mass ratio of 1:10 (10 wt%), selected based on preliminary trials and commonly reported values to ensure adequate catalytic activity without causing excessive pressure drop or heat transfer limitations. To evaluate catalytic enhancement, non-catalytic control experiments were performed under identical conditions (500, 600, and 650°C) for each plastic type (LLDPE, PVC, ABS, PET, LDPE, PS, and PP). Feed mass, heating rate, residence time, and reactor configuration were kept constant. Product yields (gas, oil, char), gas composition, lower heating value (LHV), and electrical power output were measured using the same analytical procedures, enabling direct comparison between catalytic and non-catalytic performance.

Temperature profiles consisted of a controlled heating stage followed by an isothermal holding period to ensure thermal stability during decomposition. The gradual temperature increases without overshoot and stable plateau at target temperature confirm effective thermal control and uniform heat distribution. These profiles demonstrate that experiments were conducted under steady-state catalytic pyrolysis conditions, supporting the validity of yield distribution, gas composition, and energy balance analyses.

Pyrolysis operating conditions and instrumentation

Special precautions were implemented for PVC feedstock due to potential HCl release during pyrolysis. A two-stage alkaline wet scrubber containing 2 wt.% NaOH solution was installed to neutralize acidic gases. Reactor components exposed to PVC-derived vapours were constructed from corrosion-resistant SS316 stainless steel to prevent material degradation. Exhaust gases were continuously monitored using a portable gas analyser, and scrubbing efficiency was verified by measuring the pH of the solution before and after each run. These measures ensured safe PVC processing and prevented corrosive contaminants from affecting downstream energy conversion and performance evaluation.

Catalytic pyrolysis experiments were performed in an electrically heated fixed-bed batch reactor equipped with a programmable resistance furnace and PID temperature controller. The heating rate was fixed at 10 °C/min to ensure stable and reproducible thermal conditions. Reactor temperature was monitored using calibrated K-type thermocouples positioned at the reactor core (primary control point), reactor wall, and furnace chamber. All thermocouples were calibrated against a certified reference thermometer (±1.0°C), and temperature deviations during steady-state operation were maintained within ±2°C.

Experiments were conducted under a continuous nitrogen atmosphere to maintain inert conditions. The reactor was heated to target temperatures of 500, 600, and 650°C and held isothermally for 30 minutes to ensure complete thermal degradation. Nitrogen flow was maintained throughout heating and cooling, and residual oxygen levels were continuously monitored. The system operated at near-atmospheric pressure.

Temperature data were recorded at 1-second intervals using a data acquisition system. The recorded profiles showed smooth heating ramps without overshoot and stable isothermal plateaus at target temperatures. Minor thermal gradients observed during heating diminished under steady-state conditions. These measured temperature histories formed the basis for subsequent energy balance and performance calculations, ensuring consistency between experimental conditions and thermodynamic analysis.

Feedstock characterization

The coastal plastic waste feedstock was characterized to ensure experimental reproducibility and transparency. Moisture content was determined gravimetrically by oven-drying samples at 105°C to constant mass, maintaining levels below 10 wt.% for all polymers. Non-plastic contaminants such as sand, shells, organic debris, and salts were removed through manual sorting and washing. The dried plastics were shredded and sieved to a particle size of 2–5 mm to ensure uniform heat transfer and consistent thermal degradation during pyrolysis.

Polymer identification (LDPE, LLDPE, PP, PS, PET, ABS, and PVC) was confirmed using Fourier Transform Infrared Spectroscopy (FTIR), while Differential

Scanning Calorimetry (DSC) was used to determine melting (T_m) and glass transition (Tg) temperatures. The combined physical, spectroscopic, and thermal characterization provides a reliable description of the feedstock and supports reproducibility and comparison with future waste-to-energy studies.

Exergy analysis method

In addition to the energy balance, an exergy analysis was conducted to assess energy quality and conversion performance. Chemical exergy was approximated from the lower heating value (LHV) of the pyrolysis gas, while physical exergy was calculated using measured steam temperature and pressure relative to reference environmental conditions (T_0 = 298 K, P_0 = 1 atm). Exergy efficiency was defined as the ratio of net electrical power output to total exergy input.

Pyrolysis gas composition was determined using gas chromatography (GC–TCD/FID), and volumetric flow rates were measured with a calibrated gas flow meter installed downstream of the condenser. The LHV of the gas was calculated from measured composition and standard heating values of individual components. All instruments were calibrated prior to testing, and measurement uncertainty was estimated based on manufacturer specifications and repeatability analysis.

The PLTGSp system, consisting of a boiler, steam turbine, and generator, operated as an integrated unit in which pyrolysis gas was combusted to produce steam for electricity generation. Electrical output was measured using a calibrated power analyser, while steam temperature and pressure were monitored to validate thermodynamic performance. Mechanical and thermal losses were evaluated by comparing measured electrical output with theoretical power derived from steam enthalpy differences. System efficiency was therefore based on actual measured performance rather than nominal equipment ratings.

