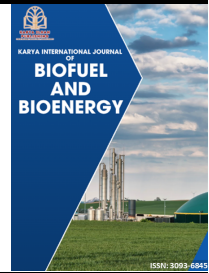




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Smart Waste Incinerator with TEG-Based Energy Recovery and Active Airflow Control

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ABSTRACT

The agricultural sector consistently produces large quantities of post harvest biomass waste, such as straw, rice husks and maize cobs. To date, the majority of this waste is still managed through open burning. This method not only causes air pollution that has a detrimental impact on the environment, but also wastes a considerable amount of potential thermal energy. Consequently, there is an urgent need for innovative waste treatment technologies capable of reducing exhaust gas emissions whilst simultaneously capturing waste heat for conversion into decentralised electrical energy for farming communities. The main challenges in implementing small-scale biomass incineration technology are extreme fluctuations in combustion temperature and an inconsistent oxygen supply, which ultimately result in very low thermal conversion efficiency. Given these conditions, the problem statement for this concept centres on how to precisely control the stability of the combustion chamber temperature when agricultural waste with varying moisture content is incinerated, and how to integrate a Thermoelectric Generator (TEG) module to achieve the maximum temperature gradient (ΔT) between the hot and cold sides for optimal electrical power generation. To address these issues, this article proposes the concept of a "Smart Incinerator Based on a Thermoelectric Generator with an Active Airflow Control System". The primary objective of this innovation is to design an incineration system capable of automatically regulating the oxygen supply (closed-loop control) based on real-time temperature readings, thereby ensuring more complete and consistent combustion of agricultural waste. This thermal stability is specifically designed to maintain the optimal performance of the TEG module array, thereby ultimately generating maximum electrical energy output that is environmentally friendly and can be directly utilised to meet farmers' operational needs.

1. Introduction

The agricultural sector produces large quantities of biomass waste, including rice straw, rice husks, maize cobs and other crop residues. These materials contain significant amounts of organic and chemical energy, making them a potential source of renewable energy. However, agricultural waste is still often managed through low-value disposal practices, including open-field burning. The

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burning of crop residues is widely recognised as an environmental problem, as uncontrolled burning can release fine particulate matter, carbon monoxide, volatile organic compounds and other harmful pollutants into the atmosphere [12], [13]. In addition to its environmental impact, uncontrolled burning also represents an inefficient utilisation of energy from agricultural biomass.

Open burning is particularly problematic because the combustion process occurs without proper control over temperature, residence time and oxygen supply. Previous reviews have reported that incomplete biomass combustion can increase the formation and emission of pollutants, including polycyclic aromatic hydrocarbons (PAHs), fine particulate matter and other organic compounds [10], [12]. The moisture content and chemical composition of biomass also influence its combustion behaviour. Biomass with a relatively high moisture content requires additional thermal energy for water evaporation, which can affect ignition, flame stability and combustion temperature [3]. Consequently, a more controlled thermal conversion process is required to transform agricultural residues into useful energy whilst minimising the negative impacts associated with uncontrolled combustion.

Controlled biomass combustion offers an alternative approach to enhancing the utilisation of agricultural residues. One key operational parameter in biomass combustion is the combustion air supply, as the availability of oxygen directly influences the combustion rate, flame stability, temperature distribution and the characteristics of complete fuel combustion. Numerical studies on biomass combustion have shown that changes in air supply can significantly affect combustion behaviour and temperature distribution within the combustion chamber [10]. Excessive air supply can increase heat loss, whilst insufficient air supply can lead to incomplete combustion. Therefore, maintaining the correct airflow conditions is crucial for achieving stable and efficient biomass combustion.

The development of active airflow control systems can provide a means of responding to changes in combustion conditions in real time. Rather than maintaining a constant air flow rate, an active control system can adjust the combustion air supply based on temperature measurements or other operational parameters. Recent research on biomass combustion systems also emphasises the importance of controlling thermal conditions, as temperature fluctuations can reduce stability and energy utilisation in the combustion process [10]. In this context, temperature can be used as a practical feedback variable to regulate the operation of blowers or air supply actuators. Such a closed-loop approach forms the basis for the development of intelligent combustion systems capable of adjusting their air flow to the varying conditions of biomass combustion.

In addition to improving combustion control, the thermal energy generated during biomass combustion can be further utilised through waste heat recovery. Much of the energy released during combustion is transferred to the hot flue gases and surrounding components, and if not utilised, this energy may be lost to the environment. Thermoelectric generators (TEGs) offer a solid-state approach to directly converting a portion of this thermal energy into electrical energy via the Seebeck effect. TEGs have attracted attention in waste heat recovery as they have no moving mechanical parts and can directly convert temperature differences into electricity [15], [16]. Their application in biomass-based thermal systems has also been demonstrated. Experimental studies show that TEG modules can be integrated with biomass combustion systems to recover heat and generate useful electrical power [8], [9].

The electrical performance of a TEG is highly dependent on the temperature difference between its hot and cold sides. Therefore, maintaining the correct thermal gradient is a key consideration in the integration of TEGs with combustion systems. Research on TEG systems indicates that uneven and fluctuating temperature distributions can affect electrical performance and complicate the process of achieving optimal power output [15], [16], [17]. In biomass boiler applications, the

integration of TEG modules has demonstrated the potential to recover thermal energy from the combustion process, although factors such as heat transfer conditions and temperature distribution.

2. Methodology

2.1 Research Approach

This research uses a literature-based engineering design approach to develop a conceptual smart waste incinerator for agricultural biomass waste utilization. The proposed system combines controlled biomass combustion, thermoelectric generator (TEG)-based waste heat recovery, and active airflow control. Unlike an experimental study, this research does not conduct direct performance testing of the proposed incinerator. Instead, the technical basis of the system is obtained from relevant studies published between 2022 and 2026 [1]–[19].

