



Innovative Learning During the COVID-19 Lockdown but also Applicable Under Other Major Constraints: Harnessing Thermoelectric Materials in Hands-On Experiences Out of The Laboratory

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Abstract

The global impact of the COVID-19 pandemic on educational and research activities has been very significant, particularly in developing nations with limited access to virtual resources. This research, conducted in Colombia during the March 2020 lockdown and subsequent periods with restricted intercity mobility, focuses on engaging undergraduate engineering students in self-directed learning involving thermoelectric materials and their applications, fully conducted from their homes. Two case studies were investigated. The first, explored the generation of energy from extractor hoppers, using the smoke and heat produced during food cooking. The second, consisted of a feasibility analysis for energy production from chicken manure compost. The following study describes the designs and processes employed in these two cases and highlights their learning outcomes. These results not only have potential for scalable industrial applications but also offer valuable insights applicable to similar restrictive contexts around the world. Therefore, the study showed two major findings: first, it is feasible to implement for everyday processes at low costs, such as cooking; second, with the correct methodology, almost any skilled student even virtually can produce significant data and results for the sustainability of the planet.

Keywords: Thermoelectric applications; Active learning (AL); Energy recovery; Circular economy; Thermoelectric properties.

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1. Introduction

The rapid advancements in technology and the population growth during the 20th century led to increased energy demands and a rise in power outages.^[1] This situation accelerated the need for sustainable technologies for mitigating their adverse environmental effects. Thermoelectric technology has emerged as a promising solution for using waste heat from various energy sources and by using the thermoelectric (TE) effect, which converts temperature differences into electrical voltage (known as the

Seebeck effect).^[2] Consequently, thermoelectricity from diverse heat sources has become a possible alternative for electricity generation. Numerous applications leveraging the Seebeck effect have been used in industries such as automotive and aerospace, utilizing waste heat to generate electricity.^[3] One of the key advantages of TE technology lies in its ability to reduce the negative impact of waste heat on the environment. Unlike traditional methods, thermoelectricity does not produce carbon dioxide, requires minimal maintenance, and boasts high durability.^[4] While it's true that thermoelectric generator (TEG) efficiency is relatively low due to the current material properties, enhancements in the intrinsic qualities of TE materials and optimizations in TEG structure offer avenues for efficiency improvements.^[5]

Research in TE technology is on the rise, exploring a variety of materials that includes Bi₂Te₃,^[6] PbTe,^[7] SiGe,^[8] Sb₂Te₃,^[9] and Zn₄Sb₃,^[10] among others. However, TE generators designed for energy harvesting still face several limitations,^[11] including low thermal efficiencies, uneven temperature distribution, relatively high costs for large-scale

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implementation (especially in developing nations), and concerns about the sustainability of materials and processes.^[12,13] Despite these challenges, TE cells have demonstrated their efficacy in various applications, such as industrial furnaces,^[14] chimneys,^[15] and heat recovery from car exhaust systems.^[16]

A significant portion of human-generated energy is dissipated in various ways, including industrial processes, heating/cooling systems, and buildings, ultimately ending up in cooling towers, radiators, or heat sinks.^[17,18] Consequently, the ability of TE technology to capture this waste heat and convert it into usable energy has led to its adoption across diverse industries. This field is a vibrant area of research, offering genuine potential to counteract this heat wastage.^[19-21] Although TEG systems currently require energy storage components for efficient energy reuse and their efficiency needs enhancement, their ongoing development holds the promise of recovering and effectively utilizing low-grade energy.^[22,23]

One of the major contributors to wasted energy is the infrastructure, particularly buildings. Currently, building energy consumption, including operational and maintenance needs, can account for up to 40% of the total global energy demand.^[24] Given the high energy requirements in households, enhancing the efficiency of household appliances is crucial to mitigate the environmental impact they cause.^[25] The first case study in this research delves into the implementation of TE technology in kitchen hobs, a common household scenario with significant potential for widespread application due to the energy lost during cooking. Additionally, integrating TEGs into kitchen hobs diversifies the typical renewable energy sources used at home,^[26,27] promoting sustainability and circular economy practices among the general population. This case study assesses both energy consumption and TE performance. This application is noteworthy because it not only improves process efficiency, but also because it recycles wasted energy, contributing to public education on the subject. Energy losses occur in various processes, including storage and waste decomposition, where organic disintegration reactions lead to a rise in temperature.^[28] Hence, the second case study investigates a TE system in chicken manure compost. The goal was to estimate the energy generation potential of this system. Recognizing that energy efficiency is pivotal in managing the escalating global energy demands,^[29] this case study is groundbreaking as it explores utilizing the energy lost in chicken manure compost, later employed for soil fertilization.

On the other hand, the world panorama suffered important transformations due to the Covid-19 pandemic. In Colombia, a broad blockade was imposed from March 25 to August 31, 2020, with a duration of 5 months and 7 days. This blockade, one of the longest in the world, had far-reaching implications on several fronts, including the economy,^[30] mental health,^[31] technology,^[32] and education,^[33] among other factors.

During the pandemic lockdown, teaching and research

activities at all educational levels were profoundly affected, with mobility restricted to essential personnel only, such as firefighters, police, and health professionals. The University of Antioquia experienced similar restrictions, with courses and laboratories completely closed. As a result, research initiatives came to a standstill and teaching moved to virtual platforms. Numerous projects, especially those addressing critical areas such as sustainability, were abruptly interrupted. This disruption affected both students and ongoing initiatives, exacerbating the mental health problems of homebound students.

Colombia, being a developing country with multiple challenges related to sustainability, including recycling,^[34-36] green materials,^[37] clean energy,^[38] or circular economy,^[35] witnessed a setback in progress. Environmental sustainability is closely linked to education and, at all levels of education, Active Learning (AL) methodologies have gained popularity among students and teachers.^[39,40] Despite the challenges, many students and professionals engaged in innovative strategies, such as additive manufacturing (commonly known as 3D printing), to produce essential components in support of healthcare professionals and hospitals during the pandemic.^[32] AL is widely celebrated in higher education for both students and educators.^[41] Within the realm of engineering education, various AL methods underscore the importance of honing skills such as communication, teamwork, leadership, and management to achieve academic success.^[42] In their study, Puente and Jansen^[43] detailed their experience with the Power Conversion project, employing design-based learning (DBL) as an active method. They observed that students not only accumulate knowledge but also apply it creatively to develop innovative practical solutions. Another effective AL approach is the use of case studies, which has been proven to enhance classroom engagement and success rates.^[44] This method fosters information retention and critical thinking skills, leading to heightened interest and persistence compared to traditional lecture-based instruction. Additionally, in the realm of higher education, online learning is gaining popularity. Coupled with AL methods, online platforms are fostering increased student engagement in the learning process, aided by the expanded possibilities of digital infrastructure.^[45,46] A case study is a method understood as an AL approach, characterized by a detailed and comprehensive exploration, employing both qualitative and quantitative methods of a singular phenomenon.^[47] In this study, two cases were utilized, aligning with positivist principles in higher education, including controls, replication, reliability, and generalization.^[48] This methodology is compelling because it typically focuses on a single case while considering the broader context, thus encompassing numerous variables and qualities.^[49] By drawing on real-life experiences, this method enhances engagement with subject competencies, fostering a deeper understanding.^[50,51]