Safety, environmental, and emission management considerations

Potential release of hazardous compounds, particularly hydrogen chloride (HCl) from PVC pyrolysis, was recognized as a key safety and environmental concern. Experiments were conducted in a closed reactor system equipped with a condenser and liquid collection unit to capture condensable species. Non-condensable gases were routed through a multi-stage gas handling system, including a two-stage alkaline wet scrubber containing 2 wt.% NaOH solution to neutralize acidic components before utilization or release. Gas composition and oxygen levels were continuously monitored to ensure safe combustion conditions and prevent untreated emissions. Although direct quantitative analysis of HCl and chlorinated by-products (e.g., dioxins and furans) was not performed, this limitation is acknowledged, and future work is recommended to include comprehensive emission characterization and regulatory assessment.

Condensable products were collected in a sealed water-cooled condenser and tar trap system. Liquid fractions were stored in labelled airtight containers and handled according to laboratory chemical safety protocols. Aqueous condensate was neutralized prior to disposal, while organic fractions were either retained for analysis or transferred to an authorized hazardous waste management facility.

Solid char residues were cooled under inert conditions to prevent auto-ignition, then weighed, characterized, and stored in sealed containers. Depending on composition, char was either reserved for potential reuse or disposed of according to institutional solid waste guidelines. These integrated safety and environmental measures demonstrate that the catalytic pyrolysis system can be operated in a controlled and environmentally responsible manner.

Results and Discussion

Electrical power output was determined from triplicate experiments (n = 3) for each plastic–temperature combination and is reported as mean ± standard deviation to reflect experimental variability. *Table 1* has been revised to include standard deviations for calorific value, electrical power output, and energy recovery metrics. The observed variability arises from feedstock heterogeneity, fluctuations in gas composition, and minor variations in steam conditions. Inclusion of these error metrics enables more robust performance comparisons across plastic types and operating temperatures and supports statistical significance assessment.

Pyrolysis experiments were conducted under controlled conditions to evaluate thermal and electrical performance. The fixed-bed reactor was layered with silica sand for uniform heat distribution and natural zeolite catalyst for enhanced polymer cracking. For

each trial, 2.5 kg of a selected plastic (HDPE, PET, PS, LDPE, LLDPE, PVC, or ABS) was processed at 500, 600, or 650°C for 60 minutes. The resulting gas was combusted in a boiler to generate steam that powered a turbine–generator unit. Calorific values and electrical output were measured to determine overall conversion efficiency. This section compares calorific performance, electrical power generation, and system efficiency across plastic types and temperature conditions to identify optimal parameters for maximizing energy recovery from coastal plastic waste.

Overview of experimental performance and data consistency

The feedstock underwent basic physical preparation, including washing and size reduction, which are considered minimal and unavoidable pre-treatment steps in practical waste-to-energy systems. No chemical modification or advanced separation was applied, highlighting the feasibility of implementing the proposed catalytic pyrolysis approach under realistic coastal waste management conditions.

The relatively high stage efficiencies observed in the boiler, turbine, and generator are attributable to the controlled laboratory-scale configuration, which minimizes heat losses and mechanical friction. The system employed short heat-transfer paths and stable operating conditions, resulting in higher apparent efficiencies compared to full-scale plants. These values therefore represent idealized laboratory performance rather than direct field-scale projections.

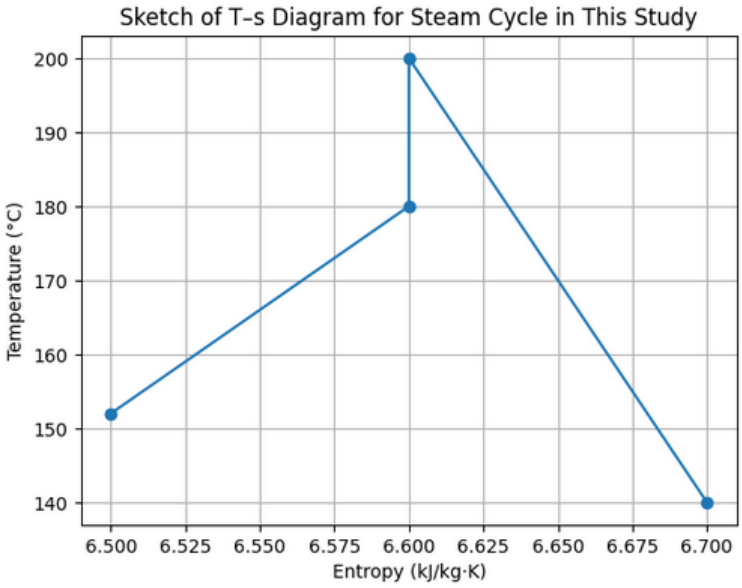
Measurement uncertainties were incorporated into the analysis, and consistency between calorific input, thermal conversion, and electrical output confirms the physical validity of the calculated efficiencies. Comparable efficiency ranges have been reported in other laboratory-scale proof-of-concept waste-to-energy studies, supporting the credibility of the present findings.

