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Calorific value analysis of coastal plastic waste for electric power generation in Selayar Islands

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Abstract: The electricity reserve in the South and Southeast Sulawesi (SULBAGSEL) region in March 2024 was only 167.01 MW, indicating a potential energy crisis. Selayar Islands Regency, with an electrification ratio of just 57%, is among the lowest in South Sulawesi. With a population of 140,312 and household waste production of 25,774 tons per year, the region also faces serious waste management challenges. Notably, coastal plastic waste contributes around 2.179 tons per day. This study aims to analyze the potential for generating electrical energy from coastal plastic waste based on its calorific value. The analysis was conducted using proximate analysis, followed by energy potential estimation using both traditional and Bento methods. The results show that polystyrene (PS) has the highest energy potential at 733,297 kWh/year, while low-density polyethylene (LDPE) has the lowest at 514,140 kWh/year. The findings confirm that higher net calorific value (NCV) corresponds to greater electricity generation potential. The novelty of this study lies in integrating coastal plastic waste profiling with energy conversion analysis specific to a remote island context. As a recommendation, further research should explore the development of small-scale waste-to-energy facilities tailored to isolated coastal areas such as the Selayar Islands.

Keywords: *Calorific value, Coastal plastic waste, Electrical energy.*

1. Introduction

Indonesia is currently facing a serious challenge in the form of an electric energy crisis [1]. The growing demand for electricity is not being met by a proportional increase in power generation capacity, leading to a substantial energy shortfall [2, 3]. This issue is particularly evident in remote regions, including several areas within South Sulawesi Province, where many communities still lack access to electricity. As of March 2024, the available electricity reserve in the southern Sulawesi region (SULBAGSEL) stands at just 167.01 MW, reflecting the province's critical energy condition.

Three regencies in South Sulawesi Province—Jeneponto, Pangkep, and the Selayar Islands—have the lowest electrification ratios. The Selayar Islands, in particular, have an electrification rate of only 57%. This low level of electrification is mainly due to the fact that many villages are located on remote islands and in mountainous areas. However, these remote regions possess abundant natural resources such as water, wind, and solar energy, which offer significant potential for electricity generation. The government has undertaken numerous initiatives to conserve energy while also encouraging the advancement of new and renewable energy sources [4]. Among the alternative energy options receiving increasing attention is the utilization of plastic waste and biomass as fuel for power generation [5]. This strategy not only helps in managing plastic waste but also offers a promising solution to the escalating energy crisis, especially in remote and underserved areas [6].

Plastic waste is notoriously resistant to decomposition, often requiring an exceptionally long time to break down naturally [7]. In addition to its persistence, plastic waste poses serious threats to human health, the environment, and socio-economic well-being. Indonesia is currently the world's second-

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largest source of plastic waste, producing around 175,000 tons of it each day [8, 9]. The most commonly encountered types of plastic waste in urban environments include PET, HDPE, PVC, LDPE, and PP. The increasing use of plastic across multiple sectors—especially in households—has significantly accelerated the buildup of plastic waste [10, 11]. Plastics are polymers made up of long chains of monomers. Fortunately, these polymers can be broken down through pyrolysis, a process that transforms them into liquid fuels such as kerosene, diesel, and gasoline [12, 13]. This method offers a promising dual benefit: effective plastic waste management and the generation of alternative energy.

Kedzierski, et al. [14] report that plastic waste degrades very slowly in nature, with the rate depending on both environmental conditions and the polymer's chemical structure. At the same time, Indonesia produces roughly 175,000 tons of plastic waste each day, a volume that poses a serious environmental threat not only to today's population but also to generations to come. To minimize the amount of plastic waste that pollutes the environment, recycling was originally seen as a viable management solution. However, it has become clear that recycling is both challenging and costly, primarily due to the high labor expenses involved in sorting the waste. According to the Indonesian Plastic Recycling Association (ADUPI), the elevated costs of acquiring recycled materials locally stem from the low quality of waste in Indonesia. Since waste is not separated at its source, additional labor is needed for sorting, further driving up costs [15, 16].

Figure 1.
Visual image of coastal plastic waste generation along the coastline of selayar islands regency.