This article introduces several novel aspects. First, while TE technology has found applications in numerous systems,

its potential in household and biomass systems has been poorly explored.^[52] Existing literature includes a conceptual design by Srivastava *et al.*^[53] outlining a TE kitchen system powered by rechargeable batteries through an electrical fan, although specific details regarding the energy balance were omitted. Kharshiduzzaman *et al.*^[54] have explored the generation of electrical energy from wasted heat produced by common household stoves using TEGs. In the realm of small, intermediate, and large-scale industrial applications, numerous studies and technical resources exist, utilizing TE cells to recover wasted heat effectively.^[55–57]

The current investigation reports AL and hand on laboratory work conducted at home, outside the laboratory, during the Covid-19 lockdown in Colombia. Two cases were explored remotely by students: Case I involved using TE cells in kitchen hoppers, and Case II focused on generating energy from compost made from chicken manure. The research showcased successful examples of active research and learning for engineering students in their final year. In the first case, the study examined the response of TE cells based on the water/oil cooking fluid, revealing that a single TE cell could generate up to 0.1 V of energy. The research presented the methodology, experimental design, results, and discussion. It also included a brief analysis of the recovered energy, considering the potential applications of thermoelectricity. In the second case, an analysis of a home composting system was conducted to determine its maximum temperature. The teaching and learning activities were carried out using simple and affordable materials, aligning with a strategy to enhance sustainable practices in the country's industries. In both cases, the primary objective was to assess the feasibility of energy generation using these systems. Throughout the 20-day testing period, the composting system reached a peak temperature of 40.5 °C on day 9, confirming the feasibility of energy generation in composting setups. The significance of this study lies in demonstrating the success of active methods, even in challenging situations like the COVID-19 lockdown in Colombia. Importantly, these methods have broader applications and can be implemented in various scenarios worldwide, including war zones, areas with limited access, conflict-prone regions, educational environments involving students with disabilities or health issues, developing countries, and more. The case studies in this research illustrate how different projects can facilitate learning within a subject area. In this context, projects involving TE cells were specifically chosen to enhance the understanding of TE concepts.

This study aims to address several key research questions: How can we improve the efficiency of thermoelectric generators to maximize energy conversion from waste heat sources. What are the latest advancements in thermoelectric materials, and how can they be leveraged to enhance the performance and durability of TE systems. What are the potential applications of thermoelectric technology beyond traditional industrial settings, and how can they contribute to

sustainability in diverse sectors such as transportation, agriculture, and construction. What are the main challenges hindering the widespread adoption of thermoelectric systems, and how can we overcome them through technological innovation and policy support. How can active learning methodologies and real-world research experiences enhance engineering education, particularly in the context of thermoelectric technology and sustainable energy practices.

2. Materials and methods

2.1 AL Through remote case studies

AL involves engaging students in activities that compel them to generate, work on, and apply ideas within the learning subject.^[58] This approach typically concerns collaborative learning groups, fostering the development of social interaction skills.^[59] According to Bonwell and Eison, AL strategies encompass "instructional activities involving students in doing things and thinking about what they are doing".^[60]

The case study methodology, in general, provides students with an open environment rich in resources, reinforcing learning and offering support during their studies.^[61,62] This method explores phenomena ranging from simple to complex, enhancing the student understanding.^[63] In this research, the case study methodology was employed as a teaching and learning tool for two TE material applications. These applications were chosen by students and the professor based on the topic's significance in summarizing essential concepts related to TE applications. The selection criteria also included the feasibility of conducting the research remotely, away from the university, with guidance provided online. Additionally, the projects required device utilization and experimental setups.

In this investigation, the students were provided with essential devices such as dataloggers, while other materials and equipment were expected to be sourced locally by the students. Communication for teaching and meetings were via virtual platforms like Google Meet, with a minimum of two scheduled meetings per month. Additional meetings were accommodated based on students' needs. Evaluation was conducted through virtual observations of the implemented case studies, supported by reports containing pictures, videos, data, and oral assessments of project progress.

2.2 Conducting remote thermoelectric research: materials, methods, and virtual collaboration in Colombian cities

Materials and methods were chosen based on their availability to students in intermediate to large cities across Colombia. The selected items included thermocouples, TE cells, dataloggers, furnaces, and other common heat sources. The project took place in two different households, with virtual review meetings held every 15 days. These sessions were predominantly conducted through Google Meet, ensuring a minimum of 12 review meetings before the project's completion. Table 1 outlines the key parameters of these

projects. These initiatives occurred in two distinct Colombian cities due to the students' locations and served as undergraduate research projects. The projects were subject to specific constraints, such as the substantial mobility limitations within the cities due to the enforced lockdown regulations.

Table 1. Investigative parameters employed in the study.

Parameters	Case I:	Case II: Compost
	Thermoelectric in Hopper	from Chicken Manure
Project type	Green technologies	Green technologies
Nature of the project	Experimental	Experimental
Percentage of evaluation in AL	100%	100%
Number of evaluations	12	12
Percentage of materials and devices acquired by students	100%	100%
Required devices	TEG, datalogger or thermocouple	TEG, datalogger or thermocouple
Project duration (months)	6	6

2.3 Case study I: implementation of TE system in kitchen hopper

The initial step in constructing the assembly involved creating a detailed CAD design for the hopper. Once the design was finalized, the required material was calculated, and the pieces were cut, utilizing triplex wood for this purpose. To ensure robust joints, wood glue and tape were employed. The interior of the hopper was lined with aluminum to facilitate effective heat transfer and prevent heat loss through the wooden walls, which have low thermal conductivity. The TE cell used for the experiment was the TEC1-12706,^[64] as specified below.

The extraction process began with the design of the extractor model made to determine the dimensions of the components in contact with the cookware and ovens. Fig. 1(a) shows the model created with Autodesk Inventor. Once the material calculations were completed, the parts were cut and the assembly proceeded, as shown in Fig. 1. To ensure the strength of the joints, masking tape and wood glue were used during assembly. The inside of the hopper was lined with aluminum foil, a highly conductive material, see Fig. 1(d). This lining served to minimize energy losses within the structure by efficiently utilizing the heat generated by the steam source.