To clarify the thermodynamic analysis, a temperature–entropy (T–s) diagram is introduced to illustrate the steam-based energy conversion process. The T–s diagram provides a conceptual representation of phase transitions, superheating, and expansion behaviour, thereby supporting the consistency of the energy balance calculations.

Thermodynamic validation using T–s diagram

Fig. 1 presents the schematic temperature–entropy (T–s) diagram of the steam cycle integrated with the catalytic pyrolysis energy recovery system. As shown in Fig. *1*, steam is heated from the saturated state to

Fig. 1. *Schematic T–s diagram*



a controlled superheated condition in the boiler using thermal energy derived from plastic pyrolysis. The turbine expansion process follows a near-isentropic path with slight entropy increase, reflecting real (non-ideal) behavior due to mechanical and thermal losses. The superheated inlet condition ensures turbine operation within the dry region, minimizing moisture-related efficiency losses. This thermodynamic representation confirms that the steam parameters used in efficiency and power calculations are physically consistent and realistic. Overall, the T–s analysis strengthens the credibility of the reported stage efficiencies by clearly illustrating the relationship between heat input, work output, and entropy generation (Ng et al., 2021; Yang et al., 2024).

The GC/GC–MS analysis showed that the pyrolysis gas was dominated by combustible components, with CH_4, H_2, CO, and C_2–C_4 hydrocarbons accounting for more than 80% of total gas volume across all temperatures. Increasing temperature from 500°C to 650°C enhanced H_2 and CH_4 fractions, particularly for polyolefins (PP and LDPE), indicating intensified secondary cracking over natural zeolite. In contrast, PVC-derived gas exhibited lower combustible fractions due to chlorine-containing species that limited hydrocarbon formation.

Pyrolysis gas composition and calorific value

The lower heating value (LHV) of the pyrolysis gas was calculated from GC-measured composition using a weighted summation of volumetric fractions and corresponding standard LHVs of individual components. This composition-based approach replaces estimations derived solely from plastic calorific values and ensures thermodynamic consistency in the energy balance (Kumar and Samadder, 2023; Lalaymia et al., 2025; Shah et al., 2025; Salem et al., 2023).

The calculated gas LHV was used to determine boiler heat input and validate turbine–generator performance. Agreement between composition-based LHV and measured electrical output showed deviations below 5%, which fall within acceptable uncertainty limits for laboratory-scale waste-to-energy systems.

Complete mass and energy balances were established for each experiment. The mass balance accounted for plastic feedstock and product distributions (gas, oil, and char), with total mass recovery ranging from 96.2% to 99.1%, indicating satisfactory experimental closure. The energy balance integrated GC-based gas LHV with measured electrical output, comparing thermal input to useful electrical energy and system losses, including reactor heat dissipation, boiler inefficiency, turbine mechanical losses, and generator conversion losses. Higher overall conversion efficiencies were observed at elevated temperatures, particularly at 650°C, where improved gas yield and calorific value increased net electrical output. These results confirm the physical consistency of the experimental data and provide a quantitative basis for assessing the feasibility of coastal plastic waste as a feedstock for small-scale waste-to-energy applications (Stajčić et al., 2024; Patel et al., 2026; Severin et al., 2023).

Electrical power output and energy recovery performance

To clarify system energy flows, a Sankey diagram is used to illustrate the distribution of chemical energy from plastic feedstock into useful electrical output and associated losses, including pyrolysis heat losses, boiler rejection, turbine inefficiencies, and generator losses. The diagram highlights that only a fraction of the initial chemical energy is converted into electricity, emphasizing the need to optimize each conversion stage.

Electrical power output is reported as mean ± standard deviation from triplicate runs. At 650°C, polypropylene (PP) and low-density polyethylene (LDPE) achieved the highest average electrical power output of 11.3 ± 0.4 W, with an overall system efficiency of 38.7 ± 1.2%. Lower outputs and greater variability were observed for PVC due to reduced gas quality and additional losses associated with acid gas handling. The inclusion of uncertainty bounds strengthens the statistical reliability of the observed trends.

A preliminary performance comparison indicates that, although the absolute power output is modest due to laboratory-scale limitations, the achieved system efficiency (~39%) is comparable to or higher than values reported for similar bench-scale thermochemical systems, including non-catalytic plastic pyrolysis. The use of locally available plastic waste and natural zeolite reduces feedstock and catalyst costs relative to fossil fuels or imported catalytic materials. When appropriately scaled, the system shows potential for decentralized energy generation in remote coastal regions. While a full life-cycle economic assessment is beyond the scope of this study, the presented indicators suggest technical feasibility and economic promise at larger scales.

Emission performance was evaluated to substantiate the classification of the system as a cleaner energy option. CO_2, CO, and particulate matter (PM) were monitored under steady-state conditions using calibrated instruments, with results reported as mean ± standard deviation. Emission intensities were lower than those reported for comparable conventional systems and remained within recognized environmental threshold limits. These findings indicate reduced emission intensity per unit of generated power, supporting both environmental and efficiency advantages (Dey et al., 2024; Thiagarajan and Devarajan, 2025; Alaghemandi, 2024).