The research is conducted through several stages, starting from the identification of the research problem and objectives, followed by literature searching and selection, data extraction, data classification, data processing, system design, and technical analysis. The results from previous studies are used as references for determining the operating principles and technical considerations of the proposed system.

The overall research procedure is presented in Figure 1.

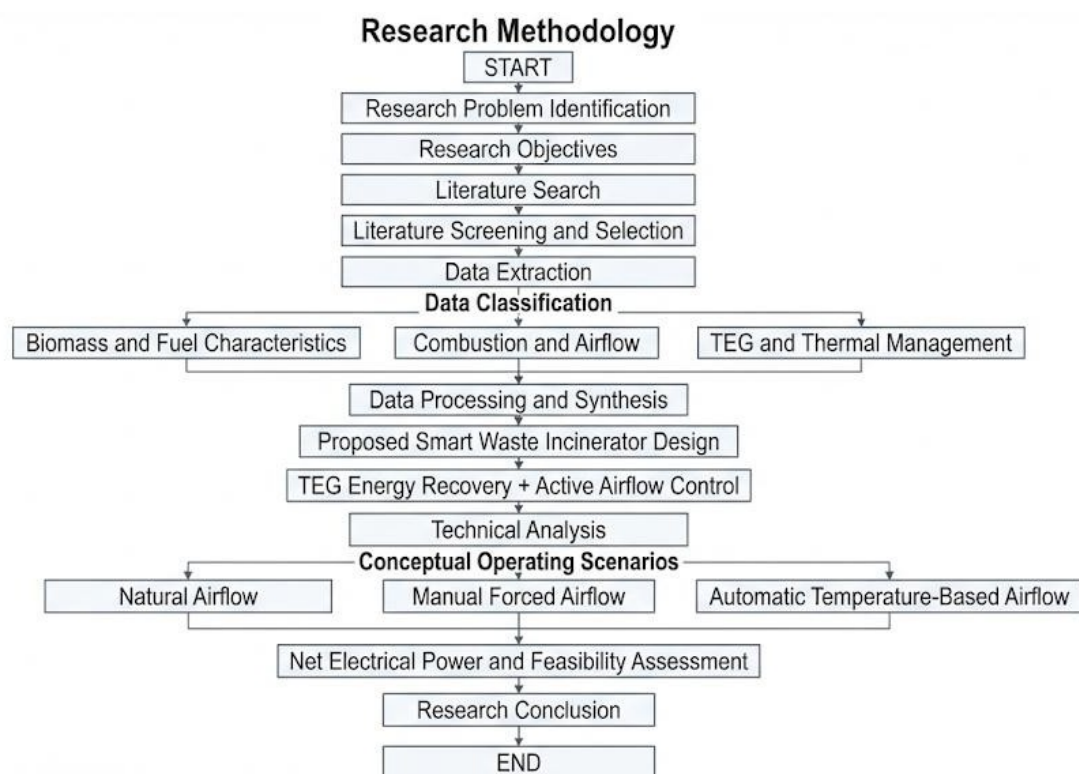


Fig. 1. Research methodology flowchart

Figure 1 shows the relationship between the main stages of the research. The process begins with the identification of the problem related to agricultural biomass waste utilization and uncontrolled biomass combustion. The process then continues with the collection and selection of relevant literature, extraction of technical data, processing and synthesis of the literature data, and development of the proposed incinerator system. The final stages focus on technical analysis,

conceptual operating scenarios, and assessment of the potential net electrical output of the proposed system.

2.2 Literature Search and Selection

The literature review was conducted to obtain technical information related to agricultural biomass combustion, thermoelectric energy recovery, thermal management, airflow control, and biomass-based energy conversion systems. The literature was selected primarily from journal articles published between 2022 and 2026 to comply with the recent-reference requirement of the research. The literature search focused on several groups of studies. The first group concerns the characteristics and utilization of agricultural biomass waste, particularly crop residues such as rice straw, corn residues, and other agricultural waste. The second group concerns biomass combustion, heat generation, and airflow management. The third group focuses on the application of TEGs for converting combustion waste heat into electricity. The fourth group covers TEG thermal management, cooling systems, DC–DC converters, and the integration of TEG-generated electricity with auxiliary systems such as cooling fans [1], [9], [15]–[17].

Relevant literature was identified using keywords such as agricultural biomass waste, biomass combustion, biomass stove, thermoelectric generator, waste heat recovery, biomass-powered TEG, forced draft, airflow control, and thermoelectric thermal management.

The selected studies were then evaluated based on their relevance to the proposed system. Particular attention was given to studies that reported measurable technical parameters, including combustion or flue-gas temperature, TEG temperature difference, electrical voltage, current, power output, cooling method, airflow configuration, and auxiliary power consumption.

Studies that did not directly provide information relevant to the proposed system were not used as primary technical references. When a required parameter was not reported in a selected study, it was identified as NR (Not Reported) rather than being estimated from unrelated information.

2.3 Data Extraction and Experimental Data Reported in Previous Studies

The selected literature was systematically reviewed to extract technical data that could support the proposed system design. The extracted parameters were grouped into three main categories: biomass combustion, airflow and thermal management, and TEG energy conversion.

For biomass combustion, the extracted information includes biomass type, heating conditions, combustion or flue-gas temperature, and the general characteristics of the combustion system. For airflow and thermal management, the extracted information includes the use of natural or forced airflow, cooling configuration, fan operation, and thermal management methods. For the TEG system, the extracted parameters include the number of TEG modules, temperature difference, voltage, current, electrical power, and auxiliary power consumption when reported.

Table 1 summarizes selected experimental data reported by previous studies that are relevant to the proposed system.