Subsequently, a data collector and TE cell were installed. To close the circuit, a 1 Ω resistor was incorporated and the equation $V = I \cdot R$ was applied to determine the current value. TE TEC1-12706 TE cells were used in the experiments.^[64] Fig. 1(e) gives an overview of the cell dimensions and general

performance specifications. For alumina (Al₂O₃) with bismuth tin (BiSn), the typical performance specifications at 25 °C include $Q_{\max} = 50$ W, $\Delta T_{\max} = 66$ °C, $I_{\max} = 6.4$ A, $V_{\max} = 14.4$ V, and Module resistance = 1.98 Ω . At 50 °C, the specifications include $Q_{\max} = 57$ W, $\Delta T_{\max} = 75$ °C, $I_{\max} = 6.4$ A, $V_{\max} = 16.4$ V, and Module resistance = 2.3 Ω .

2.4 Case study II: implementation of a TE system in chicken manure composting

In this experiment, 60 kg of raw chicken manure, 20 kg of topsoil, and 1L of water mixed with lemon juice at room-temperature were utilized. These materials were sourced from Vijes, Valle del Cauca, Colombia. To prepare the materials, the chicken manure was first sifted to remove unwanted elements like feathers and stones commonly found in poultry houses. Following this process, the resulting chicken manure met specific criteria defined by previous studies:^[65] pH 8, approximately 80% dry material, around 60% organic materials, and low levels of N, P, K, Ca, Mg, and Na (all below 10%). Additionally, Fe, Mn, Cu, and Zn were present in concentrations of 500, 300, 40, and 500 mg/kg respectively, as reported by SENA (Colombian National Institute of Learning).^[66]

For the compost preparation, the chicken manure, topsoil, and lemon juice were thoroughly mixed in a 20 L container (as shown in Fig. 2). To cover the compost, a fique mesh (made from fiber from the *Furcraea andina*) was used to enclose the upper part of the container. This was done to partially trap gases generated during the composting process, aiming to elevate the material's temperature until it reached the thermophilic stage before returning to room temperature. To monitor the compost's temperature, a data logger with an external thermocouple was utilized. The thermocouple was inserted into the center of the container, as depicted in Fig. 2. This experiment took place at an altitude of 987 meters above sea level, with temperatures between 19 and 30 °C. Temperature measurements were automatically recorded every 30 minutes using a data logger. The experiment was conducted in a relatively controlled environment, shielded from direct sunlight to prevent sudden changes in the working conditions.

2.5 Controls implemented in the experiments

In this study, materials and methods were chosen based on their availability to students in intermediate to large cities across Colombia. The selected items included thermocouples, TE cells, dataloggers, furnaces, and other common heat sources. The project took place in two different households, with virtual review meetings held every 15 days. These sessions were predominantly conducted through Google Meet, ensuring a minimum of 12 review meetings before the project's completion.

To strengthen the credibility of the results, several control measures were implemented, outlined comprehensively in Table 2.

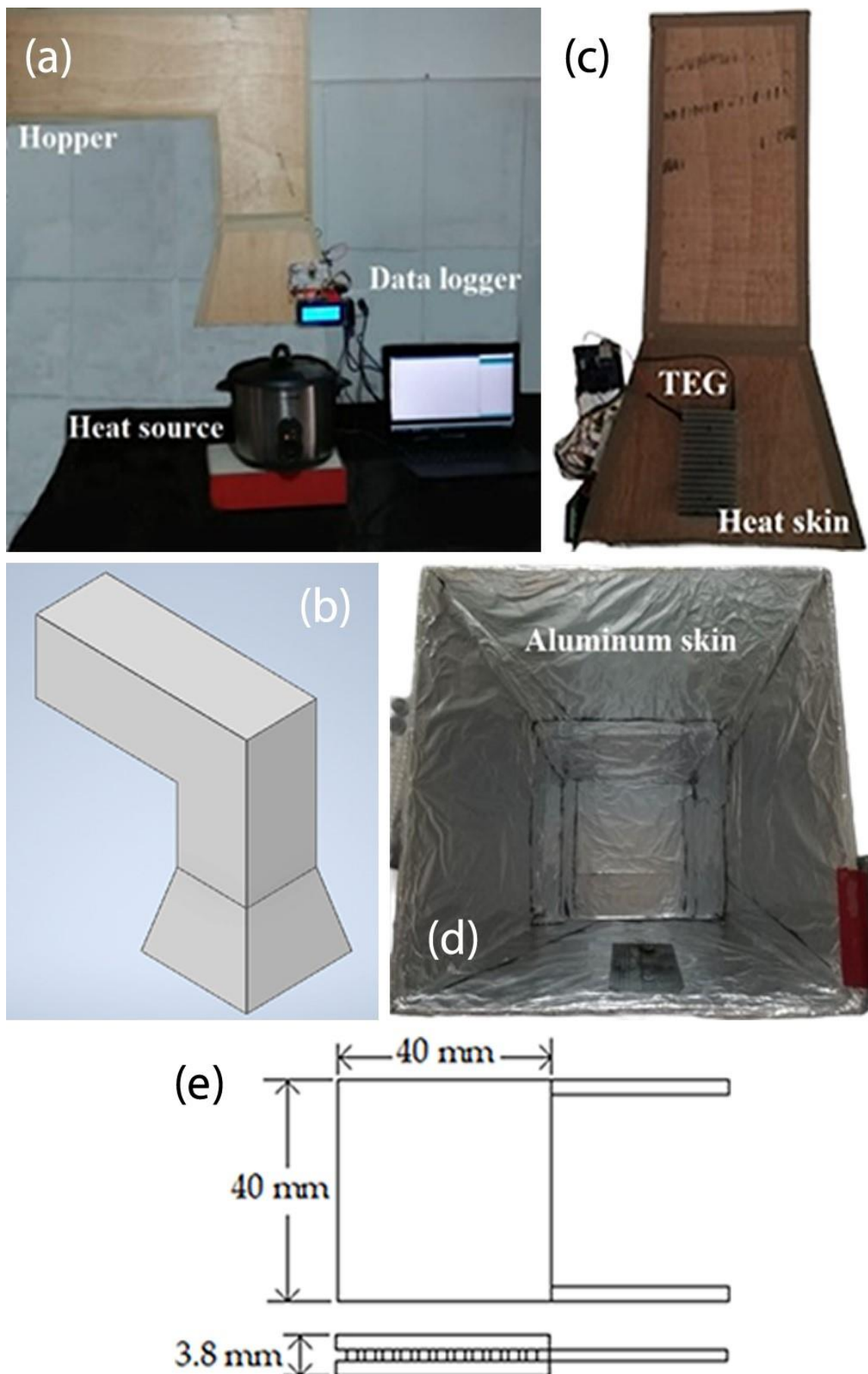


Fig. 1 Design and Assembly of the Extractor Model for Energy Generation, (a) Assembly, (b) CAD design, (c) Side View, (d) Internal bottom View, (e) TEC details.

