

Educational Innovation in Sustainable Engineering: Performance and Economic Analysis of Waste Cooking Oil-Fueled Crucible Furnaces for Aluminum Melting

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(Received: April 22, 2026; Revised: June 6, 2026; Accepted: June 12, 2026)

Abstract

This study investigates the feasibility of utilizing waste cooking oil (WCO) as an alternative fuel for aluminum melting in a small-scale crucible furnace, with integration into sustainable engineering education. An experimental design was employed to evaluate thermal performance, fuel efficiency, and cost-effectiveness. The results indicate that WCO can reach a maximum temperature of 900°C within 20 minutes, comparable to that of a WCO–diesel mixture (850°C). Furthermore, WCO demonstrated a 5.13% improvement in fuel efficiency and a reduction in fuel costs of approximately 70%.

The findings confirm that WCO is a viable and cost-effective alternative fuel that supports circular economy principles and sustainable engineering practices. In addition, the developed system demonstrates potential as a practical learning tool for experiential learning in sustainable engineering education, thereby contributing to educational innovation.

Keywords: Waste Cooking Oil, Aluminum Melting, Crucible Furnace, Sustainable Engineering Education, Cost Efficiency, Circular Economy

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Introduction

The increasing global demand for sustainable energy solutions has significantly influenced industrial processes and engineering education. The manufacturing sector, in particular, faces growing pressure to reduce reliance on fossil fuels while improving cost efficiency and environmental performance. Aluminum, widely used in construction, automotive, and household industries, requires substantial thermal energy during melting, typically derived from fossil fuels such as diesel and electricity. This results in high operational costs and increased carbon emissions. At the same time, waste management has become a critical issue, especially in developing countries where improper disposal of waste cooking oil (WCO) leads to environmental pollution and public health risks. WCO, generated in large quantities from household and commercial activities, can contribute to water contamination and greenhouse gas emissions if not properly managed (Zulfa, 2024). Converting WCO into an alternative energy source aligns with circular economy principles, which emphasize transforming waste into valuable resources (Geissdoerfer et al., 2017). WCO has gained attention as a fuel for thermal systems due to its availability, relatively high calorific value, and lower cost compared to conventional fuels (Demirbas, 2009). Previous studies have shown that vegetable oils can be used effectively in combustion systems with performance comparable to that of fossil fuels (Saidur et al., 2011). However, most research focuses on large-scale industrial applications, with limited attention to small-scale systems suitable for local industries and educational use. Meanwhile, engineering education is shifting toward sustainability-oriented learning. Education for Sustainable Development (ESD) promotes experiential learning and real-world problem-solving (UNESCO, 2020). Integrating sustainable technologies into learning environments helps develop critical competencies such as systems thinking and innovation (Lozano et al., 2017).

In addition, the next phase of this study aims to utilize the research findings as a foundation for developing instructional modules or training programs designed to transfer knowledge to local communities. Such applications are expected to support community-based learning and promote the practical adoption of waste-to-energy technologies, thereby strengthening sustainable practices at the grassroots level.

Therefore, this study investigates the use of WCO in a small-scale furnace, integrating technical performance, cost analysis, and educational application to support sustainable engineering practices.

Objectives

This study aims to:

- 1) Design and develop a small-scale crucible furnace using waste cooking oil (WCO) and evaluate its thermal performance under different fuel conditions.
- 2) Compare the performance of WCO with conventional fuel mixtures (WCO–diesel) in terms of heating rate, peak temperature, fuel consumption, efficiency, and cost-effectiveness.
- 3) Assess the applicability of WCO within a circular economy framework, with a focus on waste-to-energy conversion and resource utilization.

Literature Review

Alternative Fuels in Thermal Systems

The use of alternative fuels in thermal applications has been widely studied as a strategy to reduce dependency on fossil fuels and mitigate environmental impacts. Biomass-derived fuels, including vegetable oils and waste cooking oil, have been identified as viable energy sources due to their renewable nature and relatively high energy content (Saidur et al., 2011). According to Demirbas (2009), vegetable oils possess combustion characteristics suitable for industrial heating processes, particularly when properly atomized. Waste cooking oil (WCO) has attracted attention because of its dual benefits for waste management and energy production. It can be converted into biofuel or directly used in combustion systems with minimal processing. Similarly, Panwar et al. (2011) emphasize that renewable energy sources, such as WCO, significantly reduce greenhouse gas emissions and improve energy security. Despite these advantages, challenges remain in combustion stability, viscosity, and consistency in fuel quality. Studies suggest that blending WCO with diesel can improve ignition properties, although this may increase operational costs (El-Adawy et al., 2013). Therefore, further research is required to evaluate the feasibility of using WCO as a standalone fuel in small-scale thermal systems.