Table 1

Experimental data reported in previous studies related to biomass combustion and TEG-based energy recovery

Study	Biomass / System	Main Reported Parameters	Reported Electrical Output
Ru et al. (2022) [1]	Stove-powered TEG, 40 modules	$\Delta T = 140\text{--}153\text{ }^{\circ}\text{C}$; water cooling; DC–DC converters	137 W total; 119 W net; 113 W load
Tambunan et al. (2022) [5]	Wood chips	Average voltage = 1.08 V	Current and power: NR
Tambunan et al. (2022) [5]	Candlenut shells	Average voltage = 1.08 V	Current and power: NR
Tambunan et al. (2022) [5]	Corn cobs	Average voltage = 1.08 V	Current and power: NR
Tambunan et al. (2022) [5]	Coconut shells	Average voltage = 0.79 V	Current and power: NR
Sornek & Papis-Frączek (2023) [2]	Wood-fired heating stove	Flue-gas temperature $\approx 623\text{ K}$	15.9 W maximum
Li et al. (2023) [3]	Biomass combustion-powered TEG	Heating power = 750 W; system mass = 7.6 kg	23.4 W
Usón et al. (2023) [4]	25 kWth biomass boiler; 6 TEG modules	Pine pellets and agropellet	Up to 60 W
Madi et al. (2025) [6]	25 kWth biomass boiler; 6 TEG modules	TEG with series/parallel configuration	0.684 W series; 0.301 W parallel
Pandit et al. (2025a) [7]	25 kWth biomass boiler; 6 TEG modules	12 V DC cooling fan	6.30 W peat; 6.12 W wood; 4.10 W manure
Pandit et al. (2025b) [8]	TEG-integrated biomass cookstove with heat storage	$\Delta T = 192\text{ }^{\circ}\text{C}$	8.24 W

The values in Table 1 are reported values obtained from the respective studies and are not experimental results from the present research. The differences in electrical output between studies are influenced by several factors, including biomass type, combustion conditions, TEG configuration, temperature difference, heat-transfer characteristics, and cooling method.

Ru et al. (2022) [1], for example, reported a maximum total electrical output of 137 W from a stove-powered TEG system consisting of 40 modules. The system achieved a net output of 119 W after accounting for water-pump consumption, while 113 W was delivered to the electrical load. This result demonstrates the importance of distinguishing between total generated power, net system power, and load power.

Tambunan et al [5]. (2022) reported average TEG voltages of 1.30 V for wood chips, 1.12 V for candlenut shells, 1.08 V for corn cobs, and 0.79 V for coconut shells. The study also indicated that the

generated voltage was related to the temperature difference across the TEG. However, current and electrical power were not used as numerical values in the present analysis because they were not available in the verified data used for this study.

Sornek and Papis-Frączek (2023) [2] reported a maximum electrical power of 15.9 W from a TEG system installed on a wood-fired heating stove. The reported flue-gas temperature was approximately 623 K. This temperature is treated specifically as flue-gas temperature and is not assumed to represent the TEG hot-side surface temperature.

Li et al. (2023) [3] developed a biomass-combustion-powered TEG system with a heating power of 750 W and a system mass of 7.6 kg. The system generated 23.4 W of electrical power and demonstrated the potential of biomass combustion systems for combined heat and power applications.

Usón et al. (2023) [4] investigated six TEG modules integrated into a 25 kWth biomass boiler and reported an electrical output of up to 60 W. Their study also showed that ash deposition can reduce TEG performance, particularly when agricultural biomass fuels are used. This finding is relevant to the proposed incinerator because agricultural biomass can produce ash that may affect heat-transfer surfaces.

Madi et al. (2025)[6] investigated the conversion of thermal energy from corn stalk combustion into electricity using TEG modules. After the supercapacitor charging process, the reported electrical output reached 0.684 W in series and 0.301 W in parallel configurations.

Pandit et al. (2025a) demonstrated the integration of a TEG with a forced-draft biomass cookstove, where the generated electricity was used to operate a 12 V DC cooling fan. The fan simultaneously contributed to cold-side cooling and supplied air to the combustion chamber. A maximum electrical output of 6.30 W was reported for peat, 6.12 W for wood, and 4.10 W for manure.

Another study by Pandit et al. (2025b) reported 8.24 W of electrical output at a temperature difference of 192 °C from a TEG-integrated biomass cookstove with solid heat storage. The study also demonstrated that stored thermal energy could maintain forced-draft operation for a period after the fuel supply was stopped.

These results provide technical references for the proposed system while maintaining a clear distinction between reported literature data and values calculated during the present analysis.

2.4 Literature Data Processing and Synthesis

The data obtained from previous studies were processed to identify relationships between temperature difference, TEG electrical output, thermal management, and auxiliary energy consumption. The processing was performed using equations that are commonly applied in thermoelectric energy conversion.

The temperature difference across the TEG is determined using:

$$\Delta T = T_{hot} - T_{cold}$$

where ΔT is the temperature difference across the TEG (°C), T_{hot} is the hot-side temperature (°C), and T_{cold} is the cold-side temperature (°C). The temperature difference represents the thermal driving condition available for thermoelectric conversion. A higher temperature difference can generally provide greater potential for electrical generation, although the actual output also depends on the characteristics of the TEG module and its operating conditions.

The electrical power generated by the TEG is calculated from the measured voltage and current:

$$P_{TEG} = V \times I$$

where P_{TEG} is the electrical power generated by the TEG (W), V is the electrical voltage (V), and I is the electrical current (A). Equation (1) is applied only when both hot-side and cold-side temperatures are available from the source data. If either temperature is not reported, the corresponding temperature difference is identified as NR rather than calculated using an assumed value.

The literature data were synthesized to evaluate and compare the effects of combustion conditions, temperature gradients, cooling configurations, and airflow management on thermoelectric generator (TEG) performance. The findings from this synthesis were subsequently used as the technical basis for the proposed system design.

2.5 Proposed Smart Waste Incinerator System Design

The proposed system is designed to utilize agricultural biomass waste as a fuel source while recovering a portion of the combustion waste heat through TEG modules. The system consists of a combustion chamber, heat-transfer section, TEG modules, cooling section, airflow system, sensors, microcontroller, and electrical load.