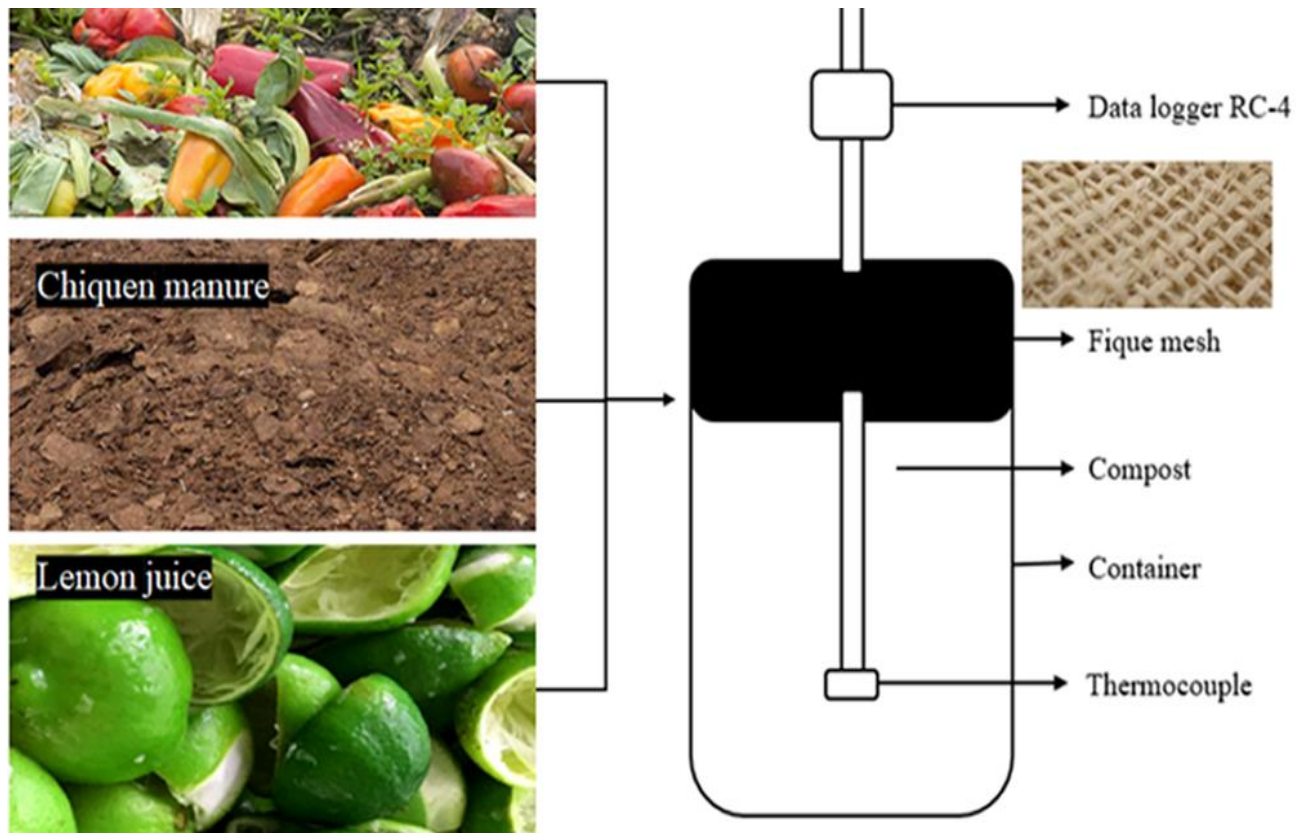


Fig. 2 Compost preparation process for Case study II: implementation of a TE system in chicken manure composting.

Table 2. Controls employed in the remote case studies.

Control	Description
Selection Criteria for Materials and Methods	The materials and methods were chosen based on their accessibility to students in intermediate to large cities across Colombia, ensuring uniformity in resources and equipment availability.
Consistency in Experimental Setup	The experimental setup, including the use of thermocouples, TE cells, dataloggers, and furnaces, was standardized across both households to ensure consistency and reliability of data collection.
Virtual Review Meetings	Regular virtual review meetings were held every 15 days via Google Meet, providing a structured platform for discussing progress, addressing challenges, and ensuring adherence to experimental protocols. A minimum of 12 review meetings were conducted, promoting continuous monitoring and feedback throughout the project duration.
Uniform Project Parameters	The key parameters of the projects, such as project type, nature of the project, percentage of evaluation in active learning (AL), number of evaluations, percentage of materials and devices acquired by students, required devices, and project duration, were standardized and documented for both Case I and Case II to maintain consistency and comparability.

These measures were put in place to minimize potential biases, establish consistency in procedures, and improve the credibility and dependability of the experimental findings.

3.Results

3.1 Thermoelectric

3.1.1 Thermoelectric research

Temperature plays a vital role in energy generation using TE cells. Consequently, temperature variations were studied based on the choice of fluid used: boiling water and oil. Temperature data were gathered using a thermocouple placed at 0.1m intervals from the heat source and up to 1m, representing the average height of the hoppers. The measurements were conducted in an environment with a constant room temperature of 20 °C. As illustrated in Fig. 3(a), the temperature curve for oil is situated above the water curve. This difference arises because oil has a higher boiling point. Therefore, when used for cooking, it reaches much higher temperatures compared to water.

The temperature difference (ΔT) between the boiling water and oil cooking fluids was 71 °C (91 °C-20 °C) and 82 °C (102 °C-20 °C) respectively, measured near the surface of the boiling fluid. These measurements were taken while considering variations in environmental temperature, typically in the range of 15 to 20 °C. Natural convection allowed the heat from the working fluid to rise within the hopper, as no ventilation system was employed.

