

DEVELOPMENT, EXPERIMENTAL CHARACTERIZATION, AND PERFORMANCE ANALYSIS OF A HYBRID SOLAR–THERMOELECTRIC GENERATOR UTILIZING BIO-COAL AND COCONUT KERNEL FEEDSTOCKS

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Abstract

The Philippines, a global leader in coconut production, generates approximately 9 billion discarded coconut husks annually, posing significant environmental challenges. This study explored the potential of harnessing this underutilized biomass as a feedstock for electrical energy generation using thermoelectric technology. The research focused on the thermochemical conversion of bio-coal and copra into electricity through the Seebeck effect. Experimental results demonstrated that an instantaneous feeding of 1kg of biomass produced a peak output of 1.200V at a temperature of **196°C**. **Comparative** analysis revealed that a larger fuel mass (1kg) achieved significantly higher peak temperatures (**492°C**) compared to smaller batches (500g), confirming the high energy density of coconut-based fuels. However, the study also identified a critical failure point: the burnout of the Thermoelectric Cooler (TEC) module due to the use of combustible structural materials (plywood) and low-thermal-tolerance adhesives (epoxy). The findings suggest that while coconut waste is a highly effective fuel source, system reliability depends on the transition from TEC to dedicated TEG modules and the implementation of refractory shielding. This research provides a foundational framework for developing sustainable, off-grid renewable energy solutions in coconut-producing regions like Eastern Visayas.

Keywords: Coconut Waste, Thermoelectric Generator (TEG), Biomass Energy, Seebeck Effect, Sustainable Agriculture, Waste-To-Energy, Philippines.

INTRODUCTION

The coconut tree (*Cocos nucifera* L.), frequently hailed as the "tree of life," remains a cornerstone of the Philippine agricultural economy and a vital source of livelihood for millions of smallholder farmers (Palis et al., 2020). In regions such as Eastern Visayas, coconut cultivation occupies approximately 42% of agricultural land, with copra serving as the primary economic driver (Castillo et al., 2021). Globally, the Philippines maintains its position as a top producer, yet the industry's focus remains predominantly on traditional products like copra meal and oil (Alouw & Wulandari, 2020).

Despite the economic value of the fruit's kernel, the processing of coconuts generates a staggering volume of biomass waste. It is estimated that 9 billion husks are either discarded or burned annually in the Philippines, contributing significantly to carbon emissions and local environmental degradation (Abad et al., 2021). While some husks are used as fuel for traditional copra drying, the inefficiency of these methods leads to wasted thermal energy and missed economic opportunities (Bawoke et al., 2023).

Furthermore, the increasing per capita waste generation in the Philippines necessitates a shift from disposal-based management to circular economy models that convert agricultural residues into high-value assets (Genuino et al., 2022). Currently, there is a lack of localized, small-

To address this gap, this research explores the transformation of coconut byproducts into a sustainable energy source using Thermoelectric Generator (TEG) technology. TEGs provide a solid-state solution for converting waste heat—generated from the combustion of coconut husks and shells—directly into electrical energy through the Seebeck effect (Siddique et al., 2020).

Recent advancements in biomass-fed thermoelectric systems suggest that agricultural residues can effectively power low-voltage applications in off-grid rural areas (Jaziri et al., 2020). By optimizing the use of coconut waste as a feedstock, this study aims to enhance the efficiency of renewable energy generation while providing a practical waste management strategy for coconut-producing regions (Pratama et al., 2021). This initiative not only promotes energy self-sufficiency but also aligns with global shifts toward sustainable, bio-based economies (Tursi, 2019).

Objectives of the Study

The main objective of this study is to Develop a Solar-Thermoelectric Generator. To achieve the main objective, the study aimed at achieving the following specific objectives:

- 1) to design and develop a prototype of the Solar-Thermoelectric Generator;
- 2) to conduct a comprehensive analysis of the combustion property and energy potential of Bio-coal and Cocos Nucifera L. Kernels; and
- 3) to assess and evaluate the performance of the Solar-Thermoelectric Hybrid Generator.

MATERIALS AND METHODS

An experimental research design was adopted to examine the causal relationship between feedstock utilization and generator performance. The independent variables were feedstock mass and feeding strategy (gradual versus instantaneous), while the dependent variables included voltage output, temperature gradient, combustion duration, and system stability. Controlled laboratory conditions enabled systematic manipulation of variables and reproducible measurements.