The combustion chamber is designed to provide a controlled environment for biomass combustion. Agricultural biomass residues such as rice straw, rice husks, corn residues, and similar materials can be considered as potential feedstocks. The combustion process produces thermal energy that is transferred toward the TEG hot side.

The TEG modules are positioned between the hot-side heat-transfer structure and the cold-side cooling structure. This arrangement allows the temperature difference produced during combustion to be converted into electrical energy. The proposed incinerator design is presented in Figure 2.

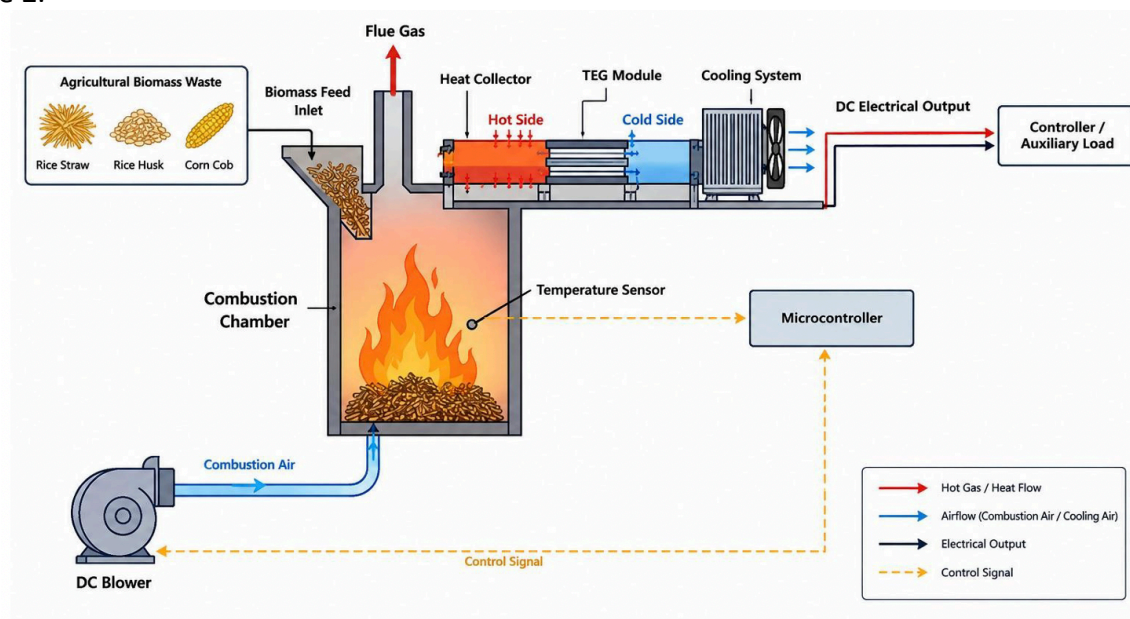


Fig. 2. Proposed smart waste incinerator design

The design shown in Figure 2 represents the authors' proposed configuration. The geometric dimensions and physical arrangement of the system are part of the engineering design developed in this research. Meanwhile, the operating principles and technical considerations are supported by the reviewed literature.

The heat-transfer section is an important part of the design because the performance of the TEG depends on the temperature difference maintained across its two sides. Therefore, the hot side must receive sufficient thermal energy from the combustion process, while the cold side must be cooled effectively to maintain a useful temperature gradient.

The design also considers the possibility of ash accumulation on heat-transfer surfaces. Ash deposition can increase thermal resistance and reduce the amount of heat transferred to the TEG. Therefore, the proposed system should provide sufficient access for cleaning and maintenance.

2.6 Energy Conversion and Active Airflow Control System

The energy conversion system consists of three interconnected functions: biomass combustion, thermoelectric energy conversion, and active airflow control. The thermal energy produced by biomass combustion is transferred to the hot side of the TEG. A temperature difference between the hot and cold sides produces an electrical output that can subsequently be used by the system. The generated electricity can be supplied to auxiliary components such as the blower, sensors, microcontroller, or other low-power electrical loads. This configuration creates a relationship between energy generation and airflow control.

The proposed active airflow control system uses a temperature sensor to monitor the combustion chamber temperature. The sensor provides temperature information to the microcontroller, which processes the measured value and determines the required blower operation. The blower then regulates the airflow supplied to the combustion chamber.

The conceptual relationship between the combustion process, TEG, sensor, controller, and blower is illustrated in Figure 3.