Table 3 was constructed based on the heights of the cell

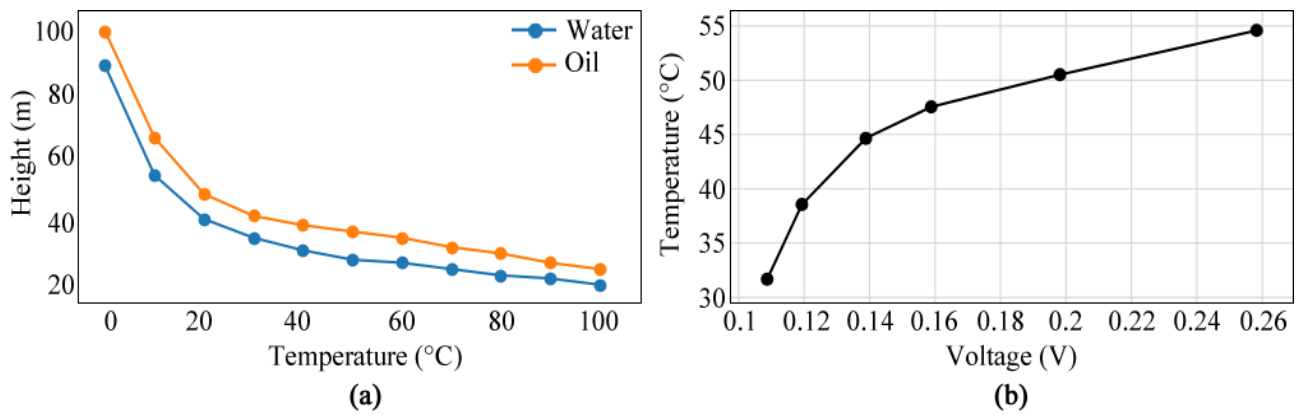


Fig. 3 (a) Temperature variation with height in boiling water and oil systems; (b) Temperature Characterization (T_h) concerning Open Circuit Voltage (V_{oc}).

relative to the heat source. The generated current, measured concerning the cell's surface temperature and the room temperature, is detailed in section 4.1.

Table 3. Variation in temperature difference relative to heat source height.

Height [cm]	Boiling ΔT [°C]	Water ΔT [°C]	Boiling	Cooking	Oil
40	12	20			
30	16	23			
20	22	30			
10	36	48			

3.1.2 Thermoelectric module

The assembly shown in Fig. 1a consists of an initial layer of aluminum foil in direct contact with the heat source. Subsequently, the TE cell is positioned, followed by heat-dissipating fins made of aluminum, specifically a structural alloy known as 6061.

In the experimentation, the TE cell employed was the TEC1-12706.^[64] Its characterization consisted of measuring the open circuit voltage (V_{oc}) versus temperature difference, over 0.5 hours. Fig. 4 illustrates that the maximum voltage generated by the TE cell corresponds to the highest temperature difference achieved within the array.

Subsequently, a curve was constructed correlating the high temperature (T_h) at the inner face of the cell with its corresponding open circuit voltage (V_{oc}), as shown in Fig. 3(b). This graph illustrates a direct relationship: as the temperature rises, the voltage generated also increases. However, this increase in voltage is limited by the maximum temperature the cell can withstand, thereby capping its generation capacity.

3.2 Composting process

3.2.1 Thermal decomposition thresholds in composting

This experiment spanned 20 days, during which the compost progressed through its thermophilic stage before eventually stabilizing at ambient temperature. Previous research indicates that significant temperature increases in composting occur only when the moisture excess facilitates adequate aeration for

gas generation.^[67] Consequently, the initial 4 days demonstrated temperature patterns closely mirroring ambient trends due to insufficient aeration.

The compost entered its thermophilic stage after 9 days of decomposition, reaching a peak temperature of 40.5 °C. Fig. 4 illustrates a rapid temperature increase as soon as the humidity reached a level conducive to gas production. This surge led to the temperature's maximum point, followed by a gradual decline, until reaching values close to the ambient temperature.

3.2.2 Generated heat and flow heat

To calculate the heat generated, the Equation 1 for heat in an exothermic process was applied. A constant mass of 60 kg and a specific heat of 4.19 kJ/kg°C were used. This specific heat value corresponds to water, as during the decomposition process, there is no reduction in mass, and heat generation primarily results from the evaporation of the free water surface.

$$Q_g = m * C_p * \Delta T \quad (1)$$

In this analysis, the heat calculation specifically covers the period until the compost reaches its thermophilic stage. During the 9-day decomposition process leading to the thermophilic stage, approximately 3620 kJ of heat were generated, reaching a maximum temperature of 40°C. Furthermore, the thermal capacity was calculated using the Equation 2^[68] for the time interval, indicating a heat flow of approximately 2 kW generated during the thermophilic stage.

$$\dot{Q} = \frac{Q_g}{\Delta t} \quad (2)$$

4. Discussion

4.1 Energy analysis of the hopper system

Following the characterization of the TE cell, the generated current was measured at various heights. Fig. 5 display the current generated from the initiation of the TE cell operation. In the case of water, higher voltages were attained compared to those achieved with oil. The expected result was derived from the higher boiling temperatures of the oil; however, its low convection coefficient led to a decrease in convective heat transfer at the cell face, which affected the efficiency of the TE cell. Fig. 5 illustrates a parallel trend in the generation curves.

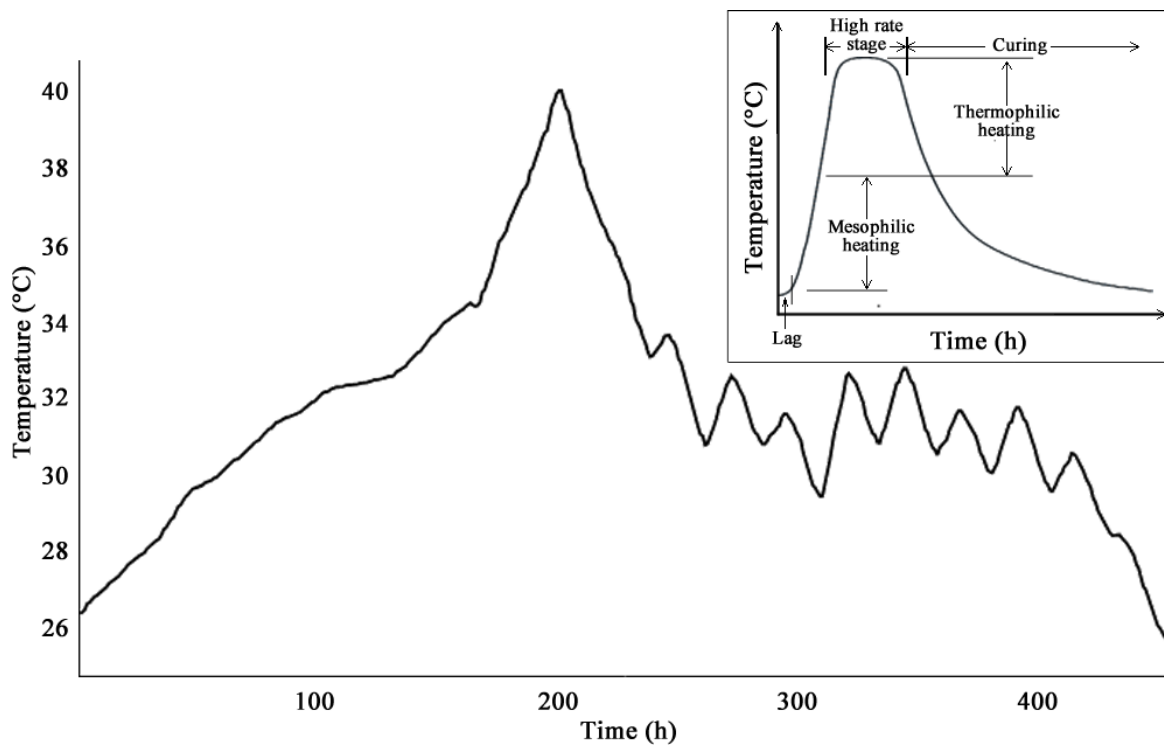


Fig. 4 Temperature variation during thermophilic stage of composting process.