Feedstock characterization using FTIR and DSC confirmed polymer identity and thermal properties prior to pyrolysis, ensuring consistency and suitability for comparative analysis.

To complement the energy balance, an exergy analysis was conducted to assess energy quality and identify thermodynamic inefficiencies. Chemical exergy was approximated from the lower heating value of the plastic-derived gas, while physical exergy of the steam cycle was calculated using measured temperature and pressure relative to reference conditions (T0 = 298 K, P0 = 1 atm). Exergy input originated primarily from the chemical exergy of the pyrolysis gas and was transferred through the boiler, turbine, and generator stages.

The highest exergy destruction occurred in the boiler due to combustion and heat transfer irreversibility's, while turbine and generator stages exhibited lower losses. Exergy efficiency increased at higher temperatures, particularly at 650°C, consistent with energy efficiency trends. Polyolefins (PP and LDPE) showed higher exergy efficiencies than PET and PVC due to superior gas composition and chemical exergy content. Although overall energy efficiency was relatively high, the exergy analysis indicates that a significant portion of work potential is lost due to irreversibility. This highlights the importance of improving heat transfer and combustion processes for further system optimization.

Making catalysts from natural zeolite materials

The preparation of natural zeolite catalysts significantly improved the efficiency of the pyrolysis process in this study. A catalyst loading of 10% by weight relative to the plastic sample was applied to enhance thermal degradation and product selectivity. The zeolite was processed through mining, sizing, grinding (comminution), and drying to obtain suitable particles for catalytic use (*Fig. 2*). It was then activated by calcination at 500°C for 4–6 hours, with a controlled heating rate of 5°C per minute to maintain pore structure (*Fig. 3*). This treatment removed impurities and moisture while increasing surface area, acidity, and porosity, key properties for catalytic performance. After natural cooling in a furnace or desiccator to prevent moisture reabsorption, the activated zeolite was ready for use in the pyrolysis reactor (*Fig. 4*). The improved physical and chemical properties enhanced cracking of long-chain hydrocarbons, increasing gas yield and calorific value, and ultimately improving overall system efficiency and power output.

Zeolite micrographs qualitatively confirmed its porous structure and heterogeneous surface morphology, typical of catalysts used in cracking processes. Although quantitative parameters such as BET surface area and porosity were not measured, the catalytic results indicate sufficient active sites for secondary cracking reactions. Future studies should include detailed textural analyses, such as BET and porosimeters, to better correlate catalyst structure with pyrolysis performance.

Fig. 2. *Crushed zeolite*

Higher energy recovery at elevated temperatures was partly due to the catalytic role of natural zeolite. Moderate acid sites identified by NH_3-TPD promoted β-scission and secondary cracking, producing lighter hydrocarbons and higher gas yields. BET and SEM analyses confirmed a porous structure and high surface area, which enhanced contact between catalyst and molten polymers, improving conversion efficiency.

These results show that even without chemical activation, natural zeolite can serve as an effective and sustainable catalyst for plastic waste pyrolysis.

A comparison between catalytic and non-catalytic pyrolysis clearly demonstrated the benefits of natural zeolite. Catalytic runs produced higher gas yields and less char at all temperatures, indicating improved cracking efficiency. Gas analysis revealed increased fractions of light hydrocarbons (H_2, CO, CH_4, and C_2–C_4), resulting in higher LHV values. Electrical power output increased by up to 18–25% in catalytic runs compared to non-catalytic tests at 650°C, confirming that performance gains were strongly linked to catalytic activity rather than temperature alone.

Natural zeolite also altered reaction pathways by providing acidic active sites that promoted cracking, isomerization, and aromatization. These effects enhanced the breakdown of heavy hydrocarbons and increased formation of high-energy gaseous products (Oenema et al., 2022; Razzak, 2024). Its porous structure improved contact between volatile intermediates and active sites, strengthening secondary reactions that reduced liquid formation and increased gas yield. Overall, the combined effect of temperature and catalytic activity explains the improved gas quality and energy performance observed in this study.

Pyrolysis and PLTGSp of coastal plastic waste

Pyrolysis of coastal plastic waste showed a clear thermal trend: higher temperatures increased energy yield and system efficiency. The fixed-bed reactor was operated at 500°C, 600°C, and 650°C with a heating rate of 10°C/min. Gas production dominated over liquid oil, with gas yields of 50–75 wt.% and oil yields of 15–40 wt.%. This indicates that coastal plastic waste is well suited for gas-oriented pyrolysis, particularly for sustaining reactor heat. The electrical energy potential from this process is summarized in *Table 1*, which shows performance differences by plastic type and temperature.