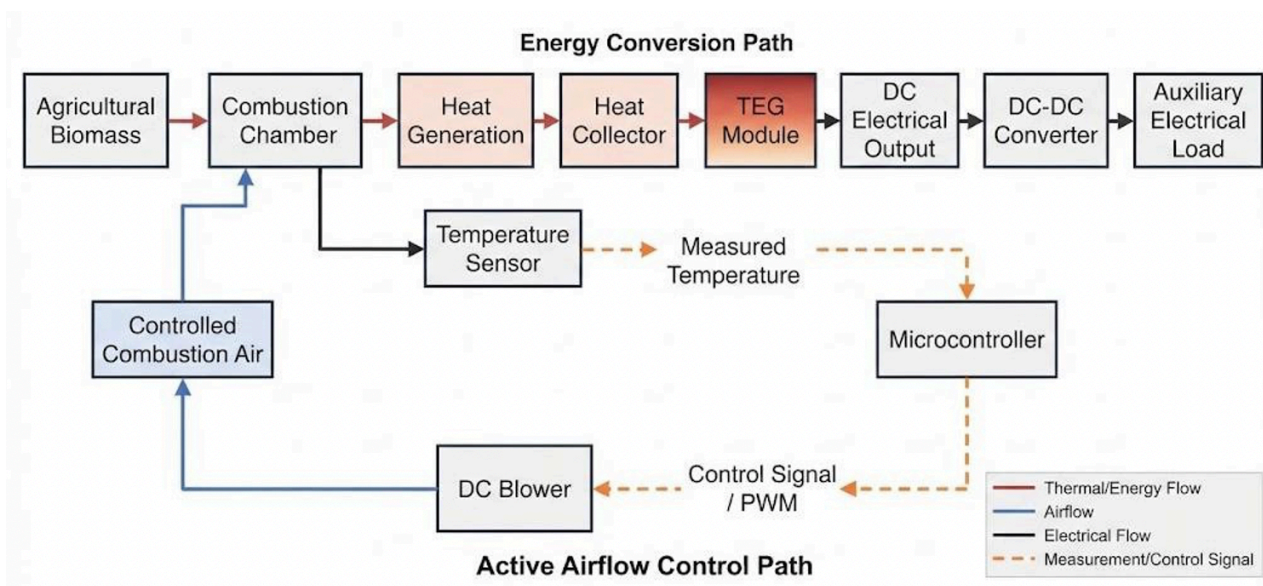


Fig. 3. Energy conversion and active airflow control system

The control concept is based on maintaining suitable combustion conditions rather than operating the blower continuously at a fixed speed. When the combustion temperature changes, the controller can adjust the airflow accordingly. This approach is intended to provide more responsive combustion management while reducing unnecessary auxiliary energy consumption.

Previous studies have demonstrated the feasibility of using TEG-generated electricity to operate cooling fans and support forced-draft combustion systems[7], [9]. Therefore, the proposed system extends this concept by introducing temperature-based active airflow control.

2.7 Literature-Based Technical Analysis

The technical analysis focuses on three main aspects: thermal performance, electrical performance, and auxiliary energy consumption.

2.7.1 Thermal Performance

Thermal performance is evaluated based on the temperature difference between the hot and cold sides of the TEG. A larger temperature difference generally provides a greater thermoelectric driving force. However, the temperature must remain within the allowable operating range of the selected TEG module.

The literature indicates that TEG performance is strongly affected by thermal management. Cooling of the cold side can increase the temperature gradient, while excessive thermal resistance or ash deposition can reduce heat transfer. Therefore, the proposed design considers both heat transfer from the combustion chamber and cooling of the TEG cold side.

2.7.2 Electrical Performance

Electrical performance is evaluated using the reported or calculated TEG power output. When voltage and current are available, electrical power is calculated using Equation (2). The comparison of literature results shows that TEG electrical output varies significantly among different biomass combustion systems. This variation is influenced by the number of TEG modules, available temperature difference, heat-transfer configuration, cooling system, and electrical conditioning system.

For this reason, the present research does not assume that the maximum output reported by one study can be directly achieved by the proposed incinerator. Instead, the literature values are used as technical benchmarks for conceptual evaluation.

2.7.3 Thermal Management and Ash Deposition

Thermal management is particularly important because the TEG requires a temperature difference across its two sides. At the same time, the TEG must be protected from excessive temperature exposure.

Ash deposition is another important consideration for agricultural biomass combustion. Accumulated ash can form an additional thermal resistance layer and reduce heat transfer between the combustion gas and the TEG heat collector. The findings reported by Usón et al. (2023) indicate that ash deposition can reduce the electrical performance of TEG systems integrated with biomass boilers[4]. Therefore, the proposed design incorporates thermal management and maintenance considerations into the system configuration.

2.8 Conceptual Operating Scenarios

To evaluate the potential contribution of active airflow control, three conceptual operating scenarios are considered. These scenarios are based on differences in the method used to supply combustion air.

Table 2

Conceptual operating scenarios of the proposed system

Scenario	Airflow Configuration	Control Method	Main Purpose
I	Natural airflow	No blower control	Baseline combustion condition
II	Forced airflow	Manual blower operation	Evaluate the effect of forced airflow
III	Forced airflow	Automatic temperature-based control	Evaluate adaptive airflow operation

Scenario I: Natural Airflow

In the first scenario, the combustion process operates without forced airflow from the blower. Air enters the combustion chamber through the available air inlets as a result of natural draft. This scenario represents the baseline condition for comparison.

Scenario II: Manual Forced Airflow

In the second scenario, a blower is used to provide additional combustion air. The blower is operated manually and does not automatically respond to combustion temperature. This configuration represents a conventional forced-air approach.

Scenario III: Automatic Adaptive Airflow

In the third scenario, the blower is controlled automatically according to combustion chamber temperature. The temperature sensor continuously provides input to the microcontroller, and the controller adjusts blower operation according to the programmed control logic.

This scenario represents the main concept of the proposed smart incinerator because the airflow system is directly connected to the measured thermal condition of the combustion chamber.

The three scenarios are conceptual comparisons based on the literature and proposed system design. They are not presented as experimentally measured results.

2.9 Net Electrical Power and Feasibility Assessment

The electrical feasibility of the proposed system is evaluated by considering not only the electrical power generated by the TEG but also the electricity consumed by the auxiliary components.

The net electrical power is expressed as:

$$P_{net} = P_{TEG} - P_{aux}$$

where P_{net} is the net electrical power available from the system, P_{TEG} is the electrical power generated by the TEG, and P_{aux} represents the total auxiliary electrical power consumed by the blower, controller, sensors, and other supporting components.

This approach is important because a TEG system should not be evaluated solely based on its gross electrical output. A system that generates electricity but consumes an equal or greater amount of electricity through its auxiliary components would provide limited or no net electrical benefit. feasibility assessment is therefore interpreted conceptually as follows:

- $P_{TEG} > P_{aux}$: the system produces positive net electrical power.
- $P_{TEG} = P_{aux}$: most of the generated electricity is consumed by the system itself.
- $P_{TEG} < P_{aux}$: the auxiliary components require more electrical power than the TEG generates.