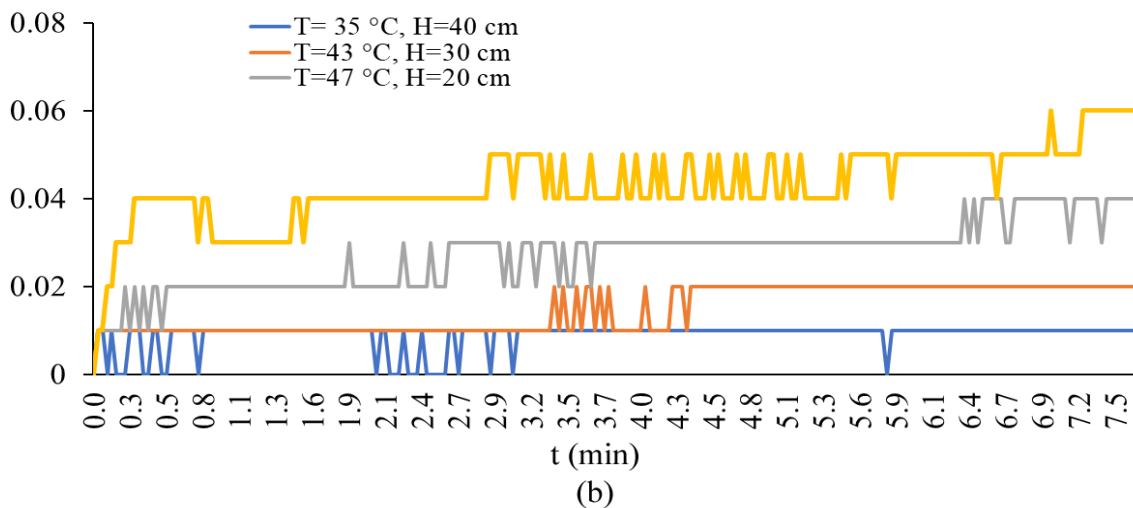
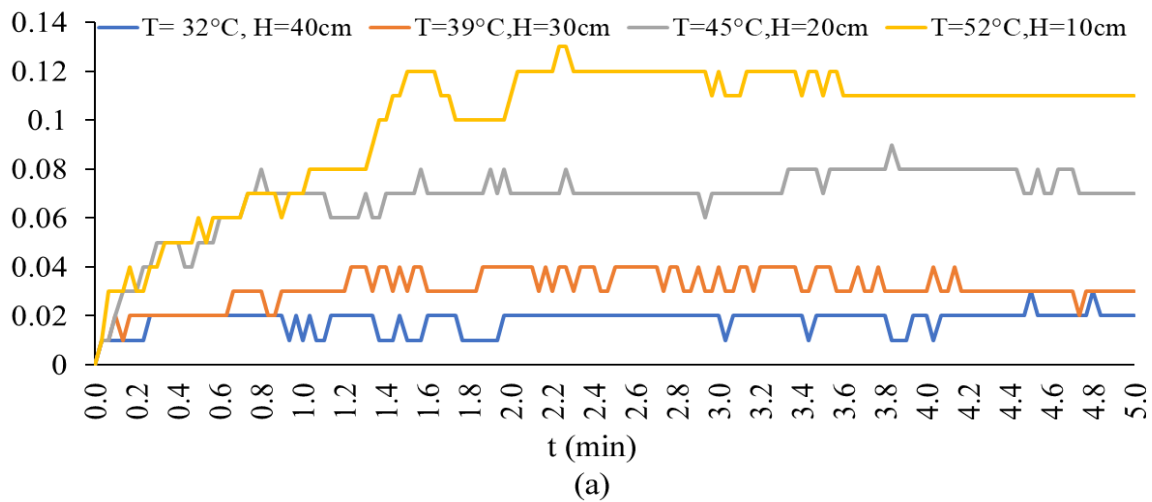


Fig. 5 Time-dependent current variation in boiling experiment (a) water; (b) oil.

Initially, the voltage shows an upward trajectory until it reaches its maximum generation potential at the current operating conditions.

4.2 Energy balance calculation

To calculate the energy recovered using the TEG, an energy balance analysis employing fundamental energy equations was conducted.^[69] The energy calculation was based on steady-state conditions, assuming no resistance to contact, convection on the inner face of the cell, and no radiation. Since the temperatures on both faces of the cell were known, it was possible to calculate the heat passing through the TE cell. This heat remained constant due to the assumed steady state. Thus, the rate of heat transferred is shown in Equation 3^[68]:

$$Q = kA \frac{\Delta T}{\Delta x} \tag{3}$$

Here, k represents the material's thermal conductivity, A signifies the transversal area, and Δx stands for the material thickness. The electric conductivity is denoted as $\sigma = 1/\rho$. The thermal conductivity was determined by assuming that σ approximates k under the thermal operating conditions of the cell. Consequently, the thermal heat transferred is given by Equation 4:

$$Q = \frac{1}{\rho} A \frac{\Delta T}{\Delta x} \tag{4}$$

$$Q = 2.51 \text{ W}$$

The maximum energy harnessed by the TEG unit is given in Equation 5:

$$P_{rec,max} = VI \tag{5}$$

$$P_{rec,max} = 0.169 \text{ W}$$

Therefore, the proportion of electrical power recuperated is summarized in Equation 6:

$$\%E_{rec} = \frac{P_{rec,max}}{Q} * 100 \tag{6}$$

$$\%E_{rec} = 6.73 \%$$

TE system performance is influenced by numerous operational factors.

4.3 Analysis of compost composition

Based on the findings depicted in Fig. 4, a comparative analysis was conducted using varying quantities of poultry manure, specifically masses of 60 kg, 83 kg, and 275 kg.^[70,71] This comparison aimed to evaluate the maximum temperature attained during the thermophilic stage over 20 days, under similar environmental conditions for each test, as illustrated in Fig. 6.