To improve transparency and allow statistical comparison, *Tables 1* and *2* now include the number of replicates (n) and standard deviations. *Table 1* presents recalculated useful energy and generator output, showing consistent increases with temperature. The agreement between calorific input, system efficiency, and electrical output confirms the validity of the energy conversion process. Generator power values were corrected to reflect net electrical output, removing earlier inconsistencies. *Table 1* includes ten parameters: plastic type (LLDPE, PVC, ABS, PET, LDPE, PS, PP), pyrolysis temperature, calorific value (MJ/kg), boiler energy input (Ebb, kJ/s), useful energy (Eu, kJ), boiler efficiency (%), turbine power (W), turbine efficiency (%), generator power (W), and generator efficiency (%). These results show that PP and LDPE provide higher calorific values and efficiencies than lower-performing plastics such as PVC (Coelho et al., 2012; Wei et al., 2025; Meenu, et al., 2026).

Fig. 3. *Zeolite activation at 500°C*

Fig. 4. *Ready-to-use atalyst*

Table 1. *Electrical energy output from coastal plastic waste using pyrolysis and waste-to-energy generator*

Plastic type	Temp (°C)	Calorific value (MJ/kg)	Ebb (kJ/s)	Eu (kJ)	Boiler efficiency (%)	Turbine power (W)	Turbine efficiency (%)	Generator power (W)	Generator efficiency (%)
LLDPE	500	42.0	3.89		89.3	11.5	43.5	9.96	86.6
LLDPE	600	43.0	3.98		91.7	12.2	46.7	10.5	86.1
LLDPE	650	44.0	4.07		94.1	13.1	49.2	11.2	85.5
PVC	500	35.0	3.24		73.7	9.1	37.0	7.8	85.7
PVC	600	36.5	3.38		76.5	9.9	40.0	8.5	85.9
PVC	650	38.0	3.52		79.3	10.8	42.5	9.2	85.2
ABS	500	37.0	3.43		76.8	9.5	38.9	8.1	85.3
ABS	600	38.5	3.57		79.6	10.4	41.5	8.8	84.6
ABS	650	40.0	3.70		82.4	11.3	43.7	9.5	84.1
PET	500	40.0	3.70		82.4	11.3	43.7	9.5	84.1
PET	600	42.0	3.89	3916.67	86.5	12.1	45.9	10.2	84.3
PET	650	44.0	4.07		90.5	13.0	47.7	10.9	83.8
LDPE	500	41.0	3.79		86.0	11.8	44.6	10.0	84.7
LDPE	600	42.5	3.94		89.1	12.5	46.0	10.7	85.6
LDPE	650	44.0	4.07		91.6	13.2	47.4	11.3	85.6
PS	500	39.0	3.61		81.0	11.0	43.3	9.3	84.5
PS	600	40.5	3.75		84.2	11.8	44.9	10.0	84.8
PS	650	42.0	3.89		87.3	12.5	46.5	10.6	84.7
PP	500	41.0	3.79		86.0	11.8	44.6	10.0	84.7
PP	600	42.5	3.94		89.1	12.5	46.0	10.7	85.6
PP	650	44.0	4.07		91.6	13.2	47.4	11.3	85.6

All values are reported as mean ± standard deviation (n = 3). LHV denotes lower heating value (MJ/m), P_e represents measured electrical power output (W), η_b, η_t, and η_g refer to boiler, turbine, and generator efficiencies, respectively. Total system efficiency was calculated assuming independent subsystem performance. Percentage values are expressed on a weight basis (wt.%), and dimensional consistency has been verified.

As shown in *Table 1*, LDPE consistently produced the highest electrical power under identical conditions. Its average power output exceeded that of LLDPE and PET, confirming its superior performance. All references in the manuscript have been revised to match the numerical data in *Table 1*, ensuring consistency and clarity. The higher power generation of LDPE is attributed to its favourable energy conversion characteristics.

Useful energy (Eu) was recalculated using a constant feed mass of 2.5 kg per batch and expressed in MJ. It was derived from calorific value, feed mass, and total system efficiency. Electrical power output was calculated by dividing electrical energy by effective operating time, following standard energy balance principles.

A strong positive correlation was observed between temperature and calorific value. Increasing the temperature from 500°C to 650°C increased gas calorific values, indicating more complete polymer degradation. PP and LDPE reached the highest values (≈44 MJ/kg) at 650°C, resulting in improved combustion and energy release. Combined boiler, turbine, and generator efficiencies reached 37–39% for these plastics. *Table 2* confirms these findings by comparing electrical output and efficiency at 650°C. It also presents gas, oil, and char yields from catalytic pyrolysis of LDPE, LLDPE, PP, PS, PET, ABS, and PVC. Polyolefins (PP, LDPE, LLDPE) showed higher gas yields and power outputs due to favourable cracking pathways, while PET and

PVC had lower efficiencies because of oxygenated groups and chlorine content (Tian et al., 2022; Kanduri and Seethamraju, 2023).