The literature data are used to establish a technical reference range for the expected performance of the proposed system. However, because the present research does not conduct direct experimental testing, the feasibility assessment remains conceptual and does not represent a measured performance value of the proposed incinerator.

Overall, the methodology provides a structured basis for connecting agricultural biomass combustion, thermoelectric energy recovery, and active airflow control into a single smart waste-to-energy system. The resulting design and analysis can subsequently be used as the basis for future prototype development and experimental validation.

3. Results

This section presents the results obtained from the literature-based analysis of biomass combustion systems integrated with thermoelectric generators (TEG). The results are used to evaluate the technical feasibility of the proposed Smart Waste Incinerator with TEG-Based Energy Recovery and Active Airflow Control.

Because this study applies a literature-based system design approach, the numerical results presented in this section are derived from previously published studies. They are used as technical references for evaluating the proposed system and are not presented as direct experimental measurements from the proposed incinerator.

3.1 Literature-Derived Performance Results

The selected studies demonstrate that biomass combustion can provide a useful thermal source for TEG-based electrical generation. However, the reported electrical output varies considerably depending on the thermal input, number of TEG modules, temperature difference, cooling method, biomass fuel, and system configuration.

The results obtained from the selected literature are summarized in Table 1. Only numerical values that were reported in the corresponding studies are included. When a parameter was not reported by the source, it is identified as NR (Not Reported).

3.1.1 Reported Electrical Performance of Biomass-Based TEG Systems

The electrical performance reported in the selected studies is summarized in Table 1. The results demonstrate a wide range of electrical output, from less than 1 W in a small-scale corn-stalk combustion system to more than 100 W in a high-capacity stove-powered TEG system.

Table 3

Reported performance of biomass-based thermoelectric energy recovery systems

Study	Biomass / Thermal Source	TEG Configuration	Reported Thermal Parameter	Electrical Output	Other Information
Ru et al. (2022) [1]	Stove combustion	40 TEG modules	$\Delta T = 140\text{--}153\text{ }^{\circ}\text{C}$	137 W total; 119 W net	Water cooling and two DC–DC converters
Sornek & Papis-Frączek (2023) [2]	Wood-fired heating stove	TEG prototype	Flue gas $\approx 623\text{ K}$	15.9 W maximum	Numerical and experimental study
Li et al. (2023) [3]	Biomass combustion	BCP-TEG, 7.6 kg	Heating power = 750 W	23.4 W	TE efficiency = 2.87%
Usón et al. (2023) [4]	Biomass boiler	6 TEG modules	Boiler = 25 kWth	Up to 60 W	Pine pellets and agropellet
Tambunan et al. (2022) [5]	Wood chips, candlenut shell, corn cob, coconut shell	Biomass stove TEG	NR	1.30, 1.12, 1.08, 0.79 V	Current and power NR
Madi et al. (2025) [6]	Corn stalk waste	TEG system	NR	0.684 W series; 0.301 W parallel	After 90 min supercapacitor charging
Pandit et al. (2025) [7]	Peat, wood, manure	TEG-integrated forced-draft cookstove	NR	6.30, 6.12, 4.10 W	TEG output used for a 12 V DC fan
Pandit et al. (2025) [8]	Biomass cookstove	TEG with heat storage	$\Delta T = 192\text{ }^{\circ}\text{C}$	8.24 W	Self-forced draft up to 40 min

NR = Not Reported in the corresponding source.

Table 1 shows that the reported electrical output differs substantially between biomass-based TEG systems. Ru et al. [1] obtained the highest output among the selected studies, with a total electrical power of 137 W and a net output of 119 W after considering the water-pump consumption. The study also reported a temperature difference of 140–153 °C across the TEG system.

Other studies reported lower electrical outputs under different system configurations. Li et al. [3] obtained 23.4 W from a portable biomass-combustion-powered TEG system with a heating power of 750 W. Meanwhile, Usón et al. [4] reported electrical power of up to 60 W using six TEG modules integrated into a 25 kWth biomass boiler.

The smaller-scale systems also demonstrate the feasibility of producing useful electrical power from biomass combustion. Sornek and Papis-Frączek [2] reported a maximum electrical output of 15.9 W from a TEG system dedicated to a wood-fired heating stove. Pandit et al. [7]

reported maximum powers of 6.30 W, 6.12 W, and 4.10 W when using peat, wood, and manure, respectively.

For agricultural waste specifically, Madi et al. [6] reported 0.684 W using a series TEG configuration after 90 min of supercapacitor charging, while the parallel configuration produced 0.301 W. These results indicate that agricultural residues can be used as a thermal source for low-power electricity generation, although the electrical output is strongly dependent on the system configuration and thermal conditions.

3.1.2 Comparative Electrical Output

To make the reported electrical performance easier to compare, Figure 4 presents the electrical output from the selected studies that reported power values in watts. The voltage-only results reported by Tambunan et al. are not included because voltage cannot be directly compared with electrical power.

Before presenting the figure, the reported electrical values were grouped according to the study and operating condition. The figure therefore provides a visual representation of the numerical results presented in Table 1.