In addition, the recycling process has the potential to cause river and sea water pollution, particularly when plastic waste is not properly managed. Plastics are produced from a variety of materials, each with unique properties and uses, which necessitates effective separation for proper recycling. One promising alternative technology for converting plastic waste into fuel for power plants is the pyrolysis process. Pyrolysis involves thermal cracking of plastic materials in the absence of oxygen, leading to the conversion of solid waste into liquid fuel and other valuable by-products. This process has garnered considerable attention due to its economic advantages and its potential to reduce environmental pollution. Not only does pyrolysis offer an effective way of managing plastic waste, but it also provides a renewable energy source, contributing to more sustainable power generation practices [17, 18].

A research gap exists in the exploration of utilizing coastal plastic waste as a potential source of electric power in the Selayar Islands Regency, particularly in relation to its calorific value. While plastic waste has been widely studied as an energy source in various regions globally, research specific to the coastal areas of the Selayar Islands is limited. The calorific value of plastic waste in this region, which is influenced by unique local environmental conditions and waste composition, remains largely unexplored.

This gap presents a significant opportunity for research, as understanding the specific characteristics of coastal plastic waste in this context could lead to more accurate assessments of its energy potential. Additionally, there is a pressing need to evaluate the feasibility of converting this waste into energy through methods such as pyrolysis or combustion, as well as to assess the economic and environmental implications of these processes. The novelty of this research lies in its focus on a specific geographic region—Selayar Islands—which has distinct environmental conditions that may influence the properties of plastic waste. The significance of this study is twofold: it not only offers a potential solution for the growing issue of plastic pollution, but it also addresses the region's increasing energy demands by exploring a sustainable, locally sourced energy solution. By filling these research gaps, this study could contribute valuable insights to the development of integrated waste-to-energy.

2. Research Method

2.1. Waste Sample Collection and Waste Characteristics Analysis through Laboratory Testing

The first step was to collect samples of plastic debris from homes and coastal areas for lab analysis to determine their chemical composition. Proximate analysis was conducted to assess the waste's characteristics. This included measuring water, ash, volatile solids, fixed carbon, and sulphur content using the gravimetric method. After preparing the samples, the proximate analysis was carried out at Hasanuddin University's Inorganic Laboratory in the Department of Mathematics and Natural Sciences.

The water content analysis was done using standard lab procedures. First, a clean porcelain cup was dried in an oven at 105°C for two hours. After cooling in a desiccator for 30 minutes, the cup was weighed (A grams). Then, about 1 gram of plastic waste was added, and the total weight was recorded (B grams). The sample was dried again in the oven at 105°C for eight hours or overnight. After that, it was cooled in a desiccator for 30 minutes and weighed again (C grams). The water content was determined by comparing the weight before and after drying.

$$\% \text{ water} = \frac{B-C}{B-A} \times 100\% \quad (1)$$

The ash content analysis was done to measure the non-combustible residue in the plastic waste sample. First, a clean porcelain cup was dried in an oven at 105°C for two hours, then cooled in a desiccator for 30 minutes and weighed (A grams). About 1 gram of plastic sample was added, and the total weight was recorded (B grams). The sample was then burned in a furnace at 650°C for three hours to remove all combustible material. After burning, the cup was cooled again in a desiccator for 30 minutes and weighed (C grams). The remaining material represents the ash content of the plastic.

$$\% \text{ ash} = \frac{C-A}{B} \times 100\% \quad (2)$$

$$\text{VM} = \left\{100 - \left(\frac{C-A}{B} \times 100\%\right)\right\} - \%water \quad (3)$$

Fixed Carbon Analysis, using the equation:

$$\text{FC} = 100 - (\%\text{water} + \%\text{ash} + \%\text{VM}) \quad (4)$$

The mathematical equation used in this study to obtain the potential utilization of electrical energy generated from plastic waste using the Traditional Method or Bento Method where the mathematical equation was as follows [19]:

Electrical Energy Potential:

Traditional Method:

NCVar = 45B – 6W

Bento Method:

NCVar = 44.75B – 5.85W + 21.2

Description:

NCVar = Net Calorific Value (kCal/kg)

B = Volatile Matter Content (%)
W = Water Content (%, adb)

Energy Recovery Potential (kWh):
= NCVar x W ton/day x 1,000 Kg/ton/ 860 kCal
= 1.16 Kg/ton kCal x NCVar x W

Energy Potential per Year (kWh):
= 1.16 x NCVar x W x 365
Note:
1 kWh = 860 kCal

Electrical Energy Potential:
= Energy Potential x nb x nt x ng
Note:
Nb = Boiler Efficiency
Nt = Steam Turbine Efficiency
Ng = Generator Efficiency

This study began with an inventory of plastic waste along the coastal areas of Selayar Islands Regency, where plastic debris frequently accumulates. Prior to determining sampling points, a preliminary survey was conducted to assess the current conditions of plastic waste buildup on the coastline. The study also included a broad and in-depth literature review focusing on the composition variables of plastic waste, including moisture content, ash, volatile matter, fixed carbon, and sulphur. Secondary data sources such as the internet, research reports, conference proceedings, and national and international journal articles were utilized to support the assessment of coastal plastic waste conversion into electricity using pyrolysis technology.

The primary data in this study were obtained from chemical laboratory tests on the composition of coastal plastic waste and its calorific value as a potential energy source. The types of plastic analysed included HDPE, PET, PP, LDPE, LLDPE, PVC, and ABS. The waste particles used ranged in size from 2–5 mm, with a moisture content of less than 10%. To reduce moisture, the plastic waste was dried under sunlight prior to testing. Moisture content was then measured using proximate analysis.

Figure 2.
Coastal plastic waste/trash sampling.

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2.2. Framework of Thinking

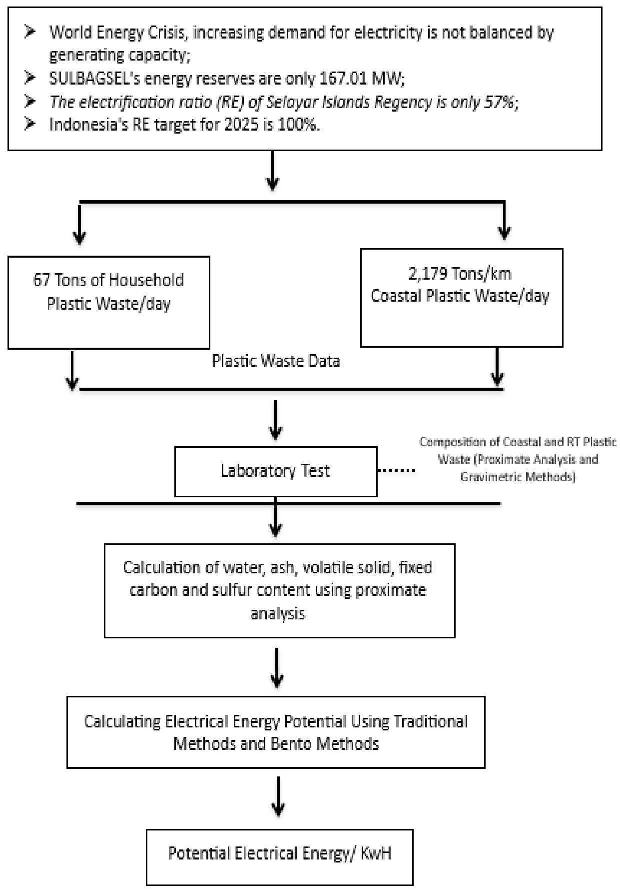

Figure 3.
Framework of thinking.

3. Results and Discussion

3.1. Proximate Analysis

Basically, various types of plastic have different compositions that can be known through proximate analysis. Proximate analysis can be defined as a technique for measuring the chemical properties of plastic compounds based on four elements, namely water content, fixed carbon, volatile content, ash content, and sulfur content. Volatile content and ash content are the main factors that affect the recovery of liquid oil in the pyrolysis process. High volatile materials lead to high liquid oil production, while high ash content decreases the amount of liquid oil, resulting in increased gas yield and char formation. These characteristics are obtained from gravimetric analysis with stoichiometric calculations. Proximate analysis is closely related to calorific value. The proximate characteristics of coastal plastic waste in Selayar Islands Regency according to its components are as shown in Table 1. Table 2 shows the results of proximal tests of household plastic waste based on its type, which are sourced from research developed by Kawai, et al. [20].