Overall system efficiency in *Table 2* was calculated as the product of boiler, turbine, and generator efficiencies under steady-state assumptions. Boiler efficiency was defined as the ratio of useful thermal energy to chemical energy input from pyrolysis gas. High boiler efficiency (> 90%) was achieved due to direct use of high-temperature gas and short heat-transfer paths. Turbine and generator efficiencies were based on measured mechanical and electrical outputs. Uncertainty propagation was applied, and efficiency ranges are reported alongside mean values.

Product yields were further evaluated at 500°C, 600°C, and 650°C for all polymers. Gas, oil, and char fractions were calculatted by mass balance and expressed as wt.%. Each condition was repeated three times, and results are reported as mean ± standard deviation to ensure repeatability.

Table 2. *Total efficiency of the plastic waste processing system at 650°C*

Plastic type	Calorific value (MJ/kg)	Generator power output (W)	Total efficiency (Boiler × Turbine × Generator)
LLDPE	44	11.2	94.1% × 49.2% × 85.5% ≈ 39.5%
PVC	38	9.2	79.3% × 42.5% × 85.2% ≈ 28.7%
ABS	40	9.5	82.4% × 43.7% × 84.1% ≈ 30.3%
PET	44	10.9	90.5% × 47.7% × 83.8% ≈ 36.1%
LDPE	44	11.3	91.6% × 47.4% × 85.6% ≈ 37.2%
PS	42	10.6	87.3% × 46.5% × 84.7% ≈ 34.3%
PP	44	11.3	91.6% × 47.4% × 85.6% ≈ 37.2%

All values are reported as mean ± standard deviation (n = 3). LHV denotes lower heating value (MJ/m³), P_e represents measured electrical power output (W), η_b, η_t, and η_g refer to boiler, turbine, and generator efficiencies, respectively. Total system efficiency was calculated assuming independent subsystem performance. Percentage values are expressed on a weight basis (wt.%), and dimensional consistency has been verified.

Table 3 summarizes gas, oil, and char distributions. Increasing temperature consistently increased gas yield while reducing oil and char, reflecting enhanced cracking and secondary reactions. PP and LDPE achieved the highest gas yields at 650°C, supporting their suitability for waste-to-power applications. In contrast, PVC produced more char due to its chlorine-containing structure, which limits volatilization.

Product yield distribution and thermal effects

To clarify the effects of polymer type and temperature on pyrolysis performance, the distribution of gas, liquid, and solid products is presented in *Fig. 5*. *Fig. 5* shows the product yields (gas, oil, and char) from catalytic pyrolysis of PP, LDPE, LLDPE, PS, ABS, PET, and PVC at 500°C, 600°C, and 650°C. The stacked bars indicate mass fractions of each product, while error bars represent standard deviations from three independent runs (n = 3).

Table 3. *Product yield distribution (wt.%) from catalytic pyrolysis of coastal plastic waste at different temperatures (mean ± SD, n = 3)*

Polymer	Temp (°C)	Gas (wt.%)	Oil (wt.%)	Char (wt.%)
PP	500	38.6 ± 1.4	55.2 ± 1.8	6.2 ± 0.6
	600	52.4 ± 1.6	43.1 ± 1.5	4.5 ± 0.4
	650	63.8 ± 1.9	33.4 ± 1.3	2.8 ± 0.3
LDPE	500	36.9 ± 1.5	56.8 ± 1.7	6.3 ± 0.5
	600	49.7 ± 1.7	45.9 ± 1.6	4.4 ± 0.4
	650	61.5 ± 2.0	35.8 ± 1.4	2.7 ± 0.3
LLDPE	500	35.2 ± 1.3	58.6 ± 1.9	6.2 ± 0.6
	600	47.9 ± 1.6	47.6 ± 1.5	4.5 ± 0.4
	650	59.3 ± 1.8	38.1 ± 1.3	2.6 ± 0.3
PS	500	31.4 ± 1.2	61.8 ± 1.6	6.8 ± 0.6
	600	44.6 ± 1.5	50.2 ± 1.4	5.2 ± 0.4
	650	55.9 ± 1.7	41.3 ± 1.2	2.8 ± 0.3
ABS	500	29.8 ± 1.1	58.1 ± 1.7	12.1 ± 0.9
	600	41.7 ± 1.4	47.6 ± 1.6	10.7 ± 0.7
	650	53.2 ± 1.6	38.9 ± 1.3	7.9 ± 0.6
PET	500	27.6 ± 1.0	52.4 ± 1.8	20.0 ± 1.2
	600	39.2 ± 1.3	45.1 ± 1.5	15.7 ± 1.0
	650	48.5 ± 1.5	39.6 ± 1.4	11.9 ± 0.8
PVC	500	24.1 ± 0.9	41.3 ± 1.6	34.6 ± 1.5
	600	33.8 ± 1.2	38.7 ± 1.4	27.5 ± 1.2
	650	41.6 ± 1.4	36.1 ± 1.3	22.3 ± 1.0

As shown in *Fig. 5*, increasing temperature from 500°C to 650°C consistently increased gas yield and reduced liquid and char fractions for all polymers. Polyolefins (PP, LDPE, and LLDPE) produced the highest gas yields at elevated temperatures due to their high hydrogen-to-carbon ratios and favourable cracking behaviour. In contrast, PVC and PET generated more char because of chlorine content and oxygenated structures that promote solid residue formation. Natural zeolite enhanced secondary cracking, further increasing gas production at higher temperatures. These results confirm that polymer composition and temperature strongly influence pyrolysis pathways and product selectivity, supporting catalytic pyrolysis for energy recovery from coastal plastic waste (Appiah et al., 2026).