The prototype incorporated 50 Peltier-type thermoelectric modules arranged in a hybrid series–parallel configuration. Ten modules were connected in series to increase voltage, while four such sets were connected in parallel to enhance current output.

The furnace and cooling tank were dimensioned to balance heat generation, dissipation, and safety. Structural materials included a metal furnace housing, a glass cooling tank, and an exhaust system for combustion gases.

Two feeding strategies were evaluated: Gradual feeding, where bio-coal was introduced at a controlled rate after ignition. Instantaneous feeding, where the entire feedstock mass was introduced at once. Voltage and temperature readings were recorded at regular intervals using a digital multimeter and thermocouples. Combustion duration was measured using a precision timer, while ambient conditions were monitored to minimize external variability.

Descriptive and comparative analyses were performed to evaluate differences in electrical output and combustion behavior between feeding strategies. Observations related to system stability, component degradation, and safety were documented and incorporated into the performance evaluation.

RESULTS AND DISCUSSION

Analysis of Instantaneous Feeding and Voltage Output

Table 2: Data obtained in Instantaneous feeding test

Combustible Material	Total Mass	Time Duration	Volt (V)	Total Duration	Temperature	
					Cool Side	Hot Side
Bio-coal	2 kg (1 kg each)	0-20 secs	0.063V	5:30 mins	34°C	60°C
		0-20 secs-1:00 min	0.100V		34°C	115°C
		1:00 min-1:30 mins	0.140V		34°C	129°C
		1:30 mins-2:00 mins	0.205V		34°C	145°C
		2:00 mins-2:30 mins	0.275V		34°C	155°C
		2:30 mins-3:00 mins	0.380V		34°C	168°C
		3:00 mins-3:30 mins	0.595V		34°C	171°C
		3:30 mins-4:00 mins	0.840V		34°C	178°C
		4:00 mins-4:30 mins	1.000V		34°C	183°C
		4:30 mins-5:00 mins	1.130V		34°C	186°C
		5:00 mins-5:30 mins	1.200V		34°C	196°C

The instantaneous introduction of 1kg of copra into the pre-burning bio-coal system resulted in a rapid, non-linear increase in thermal energy and subsequent electrical output. As shown in Table 2, the voltage output reached 1.200V at a temperature gradient of 196°C, given the constant cool side of 34°C.

This progressive rise in voltage aligns with the Seebeck effect, where the electromotive force generated is directly proportional to the temperature difference across the semiconductor pellets (Hossain et al., 2023). The significant surge observed at the 3:30

mark (from 0.380V to 0.595V) suggests that copra, characterized by high volatile matter and oil content, undergoes rapid thermal decomposition, which significantly boosts the heat flux compared to bio-coal alone (Ochoa-Cornejo et al., 2020).

Comparative Combustion Profiles (250g vs. 500g)

Figures 7 and 8 demonstrate the impact of fuel mass and feeding sequence on the thermal profile. The 1kg total mass (500g each) achieved a peak temperature of 491°C, significantly higher than the 209°C observed with the 500g total mass.

The dramatic temperature spike to 139°C within the first minute in the 1kg trial (Figure 8) confirms that bio-coal acts as an effective "starter" fuel due to its high carbon density, which stabilizes the combustion chamber for the subsequent energy-dense copra feeding (Rabaçal et al., 2021).

However, the prolonged burning time of 27 minutes suggests that while larger mass increases peak energy, it also necessitates more robust thermal management to prevent "thermal runaway" in the generator components (Sadeaq et al., 2022).