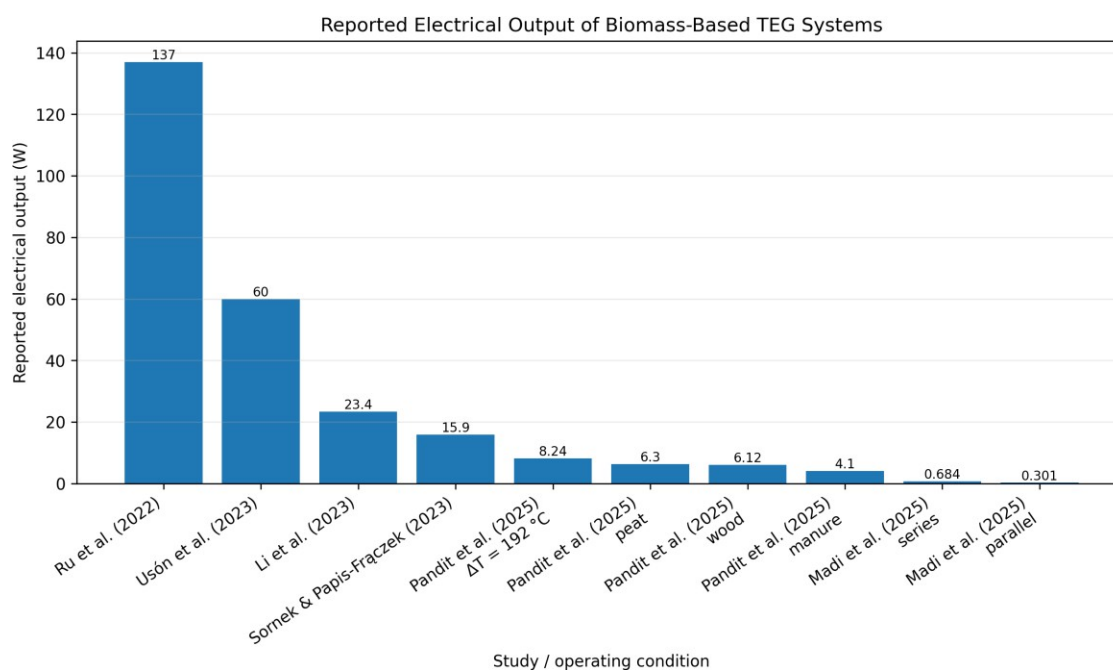


Fig. 4. Reported electrical output of selected biomass-based TEG systems

Figure 4 shows a substantial difference in the reported electrical output of the selected biomass-based TEG systems. The highest reported total output was 137 W from Ru et al. This was followed by 60 W from the biomass boiler system studied by Usón et al. and 23.4 W from the biomass-combustion-powered TEG developed by Li et al.

The lower output values were reported by smaller-scale systems. Madi et al. obtained 0.684 W in the series configuration and 0.301 W in the parallel configuration. Pandit et al. reported outputs between 4.10 W and 6.30 W for different biomass fuels.

The large difference shown in Figure 4 does not indicate that a particular configuration is universally superior. The systems have different thermal capacities, TEG module numbers, cooling

systems, biomass fuels, and electrical configurations. Therefore, the figure is used to demonstrate the range of electrical output that has been reported in biomass-based TEG applications.

For the proposed Smart Waste Incinerator, these results provide a reference for estimating the possible scale of electrical energy recovery. The actual output of the proposed system will depend on the thermal conditions achieved by the incinerator and the TEG configuration used during future experimental testing.

3.1.3 Temperature Difference and Thermoelectric Performance

The reviewed literature indicates that the temperature difference across the TEG is an important parameter affecting thermoelectric energy generation.

Ru et al. reported a temperature difference of 140–153 °C and a maximum total electrical output of 137 W using 40 thermoelectric modules. The study also reported a thermoelectric efficiency of 3.12% at a temperature difference of 140 °C.

Pandit et al. reported an electrical output of 8.24 W at a temperature difference of 192 °C using a TEG-integrated biomass cookstove with solid heat storage. These results provide evidence that maintaining a suitable temperature difference is important for obtaining useful electrical output from a TEG system.

However, the electrical output cannot be determined only from the temperature difference. The number and characteristics of TEG modules, heat-transfer conditions, cold-side cooling, electrical loading, and thermal system scale also influence the final output.

An important result for the proposed system is therefore the need to maintain a useful thermal gradient across the TEG. The combustion chamber should provide sufficient heat to the hot side, while the cold side should be cooled adequately. Stable thermal conditions are also important because large temperature fluctuations may affect the consistency of the electrical output.

It should also be noted that the 623 K value reported by Sornek and Papis-Frączek represents the flue-gas temperature, not the hot-side surface temperature of the TEG. Therefore, this value is not directly used as the TEG hot-side temperature in the analysis.

3.1.4 Electrical Output and Auxiliary Power

The literature results show that the gross electrical output of a TEG system is not necessarily equal to the electrical power that can be used by the final application. Some of the generated electricity may be consumed by auxiliary components such as cooling systems, blowers, controllers, and sensors.

Ru et al. reported 137 W of total electrical power and 119 W of output power after considering the electrical consumption of the water-cooling pumps. This result demonstrates that auxiliary electrical consumption can reduce the useful output of a TEG-based energy recovery system.

This condition is directly relevant to the proposed Smart Waste Incinerator. The proposed system requires electrical energy for the blower, temperature sensor, microcontroller, and other control components. Therefore, the electrical energy generated by the TEG should first support the required auxiliary loads before the remaining energy is considered available as useful external output.

The literature also demonstrates that TEG-generated electricity can be used directly to operate auxiliary components. Biomass cookstove systems have used TEG-generated electricity to operate forced-draft fans and cooling systems[7], [8], [9]. This approach provides a suitable reference for the proposed active airflow control system.

The result indicates that the proposed system should not evaluate performance only from the maximum TEG power. The amount of electrical power remaining after auxiliary consumption is also important for determining whether the energy recovery system provides useful electrical energy.

3.1.5 Results Related to Active Airflow Control

The reviewed literature provides supporting evidence for the integration of forced airflow with biomass thermal systems. Airflow influences the combustion process because the combustion reaction requires a suitable supply of air. However, the literature reviewed in this study does not provide one universal airflow value that can be directly applied to the proposed incinerator.

Pandit et al. demonstrated the integration of TEG-based electricity generation with a forced-draft biomass cookstove. In this configuration, electrical energy generated by the TEG was used to support the operation of the forced-draft system.

Another study by Pandit et al. reported an optimized biomass cookstove with TEG integration and solid heat storage. The system achieved 8.24 W of electrical output at a temperature difference of 192 °C and was able to maintain self-forced-draft operation for up to 40 minutes after the fuel supply was stopped.