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Table 1.
Proximate test results of coastal plastic waste based on type.

No.	Sample Code	Composition					Calories (kCal/kg)
		Water	Ash	Volatile Matter	Fixed Carbon	Sulphur	
7	PS	0.40	1.21	98.18	0.21	0.241	4037
2	HDPE	1.08	0.56	95.49	2.87	0.076	4011
6	PP	3.77	0.73	93.87	1.64	0.181	3967
3	PVC	1.64	1.41	96.67	0.29	0.070	3964
4	LLDPE	4.40	0.86	93.39	1.36	0.182	3774
8	Others	21.10	3.86	71.91	3.13	0.091	3749
1	PET	6.89	5.33	79.97	7.82	0.051	3256
5	LDPE	0.90	0.26	98.65	0.18	0.122	3096

Table 2.
Proximate test results of household plastic waste based on type.

No.	Sample Code	Composition					Calories (kCal/kg)
		Water	Abu	Volatile Matter	Water	Sulphur	
2	HDPE	0	0.18	99.81	0.01	0.09	4320.72
3	PVC	3.3	4.9	90.9	1.1	0.17	3319.58
1	PET	0.9	2	96.6	0.5	0.09	2344.78
4	LLDPE	8.6	19	75	1.6	Not Available	Not Available
5	LDPE	8.2	18.4	74.2	1.8	Not Available	Not Available
6	PP	9	16.2	83.5	2.1	0.07	Not Available
7	PS	1.5	6.7	69.5	1.9	0.14	Not Available
8	Others	20	14.9	74.1	2.6	Not Available	Not Available

The results of the proximate test show that Volatile Matter, Water Content, and Calorific Value are the main factors influencing the potential electrical energy from each type of coastal plastic waste. Among all types, Polystyrene (PS) has the highest calorific value at 4,037 kCal/kg, while Low-Density Polyethylene (LDPE) has the lowest at 3,096 kCal/kg. However, LDPE has the highest Volatile Matter at 98.65%, and the lowest is found in "Others" plastic types at 71.91%. The results also show that higher water content in plastic waste leads to lower Volatile Matter levels. Compared to household plastic waste, coastal plastics like PVC, LLDPE, LDPE, PP, and PS have higher Volatile Matter, while PET, HDPE, and Others have lower Volatile Matter but also lower calorific values. This indicates that seawater affects the chemical structure of plastic waste. For PET and HDPE, seawater exposure reduces Volatile Matter by 5–16% and increases Fixed Carbon by up to 200%. On the other hand, for PVC, LLDPE, LDPE, PP, PS, and Others, Volatile Matter increases by 6–28%, but Fixed Carbon decreases by up to 2%.

A previous study by Andrady and Neal [21] showed that exposure to marine environments can lead to both physical and chemical degradation of plastic polymer structures, affecting their thermal composition [21]. This supports the findings of the current study, which indicate that seawater contamination can reduce the volatile matter content in PET and HDPE plastics while increasing their fixed carbon content. In contrast, plastics such as PVC, LDPE, and PS show an increase in volatile matter after exposure to seawater, suggesting that different polymers undergo distinct chemical reactions in marine conditions. Barnes, et al. [22] also noted that salt compounds and UV exposure in the ocean accelerate the breakdown of carbon chains in plastics, influencing their combustion properties and calorific value. Therefore, the thermal behavior changes in plastics due to seawater contamination must be considered when planning energy recovery from coastal plastic waste more accurately [22].

Based on the data above, we obtained calculation data for the potential energy that can be generated from each coastal plastic waste, namely:

Table 3.
Potential electrical energy based on type of coastal plastic waste/waste.