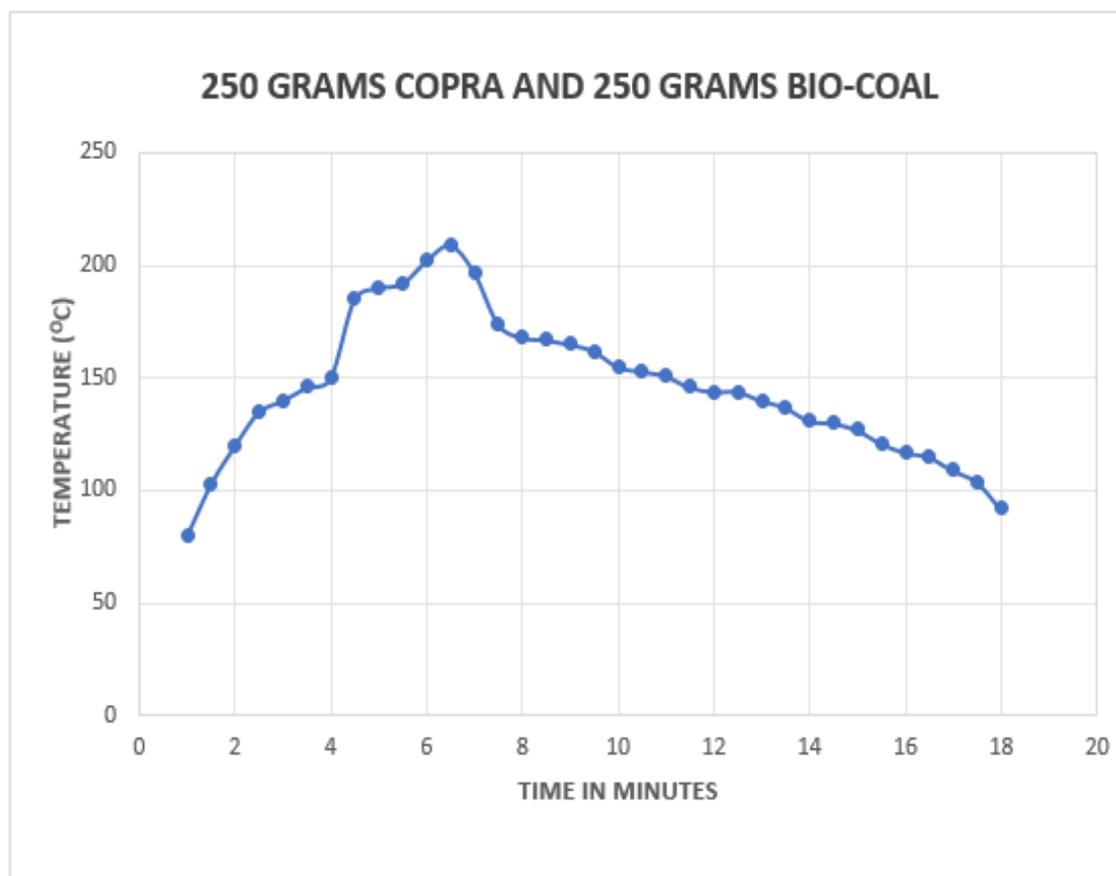


Figure 7: Data obtained using a combination of combustible materials totaling 500 grams