These findings support the concept of combining TEG energy recovery and airflow control in the proposed incinerator. The TEG can provide electrical energy for the auxiliary system, while the blower can regulate the supply of combustion air.

The proposed system extends this concept by introducing temperature-based automatic airflow control. Instead of operating the blower continuously at a fixed condition, the control system is designed to respond to changes in combustion temperature. This configuration is expected to provide a more controlled combustion condition and support a more stable thermal environment for the TEG.

However, the effect of the automatic airflow system on combustion temperature, TEG temperature difference, and net electrical output cannot yet be quantified because the proposed incinerator has not undergone experimental validation.

3.1.6 Comparison of Conceptual Operating Conditions

Based on the literature results, three conceptual operating conditions were considered for the proposed Smart Waste Incinerator.

The comparison in Table 2 represents the conceptual operating conditions used for evaluating the proposed system. It does not represent experimental measurements.

The natural-airflow condition provides a reference condition without active airflow control. In the manual condition, the operator determines when the blower is activated or adjusted. In the automatic condition, the control system uses temperature feedback to regulate the blower according to the combustion condition.

The automatic configuration is intended to establish an integrated relationship between combustion, airflow control, and energy recovery. When the combustion temperature changes, the control system can respond by adjusting the airflow. At the same time, the TEG converts part of the available thermal energy into electrical energy that can support the blower and control system.

Table 4

Conceptual Operating Conditions of the Proposed Smart Waste Incinerator

Operating Condition	Airflow Control	Thermal Condition	TEG Response	Main Limitation
Natural airflow	No forced airflow	Air supply depends on natural draft	TEG output may vary with combustion condition	Limited airflow regulation
Manual forced airflow	Manually operated blower	Air supply can be increased or decreased by the operator	TEG condition can be influenced by airflow adjustment	Depends on operator response
Automatic airflow	Temperature-based closed-loop control	Air supply is adjusted according to combustion temperature	Intended to maintain a more stable thermal condition	Requires sensor, controller, and auxiliary power

3.1.7 Net Electrical Power Feasibility

The literature-derived results indicate that biomass combustion can provide a suitable thermal source for TEG-based electricity generation. The reported electrical outputs range from 0.301 W in the parallel configuration reported by Madi et al. to 137 W of total power in the high-capacity system reported by Ru et al.

However, the feasibility of the proposed system cannot be determined only from the gross electrical output. The electrical consumption of the blower, controller, temperature sensor, and other auxiliary components must also be considered.

The results from Ru et al. demonstrate this point clearly. The system generated 137 W of total electrical power, while the reported output after the water-cooling pump consumption was 119 W. This indicates that the energy consumed by auxiliary components can have a measurable effect on the useful electrical output.

For the proposed Smart Waste Incinerator, the same principle is applied. The TEG output is first used to support the operation of the active airflow and control system. The remaining electrical power represents the useful net output that can potentially be supplied to an external load or stored. This configuration provides an important advantage for the proposed system because the TEG is not treated only as an independent electricity generator. Instead, the TEG is integrated into the combustion-control system, where its generated electricity can support the operation of the blower and control components.

Nevertheless, the actual net electrical power of the proposed incinerator cannot be determined from the current literature data because the exact TEG output and auxiliary power requirements of the proposed design have not yet been experimentally measured.

3.2 Summary of Results

The literature-based results demonstrate that biomass combustion systems can be integrated with TEGs to recover part of the available thermal energy as electrical energy. The selected studies reported electrical outputs ranging from less than 1 W to 137 W, depending on system scale, TEG configuration, thermal input, cooling method, and biomass fuel.

The results also show that the temperature difference across the TEG is an important thermal parameter. Reported systems achieved electrical generation under different temperature conditions, including 8.24 W at a temperature difference of 192 °C and 137 W at a reported temperature difference of 140–153 °C.

The reviewed studies further support the use of TEG-generated electricity for auxiliary components such as fans and cooling systems. This provides a technical basis for integrating the TEG with the active airflow control system of the proposed Smart Waste Incinerator.

Comparison of the three conceptual operating conditions indicates that automatic airflow control can provide a structured approach for responding to changes in combustion temperature. However, the expected improvement in combustion stability and net electrical output remains a design expectation and cannot be claimed as an experimentally demonstrated result at this stage.

Overall, the literature results support the technical feasibility of combining agricultural biomass combustion, active airflow control, and TEG-based energy recovery in one integrated system. Experimental testing is required in future work to determine the actual combustion temperature, TEG temperature difference, electrical output, auxiliary power consumption, net electrical power, and operating stability of the proposed Smart Waste Incinerator.

4. Conclusions

This study presents a literature-based design of a Smart Waste Incinerator with TEG-Based Energy Recovery and Active Airflow Control for the utilization of agricultural biomass waste. The results from previous studies demonstrate that biomass combustion can provide a suitable thermal source for TEG-based electricity generation, with reported electrical outputs ranging from below 1 W to 137 W depending on the thermal input, TEG configuration, number of modules, cooling system, and biomass fuel. The reviewed results also show that maintaining an adequate temperature difference across the TEG is important for supporting electrical power generation.

The proposed system integrates TEG-based energy recovery with active airflow control to improve the management of combustion conditions. The literature indicates that TEG-generated electricity can be used to operate auxiliary components such as blowers and cooling systems. Therefore, the proposed configuration considers not only the electrical power generated by the TEG but also the power consumed by the blower and control components when evaluating the useful electrical output.

The literature-based analysis supports the technical feasibility of combining agricultural biomass combustion, active airflow control, and TEG energy recovery in a single system. However, the actual combustion-temperature stability, TEG temperature difference, electrical output, auxiliary power consumption, and net electrical power of the proposed incinerator cannot yet be determined from the available literature. Experimental testing is therefore required to validate the proposed design, determine its actual operating characteristics, and evaluate its performance under different biomass types and operating conditions.

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