No.	Sample Type	Net Calorific Value (kCal/kg)			Electrical Energy Potential (kWh/year)
		Traditional	Bento	Lab Test Results	Minimum
7	PS	4.415,70	4.412,42	4.037	670.408
2	HDPE	4.290,57	4.288,06	4.011	666.090
6	PP	4.201,53	4.199,83	3.967	658.783
3	PVC	4.340,31	4.337,59	3.964	658.285
4	LLDPE	4.176,15	4.174,66	3.774	626.732
1	PET	3.557,31	3.559,55	3.256	540.710
8	Others	3.109,35	3.115,7	3.749	516.357
5	LDPE	4.433,85	4.430,52	3.096	514.140

Based on the calorific value test results shown in the table, PS (polystyrene) plastic waste has the highest net calorific value at 4.037 kCal/kg and the greatest minimum electrical energy potential at 670.408 kWh/year. This indicates that PS waste holds the highest potential as an alternative energy source compared to other plastic types. Conversely, LDPE (low-density polyethylene) has the lowest calorific value at 3.096 kCal/kg with an energy potential of 514.140 kWh/year. These findings are consistent with the study by Hopewell, et al. [23] which explained that plastics such as PS and PP typically contain higher energy content due to their dense carbon chain structures that are more readily decomposed under thermal processes [23]. The lower energy content in LDPE is also associated with its higher volatile matter and moisture content, which reduce combustion efficiency—an observation also supported by Al-Salem, et al. [24] in their thermochemical analysis of plastic waste [24].

Furthermore, PET and plastics categorized as "Others" show calorific values of 3.256 kCal/kg and 3.749 kCal/kg respectively, indicating that despite PET being widely used in domestic applications, its energy potential is relatively low. This aligns with findings by Rana and Kar [25] who noted that plastics with high oxygen content such as PET yield less energy due to the presence of functional groups that are harder to break down thermally [25]. On the other hand, the noticeable gap between traditional and laboratory-tested calorific values suggests environmental contamination, especially seawater exposure, significantly alters the actual energy potential of coastal plastic waste. This is supported by Andrady [26] who highlighted that physical and chemical degradation of plastic in marine environments can alter polymer structures, thereby reducing their thermal efficiency. Therefore, environmental factors must be carefully considered when evaluating waste-to-energy strategies for coastal plastic waste [26].

Seawater can significantly impact the caloric composition value of plastic waste through several processes. First, chemical and physical degradation processes such as hydrolysis and UV degradation can reduce the energy density of plastic. Hydrolysis, accelerated by salts and minerals in seawater, damages the polymer chains, particularly in plastics like polyester, lowering the molecular weight and energy content. UV degradation, common in the ocean, further breaks down plastic polymers into smaller fragments, leading to a reduction in stored energy. Additionally, plastics in seawater absorb water, increasing their water content, which requires more energy to evaporate before the plastic can burn efficiently, thus lowering the calorific value.

Moreover, plastics in the marine environment are prone to organic and inorganic contamination, which further affects their calorific value. Biofouling, the attachment of organisms like algae and bacteria, as well as the binding of heavy metals and other chemicals from seawater, increases the mass of the plastic but reduces its energy content. These non-calorific materials lower the overall energy released when the plastic is burned. Additionally, the degradation processes induced by seawater can lead to structural changes in the polymer, breaking down the plastic into smaller fragments. This structural breakdown further diminishes the plastic's ability to release energy, ultimately lowering its calorific composition. Figure 4 shows the plastic waste polymerization bond type 1-7.

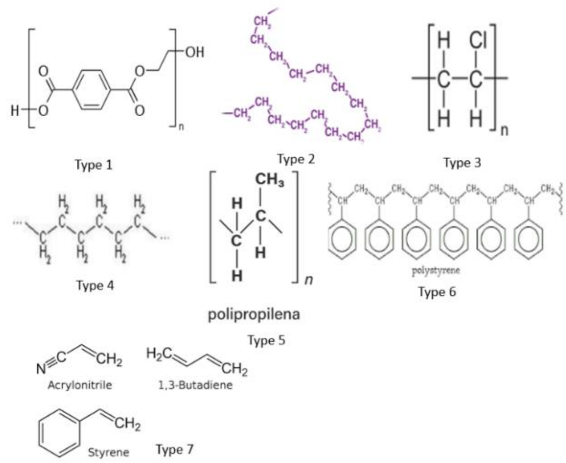

Figure 4.
Plastic Waste Polymerization Bond Type 1 – 7.