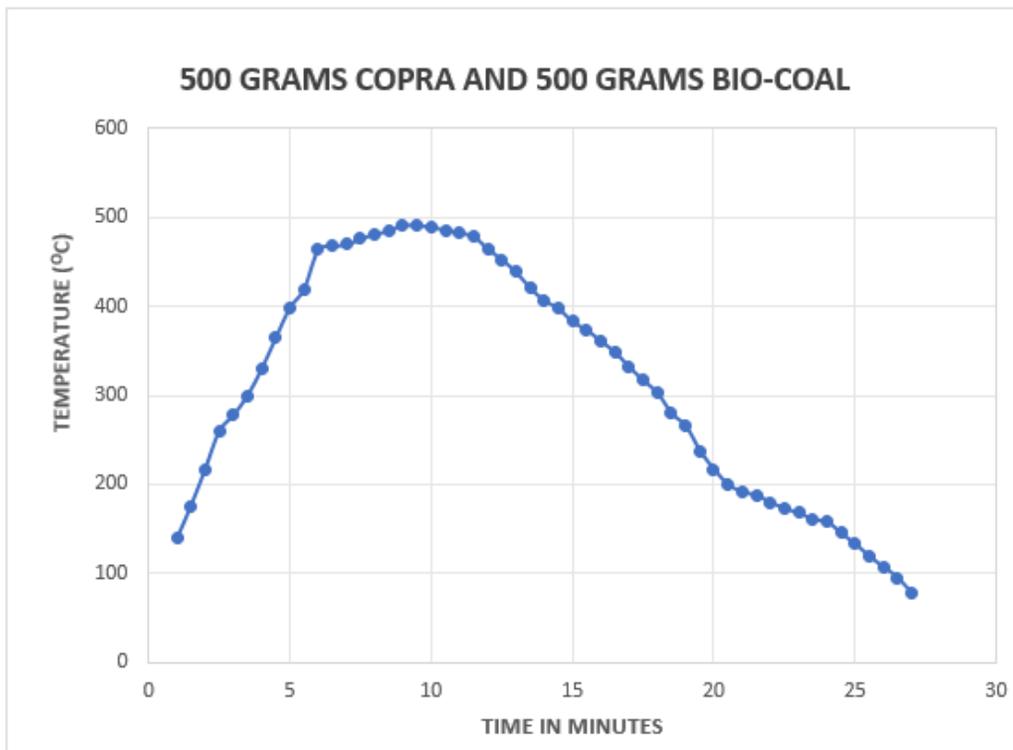


Figure 8: Data obtained using a combination of combustible materials totaling 1 kilogram

Analysis of the TEC Module



A critical observation in this study was the catastrophic failure of the TEC module, despite temperatures remaining below the theoretical limit of 200°C - 250°C. The burnout depicted in Figure 9 highlights three major engineering oversights supported by recent literature: Material Flammability: The use of plywood as a base reinforcement created a secondary fuel source. In high-heat biomass applications, non-combustible refractory

materials or calcium silicate boards are essential to prevent structural ignition (Liu et al., 2021). Adhesive Degradation: The failure of the epoxy adhesive at high temperatures led to a loss of "thermal contact" between the heat source and the module. Recent studies emphasize that standard epoxies undergo glass transition and de-bonding above 100°C - 150°C, recommending instead the use of silver-based thermal pastes or mechanical clamping (Wiriyasart et al., 2020). TEG vs. TEC Limitations: While TEC (Thermoelectric Cooler) modules are structurally similar to TEG modules, they are often designed with low-melting-point solders (138°C Bismuth-Tin). Using TEC modules for power generation often results in internal solder melting and circuit discontinuity long before the ceramic).

CONCLUSION

This study successfully demonstrated the potential of utilizing coconut agricultural waste—specifically bio-coal and copra—as a viable feedstock for thermoelectric power generation. The experimental data confirmed a direct correlation between biomass combustion intensity and electrical output, achieving a peak voltage of 1.200V. The rapid temperature increase observed during copra combustion highlights its high energy density, making it an effective fuel for localized energy solutions in coconut-producing regions.

However, the catastrophic failure of the TEC module revealed critical vulnerabilities in the prototype's structural design. The reliance on combustible materials like plywood and low-thermal-tolerance adhesives (epoxy) created a "thermal trap" that led to structural ignition and component burnout. This failure underscores that while the energy potential of coconut waste is high, the conversion technology requires specialized heat-shielding and robust material selection to withstand the high-intensity heat flux of biomass combustion.

RECOMMENDATIONS

To improve the reliability and efficiency of future coconut waste-to-energy prototypes, the following technical enhancements are recommended:

Upgrade to Specialized TEG Modules: Replace TEC (cooling) modules with dedicated TEG (power generation) modules. TEGs are manufactured with high-temperature solders and materials specifically designed to operate under the extreme temperature gradients found in biomass furnaces.

Implementation of Refractory Shielding: Eliminate all combustible structural components, such as plywood. Future designs should utilize calcium silicate boards or ceramic fiber insulation to isolate the hot zone from the sensitive thermoelectric components.

Enhanced Thermal Interface Materials (TIM): Instead of standard epoxy, use high-temperature thermal grease or graphite sheets combined with a mechanical clamping system. This ensures consistent thermal contact and allows for the differential thermal expansion of materials without adhesive failure.

Active Cooling Control: To maintain a higher temperature differential (ΔT) and prevent module burnout, implement a more robust cooling side management system, such as a liquid cooling loop or a larger aluminum heat sink with a high-CFM (cubic feet per minute) fan.

Feedstock Pre-processing: Further research should explore the pelletization of coconut husks and shells. Pelletizing the waste could provide a more controlled and sustained combustion rate, preventing the sudden "surges" in heat that can overwhelm the generator's thermal limits.

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