5. Overall perspective and observations

The results demonstrate that despite the challenges posed by the extreme lockdown during the COVID-19 crisis in Colombia, students were able to engage effectively in scientific research. They completed an entire engineering project, encompassing construction, data acquisition, calculations, and analysis. Furthermore, students showcased the potential of Thermoelectric (TE) generators as a solution for underexplored heat recovery processes, marking a significant step towards cultivating sustainable thinking in their careers.

Table 4. Project parameters summary.

Parameters	Case I	Case II
Title	Thermoelectric in hoper	Compost from chicken manure
Utilized devices	Thermoelectric generator, datalogger or thermocouple	Thermoelectric generator, datalogger or thermocouple
Materials employed	Ceramics, metals, water, wood	Ceramics, plastics, organic waste
Project duration (months)	6	6
Estimated project cost (USD)	30	20
Involvement of calculations	yes	yes
Project Completion Status	finished	finished

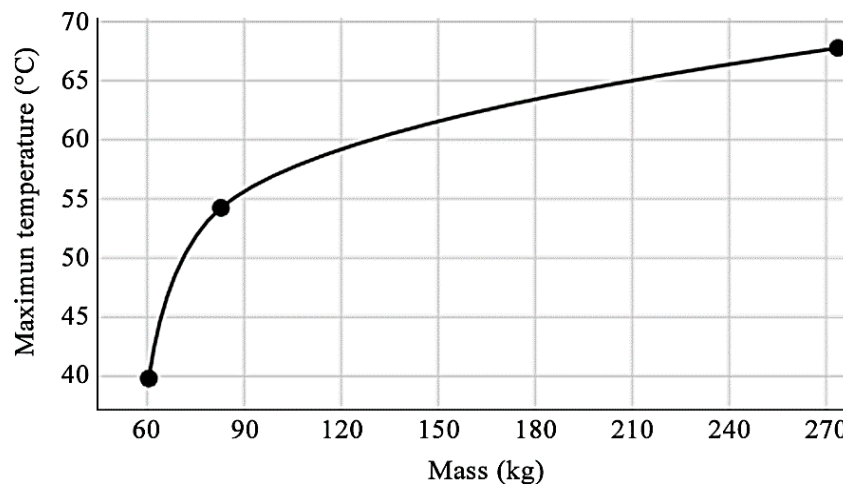


Fig. 6 Comparison of maximum temperature during thermophilic stage based on mass.

Engaging with these concepts, students were able to delve deeply into various interconnected yet crucial areas. They not only gained hands-on experience in executing an experimental project but also acquired essential skills, such as project leadership. This practical learning approach provided them with a comprehensive understanding of numerous vital concepts. Table 4 summarizes several parameters from the completed projects, highlighting the project's success in imparting multifaceted knowledge and the challenges students faced, involving diverse materials and devices.

Figure 7 illustrates the progress of the projects, which were systematically reviewed, discussed, and problem-solved during virtual meetings with the professor held every two weeks. Initially, Case II started with a lower score than Case I, mainly due to challenges in locating the necessary datalogger near the students, a problem resolved when the Laboratory sent the equipment directly to the students. Despite these initial obstacles, Case II ultimately achieved maximum scores based on its results. The grading system not only served to indicate the students' progress toward their final objectives but also played a motivational role, encouraging students to compete for better performance and results in the project.

This research has demonstrated that even under highly restrictive conditions, including limited mobility due to pandemic lockdowns, financial constraints (as the students were undergraduates), scarce availability of materials and devices, absence of face-to-face teaching, and lack of prior background knowledge (as the students had no previous training in the topic, and all interactions were virtual), active teaching methods combined with hands-on experience can effectively teach complex subjects to undergraduate students remotely. This success opens possibilities for utilizing similar approaches in equally challenging situations, such as war or conflict zones worldwide. Moreover, this method could be employed to remotely educate students in poor countries in developing regions by professors situated in other continents.

5.1 Answer to research questions

In this section, we delve into answering key research questions surrounding the advancement and application of thermoelectric technology. We focus on improving the efficiency of thermoelectric generators (TEGs) to maximize energy conversion from waste heat sources, explore the latest advances in thermoelectric materials, understand their potential applications beyond traditional industrial settings, identify key challenges hindering their widespread adoption, and examine how active learning methodologies and real-world research experiences can improve engineering education in this area.

How can we improve the efficiency of thermoelectric generators to maximize energy conversion from waste heat sources?

Improving the efficiency of thermoelectric generators (TEGs) involves a multi-faceted approach encompassing a variety of strategies. These include materials screening to discover or synthesize materials with high ZT (figure of merit), nanostructuring to design nanoscale materials, application of multilayer thin films, optimization of device design, improved heat management, exploration of hybrid systems, control of operating conditions, use of advanced manufacturing techniques, integration of TEGs into existing systems, and continued research and development efforts.

What are the latest advancements in thermoelectric materials, and how can they be leveraged to enhance the performance and durability of TE systems?

Recent advancements in thermoelectric materials offer opportunities to improve the performance and durability of thermoelectric systems. These advancements include the development of high-ZT materials, nanostructuring techniques, advanced manufacturing methods, composite and hybrid materials, and thermal management solutions. Leveraging these advancements can enhance the efficiency and reliability of thermoelectric systems in various applications.

What are the potential applications of thermoelectric technology beyond traditional industrial settings, and how can they contribute to sustainability in diverse sectors such as transportation, agriculture, and construction?

Thermoelectric technology has diverse applications beyond traditional industrial settings, offering sustainability benefits in transportation, agriculture, and construction. These applications include integrating TEGs into automotive exhaust systems, powering remote monitoring and irrigation systems in agriculture, and improving energy efficiency in construction through building-integrated thermoelectric systems.

What are the main challenges hindering the widespread adoption of thermoelectric systems, and how can we overcome them through technological innovation and policy support?

Several challenges hinder the widespread adoption of thermoelectric systems, including cost, efficiency, durability, and scale and integration. Overcoming these challenges requires technological innovation in material development, system design, and manufacturing processes, as well as policy support through incentives, subsidies, and regulations promoting the development and deployment of thermoelectric technology.

How can active learning methodologies and real-world research experiences enhance engineering education, particularly in the context of thermoelectric technology and sustainable energy practices?