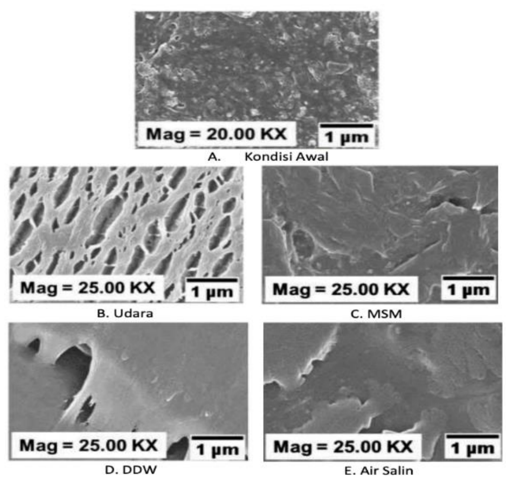

Figure 5.
Physical Changes of One Type of HDPE Plastic After Being Exposed to UV and Immersion in Seawater for 90 Days.

The differences in water content and volatile matter between coastal plastic waste and household plastic waste can be attributed to several factors. Coastal plastic waste is often exposed to harsh environmental conditions like sunlight and sea breezes, which accelerate polymer degradation through chemical reactions. Plastics such as polypropylene (PP) and polyethylene (PE) degrade slowly, but exposure to UV light and other chemicals can reduce their water content through natural evaporation. Coastal plastics also tend to absorb or retain less moisture. However, plastic types like HDPE and PET, which have denser and harder molecular structures, are more resistant to water absorption and chemical changes, making them less affected by environmental conditions compared to more flexible plastics like polypropylene and polystyrene, which have higher volatile matter content.

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In contrast, household plastic waste is typically fresher and more exposed to moisture from sources like washing, food, or drinks, which increases its water content. Household plastic waste is generally cleaner and less exposed to harsh environmental factors, meaning it is less likely to have external contaminants. Coastal plastic waste, however, is often contaminated with organic compounds from marine life or chemicals from seawater, which can increase its volatile matter. Additionally, long-term exposure to UV light causes microplastic degradation, releasing volatile chemicals. Household plastics are less exposed to these conditions, resulting in lower volatile matter compared to coastal plastic waste. Figure 6 shows the research results scheme.