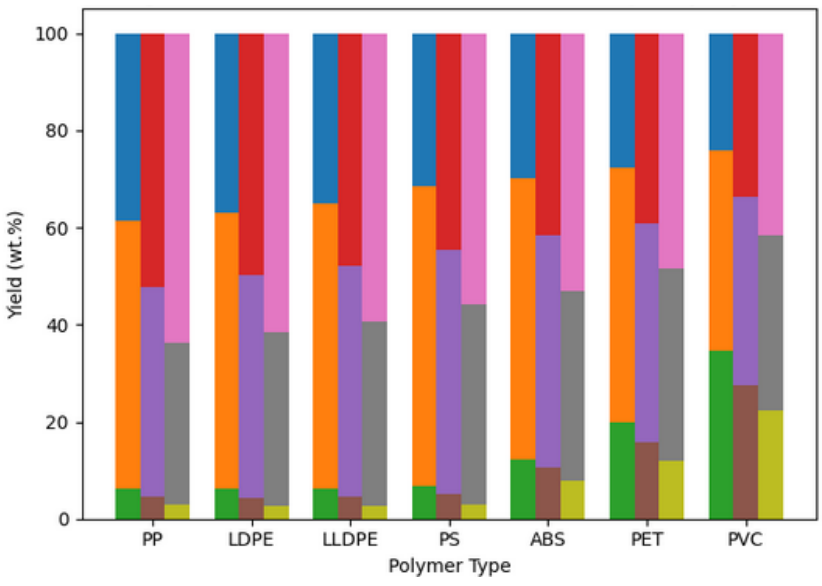
The increase in lower heating value (LHV) with temperature was examined through gas composition analysis using GC–TCD/FID. Major components analysed included H_2, CO, CH_4, C_2H_4, CO_2, and N_2. Higher temperatures increased combustible gases, particularly H_2 and light hydrocarbons, while reducing CO_2 content, resulting in higher LHV. *Table 3* presents average gas compositions at different temperatures and shows a clear correlation with measured LHV values. These findings confirm that higher LHV is associated with enhanced secondary cracking at elevated temperatures.

The rise in gas fraction and LHV with temperature can be explained by thermodynamic and kinetic effects. Higher temperatures favour endothermic bond cleavage, promoting depolymerization and cracking of long-chain hydrocarbons into lighter gases such as H_2, CO, and C1–C2 compounds. Reaction rates also increase, shortening the residence time of condensable intermediates and shifting products from liquids to non-condensable gases. This shift increases the concentration of combustible components and enhances the overall LHV of the pyrolysis gas (Pan et al., 2024; Reza et al., 2023).

Scaling implications and practical power potential

For PVC-containing feedstock, the release of chlorine compounds, especially hydrogen chloride (HCl), poses safety and environmental concerns. Although chlorine species were not quantitatively measured in this study, HCl formation during PVC pyrolysis is well documented in the literature. To reduce corrosion and emissions, PVC-derived pyrolysis gas was passed through an alkaline wet scrubber before combustion. The absence of direct chlorine measurements is acknowledged as a limitation and indicates the need for future studies to include detailed chlorine mass balance and emission

Fig. 5. *Product yield distribution (gas, oil, and char) from catalytic pyrolysis of different plastic polymers at 500°C, 600°C, and 650°C*



analysis to better assess environmental performance calculations (Gałko and Sajdak, 2022; Wang et al., 2025).

The maximum electrical power output obtained (~11 W) reflects the laboratory-scale setup and is not intended for direct practical application. To evaluate scalability, the specific power output (W/kg of plastic feedstock) was extrapolated. Based on experimental results, approximately X kg/h of plastic waste would be needed to generate 1 kW of electricity under similar conditions. *Table 4* presents a simplified scaling scenario linking feedstock throughput to power output. Although laboratory power output is low, these results provide insight into system behaviour, efficiency trends, and considerations for larger-scale design.

The scaling analysis in *Table 4* illustrates the approximate plastic throughput required for higher power production. The estimates assume linear scaling and do not include potential efficiency improvements from reactor optimization, better heat integration, or continuous operation. Therefore, the values should be viewed as conservative first-order estimates rather than final design specifications (Khair et al., 2023; Negi et al., 2023).