Active learning methodologies and real-world research experiences offer several benefits for engineering education in

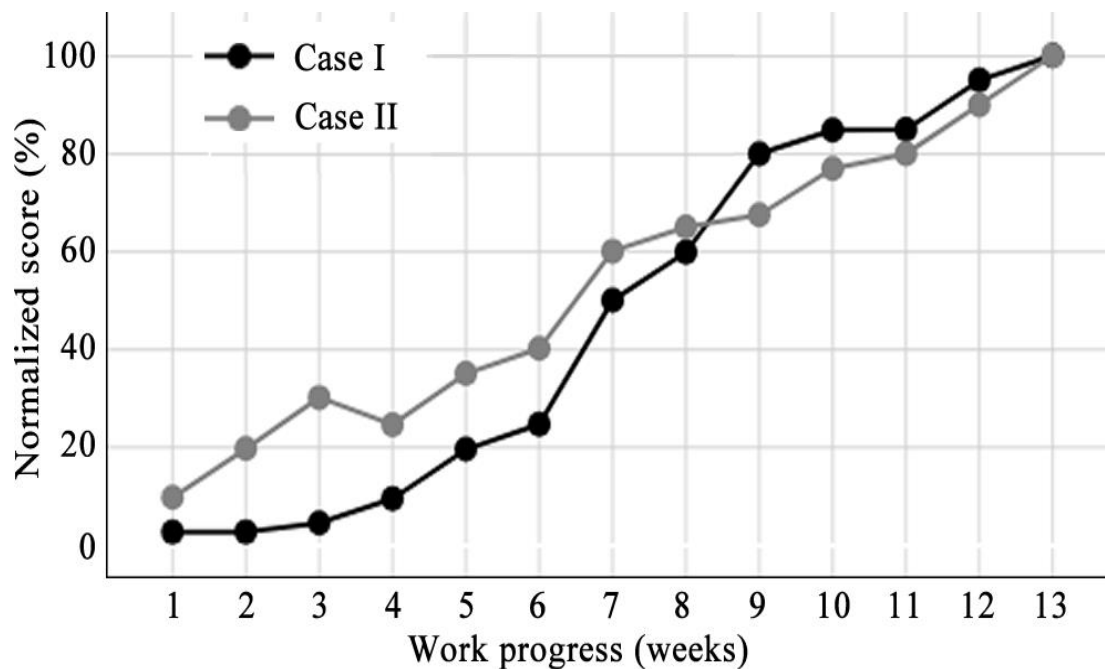


Fig. 7 Comparison of maximum temperature during thermophilic stage based on mass.

thermoelectric technology and sustainable energy practices. These benefits include increased student engagement and motivation, development of critical thinking and problem-solving skills, interdisciplinary learning, experiential learning through hands-on experimentation, professional development, and fostering innovation and creativity in sustainable energy technology.

5.2 Limitations of the study and future research directions

The energy balance analysis for the hopper system, while providing theoretical insights, has several inherent limitations that may affect its accuracy in representing real-world conditions. One key limitation is the assumption of steady-state operation, which fails to capture the dynamic nature of heat transfer within the system. Transient effects, such as fluctuations in ambient temperature, variations in fuel properties over time, and thermal behavior during ignition or extinguishing of the heat source, can introduce unsteady thermal conditions that deviate from the steady-state assumption.

Furthermore, the analysis assumes perfect thermal contact between the thermoelectric module and adjacent surfaces. However, in practical scenarios, interfacial thermal resistances due to surface roughness, gaps, or material property mismatches can impede heat flow, leading to reduced heat transfer to the thermoelectric generator (TEG). These contact resistances, often challenging to quantify accurately, may result in underestimations of the temperature differential across the TEG, consequently affecting its power output.

Additionally, the analysis neglects convective heat transfer on the inner face of the thermoelectric cell and radiative heat transfer mechanisms. While these simplifications may be reasonable under certain conditions, they can become

significant sources of error, particularly at higher temperature differentials or in scenarios involving complex geometries or surface properties that influence convection and radiation heat transfer modes.

Moreover, the thermal and electrical properties of the thermoelectric materials themselves may exhibit non-linear behavior or temperature dependencies that are not fully captured by the simplified analysis. These material property variations can influence the TEG's performance characteristics, potentially deviating from the assumptions made in the calculations.

It is important to note that the neglect of contact resistance, convection, and radiation could lead to underestimation or overestimation of the actual heat transfer rates. Consequently, the calculated heat transfer rates and electrical power recuperation might deviate from the actual values to some extent. Furthermore, while the energy balance analysis provides insights into the theoretical maximum energy harnessed by the TEG unit, it does not account for losses or inefficiencies within the system. Factors such as electrical resistance, thermal losses, and system design constraints could significantly reduce the actual electrical power recuperated compared to the calculated maximum. Therefore, the reported TE system performance of 6.73% should be interpreted with caution, as it represents an idealized scenario under ideal conditions.

To improve the accuracy and robustness of the energy analysis, future studies could incorporate more comprehensive models that account for transient heat transfer dynamics, interface resistances, and non-ideal behaviors of thermoelectric materials. Experimental validation of the theoretical predictions using different operating conditions and heat transfer fluids would also enhance the reliability of

the findings. Alternative approaches, such as numerical simulations or experimental parametric studies, could complement the analytical approach, providing a more comprehensive understanding of the complex interactions involved in thermoelectric energy conversion. Additionally, exploring different configurations or materials for the TEG unit and optimizing system parameters could further optimize performance and efficiency in practical applications.

6. Conclusions

The study cases presented in this research demonstrated remarkable success despite the challenging circumstances posed by the Covid-19 lockdown in Colombia, but applicable to situations where students or members of the academic community are under major constraints, such as public health, violence, environmental disaster, or just distance from the classrooms. This experience showcases its potential applicability in other intricate situations, including conflict zones, remote areas, and various challenging scenarios.

All techniques employed in this study significantly enhanced students' competencies beyond the technical aspects of the course. These skills included project completion, leadership, teamwork, problem-solving, and effective communication abilities.

The implementation of TE technology in extractor hoppers emerges as a promising opportunity to harness the heat generated in diverse processes where these hoppers are employed. Utilizing TE cells enhances the efficiency of processes prone to heat losses. Moreover, TE devices are user-friendly for maintenance and installation, adaptable to different hopper arrangements, and diverse geometries.

The efficient heat transfer directly on the cell faces significantly impacts their energy generation. This factor is influenced by the working fluid type, material conductivity, natural or forced convection, radiation, and other phenomena originating from the heat source.

During the experiment, a relatively swift temperature rise was observed until reaching the thermophilic stage (9 days), followed by a gradual decrease until it stabilized at ambient temperature. This decline was slightly delayed compared to the initial temperature rise, indicating asymmetrical microorganism activity during these two stages.

Lastly, it's noteworthy that the maximum temperature attained during the compost experiment was lower than some previous research findings involving these materials. This variance can be attributed to the reduced quantity of waste used, which was a consequence of the stringent lockdown restrictions in place.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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