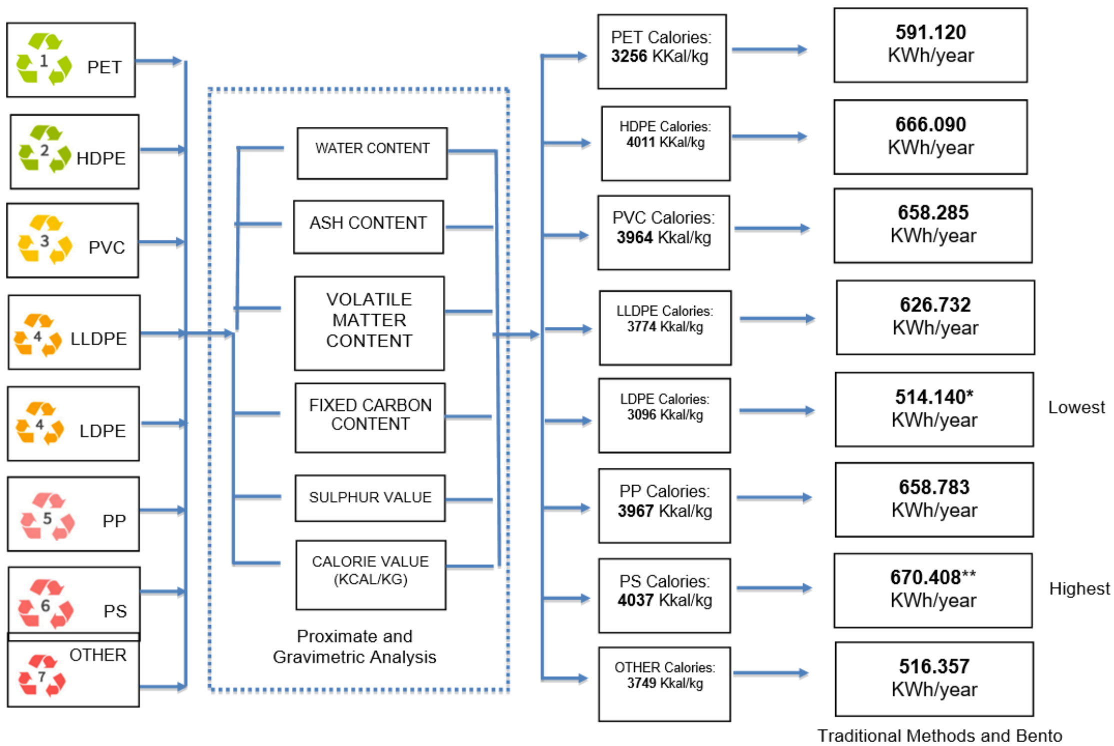

Figure 6.
Research Results Scheme.

The conversion of plastic waste into electricity offers both benefits and challenges for environmental sustainability. On one hand, it provides a solution for managing waste and reducing landfill accumulation, but it also raises concerns about gas emissions and pollutants released during combustion or pyrolysis. Greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are released, contributing to climate change. Moreover, incomplete combustion can produce toxic substances like dioxins and furans, which harm human health and the environment. Although plastic-derived fuels generate higher CO_2 emissions than natural gas, they are still lower than coal, making them a potential transitional energy source [23].

A study analyzed the life cycle of plastic-to-energy conversion, noting that pyrolysis-based energy recovery reduces plastic waste but still emits volatile organic compounds (VOCs) and particulate matter (PM10, PM2.5), which affect air quality. However, advancements in gas cleaning technologies, such as catalytic cracking and plasma-assisted gasification, have the potential to reduce harmful emissions while improving energy efficiency. The co-firing of plastic waste with biomass has also been suggested to offset CO_2 emissions, as biomass combustion reduces the overall carbon footprint. Future research

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should focus on optimizing these technologies and exploring carbon capture and storage (CCS) systems to lower CO_2 emissions [24].

To successfully implement waste-to-energy (WTE) technology, several technical factors must be considered, including the selection of conversion methods, feedstock composition, emission control, and energy recovery efficiency. Incineration, pyrolysis, and gasification each have advantages and challenges, with gasification being more efficient in energy recovery and producing fewer pollutants. However, technical challenges such as feedstock variability, temperature control, and gas cleaning must be addressed. Preprocessing, such as drying, shredding, and mechanical sorting, can improve feedstock quality. Integrating advanced emission control systems is essential for removing harmful pollutants, and hybrid WTE systems that combine gasification with renewable energy sources like solar or biomass could enhance sustainability. These advancements will help ensure that WTE technology can be safely and effectively implemented in areas like Selayar Islands while addressing environmental concerns [26].

4. Conclusion

The study highlights the significant potential of coastal plastic waste in Selayar Islands Regency as an alternative energy source, underscored by the high calorific value of the analyzed materials. This presents a dual benefit: providing a sustainable energy solution while simultaneously mitigating environmental pollution in coastal areas. The findings align with previous research on waste-to-energy technologies, supporting their feasibility in addressing plastic waste challenges and enhancing energy independence, especially in island regions. A key novelty of this study lies in its focus on coastal plastic waste, a less commonly explored resource for energy production, offering new insights for waste management strategies in such environments. However, the study also identifies the need for further research into the environmental impacts and economic feasibility of large-scale waste-to-energy implementation. Future research should prioritize optimizing plastic waste processing methods, integrating these technologies with existing energy infrastructure, and considering the socio-economic implications of adopting waste-to-energy solutions in coastal communities. These efforts can play a pivotal role in promoting sustainable waste management practices and supporting environmental conservation in coastal regions.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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