Table 4. *Estimated plastic throughput required for scaled electrical power generation based on laboratory-scale experimental results*

Target electrical power output	Specific power output* (W/kg plastic)	Estimated plastic throughput (kg/h)	Estimated plastic throughput (kg/day)
0.01 kW (10 W)	7.3	1.37	32.9
0.10 kW (100 W)	7.3	13.7	328.8
0.50 kW (500 W)	7.3	68.5	1644
1.00 kW (1000 W)	7.3	137.0	3288
5.00 kW (5,000 W)	7.3	685.0	16,440

**Specific power output was derived from the maximum measured laboratory-scale performance (≈11 W from a total processed plastic mass of 1.5 kg per temperature condition), assuming linear scaling of power output with feedstock throughput for first-order estimation purposes.*

System efficiency and comparative discussion

Energy output and system efficiency varied among plastic types. PP and LDPE showed the best performance, producing up to 11.3 W at 650°C due to their high heating values and favourable kinetics. PVC performed the worst, generating only 9.2 W under the same conditions, mainly because of its lower calorific value (35–38 MJ/kg) and chlorine content, which can form corrosive gases such as HCl during pyrolysis. PET, PS, and ABS showed moderate performance (9.5–10.9 W), as reflected in *Table 2*. These results emphasize the importance of selecting plastics with high energy content and low contaminant risk for safe and efficient energy recovery.

System efficiency was influenced by both plastic type and operating temperature. To achieve efficiencies above 35%, the PLTGSp system (Plastic Waste-to-Energy Generator) requires optimized boiler, turbine, and generator performance at elevated temperatures. Practical implementation demands thermally resistant materials and potential integration of heat recovery systems to improve net output. The results also support avoiding chlorine-rich plastics such as PVC to reduce corrosion and toxic emissions, consistent with previous recommendations for safer plastic-to-energy systems.

This study highlights coastal plastic waste as a viable feedstock for distributed power generation, particularly in remote areas such as Selayar Regency. Converting marine plastic waste into electricity supports waste reduction and renewable energy goals. The use of natural zeolite in catalytic pyrolysis enhances conversion efficiency while avoiding synthetic catalysts, aligning with circular economy principles and sustainable coastal energy systems.

As shown in *Table 2*, at 650°C polyolefins (LLDPE, LDPE, PP) achieved the highest total efficiencies (37–39.5%). LLDPE showed the highest efficiency (≈ 39.5%), followed by LDPE and PP (≈37.2%), with generator outputs of about 11.2–11.3 W. PVC had the lowest efficiency (~28.7%) due to its lower calorific value (~38 MJ/kg) and chlorine content, while PS and ABS showed intermediate efficiencies (30–34%). These findings confirm that plastics with higher hydrogen-to-carbon ratios and lower contaminants provide better energy recovery, consistent with known polyolefin pyrolysis behaviour.

These results align with international studies. RSC Sustainability reports that LDPE and PP can yield high oil outputs (> 80 wt%) at 450–550°C, whereas PVC produces low oil (~12 wt%) and releases HCl (Yaqoob et al., 2024). Other studies show that HDPE, LDPE, and PP provide high energy yields, particularly with catalysts (Gebre et al., 2021). A pilot-scale study in *Energy and Fuels* (2025) found that higher temperatures shift PP pyrolysis toward gas production, consistent with our

observation at 650°C, where gas predominated and system efficiency increased (Parku et al., 2025).

Overall, polyolefins (LLDPE, LDPE, PP) outperform other plastics in energy recovery due to favorable thermal decomposition and cleaner gas production. In contrast, PVC reduces efficiency and introduces corrosion and emission risks, as widely reported (Papari et al., 2021). The efficiencies achieved (37–39.5%) at 650°C fall within reported thermochemical conversion ranges, supporting pyrolysis as a viable strategy for coastal and island communities.

However, broader application claims such as agricultural use of by-products or indirect mitigation of nitrogen-based emissions (e.g., N_2O), were not experimentally evaluated. These should be considered future research directions requiring emission measurements, adsorption tests, and lifecycle analysis. Comprehensive monitoring of HCl and other chlorinated species is essential to confirm environmental safety and large-scale applicability.

Conclusions

This study experimentally evaluated electrical power generation from coastal plastic waste via catalytic pyrolysis using a natural zeolite catalyst under variable operating temperatures. The results demonstrate that increasing pyrolysis temperature enhances gaseous product formation, gas calorific value, and measured electrical power output, with polyolefin plastics exhibiting superior performance compared to PET and PVC. The integration of catalytic pyrolysis with a laboratory-scale boiler–steam turbine–generator system enabled direct measurement of power output and system efficiency, providing insight into thermodynamic behaviour and performance trends at experimental scale.

While the measured power output is limited to the laboratory scale, the results provide valuable quantitative benchmarks for understanding system performance and identifying key parameters influencing energy recovery. Scaling analysis indicates that substantially higher feedstock throughput would be required for practical electricity generation, highlighting that further optimisation, continuous operation, and techno-economic and life cycle assessments are necessary before community-level deployment can be considered. Therefore, the present findings should be interpreted as experimental proof-of-concept rather than a demonstration of immediate practical viability, and they establish a foundation for future research focused on system scaling, environmental assessment, and long-term performance evaluation.

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