Circular Economy and Waste-to-Energy Concept

The circular economy framework promotes transforming waste into valuable resources, thereby reducing environmental impact and enhancing economic efficiency. Geissdoerfer et al. (2017) define circular economy as a regenerative system in which resource input and waste generation are minimized through reuse, recycling, and energy recovery. In the context of waste cooking oil, the waste-to-energy approach represents a practical application of circular economy principles. Converting WCO into fuel for aluminum melting not only reduces waste disposal issues but also creates an alternative energy source for industrial use (Wei et al., 2020). This approach is particularly relevant for small and medium enterprises (SMEs), which often face constraints in energy costs and resource availability. Recent studies have also emphasized the importance of integrating circular economy practices

into local production systems. Torre and Bourdin (2026) argue that decentralized energy systems using waste-derived fuels can enhance resilience and sustainability at the community level. Thus, the application of WCO in small-scale furnaces is a scalable, context-appropriate solution.

Engineering Education and Sustainability Integration

The integration of sustainability into engineering education has become a key priority in recent years. Lozano et al. (2017) argue that engineering programs must incorporate sustainability principles to prepare graduates for complex global challenges. This includes not only theoretical knowledge but also practical applications that allow students to engage with real-world problems. Education for Sustainable Development (ESD) frameworks emphasize active learning approaches, such as project-based learning and laboratory experimentation (UNESCO, 2020). By incorporating sustainable technologies into educational settings, students can develop competencies in critical thinking, innovation, and environmental responsibility. Furthermore, experiential learning through hands-on engineering projects has been shown to significantly enhance student engagement and learning outcomes (Li et al., 2019). In this regard, the use of WCO-based furnaces in laboratory settings provides a valuable platform for integrating sustainability concepts into engineering practice.

Practical Contribution

Although previous studies have explored the use of alternative fuels and circular economy principles, several research gaps remain. First, limited research has focused on small-scale furnace systems suitable for SMEs and educational institutions. Second, there is a lack of integrated studies that combine technical performance, cost analysis, and educational applications. Third, the role of such systems in supporting sustainability-oriented learning has not been fully explored. This study addresses the gaps identified in Table 1

Table 1 Gap Analysis of this research

Literature Area	Existing Studies	Identified Research Gap	Contribution of This Study
Alternative Fuels in Thermal Systems	Studies confirm that biomass and vegetable oils can be used as alternative fuels in combustion systems (Saidur et al., 2011; Demirbas, 2009)	Most studies focus on large-scale industrial applications; limited focus on small-scale furnaces	Develops and experimentally tests a small-scale crucible furnace suitable for SMEs and educational use

Table 1 (continued)

Literature Area	Existing Studies	Identified Research Gap	Contribution of This Study
Waste Cooking Oil Utilization	WCO is widely studied for biodiesel production and engine applications	Limited research on direct combustion uses in metal melting furnaces	Demonstrates the feasibility of direct WCO utilization for aluminum melting without complex processing
Circular Economy Application	Circular economy emphasizes waste-to-energy and resource efficiency (Geissdoerfer et al., 2017)	Lack of practical case studies linking circular economy with engineering operations and local industry	Provides an applied waste-to-energy model using WCO in real engineering processes
Engineering Education for Sustainability	Sustainability integration improves competencies in engineering education (Lozano et al., 2017; UNESCO, 2020)	Limited integration of real engineering systems into learning environments	Proposes a hands-on educational model using WCO furnace for experiential learning
Cost and Economic Analysis	Existing studies often focus on technical performance	Insufficient analysis of cost efficiency in alternative fuel systems	Provides a quantitative cost analysis showing ~70% fuel cost reduction
Integrated Approach (Technical with Economic and Educational)	Most studies examine technical or environmental aspects separately	Lack of holistic integration across engineering, economics, and education	Develops a multi-dimensional framework combining performance, cost, and education (including 4P-AF concept)

Table 1 summarizes the key research gaps identified in the literature and highlights the contributions of this study to addressing them. Despite extensive research on alternative fuels and circular economy applications, three critical gaps remain. First, existing studies primarily focus on large-scale industrial systems, with limited attention to small-scale furnaces suitable for SMEs and educational environments. Second, prior research often examines technical

performance in isolation, without integrating with economic analysis or sustainability frameworks. Third, the application of such systems in engineering education remains underexplored, particularly in terms of experiential learning and real-world implementation. This study addresses these gaps by developing a small-scale WCO-based furnace that integrates performance evaluation, cost analysis, and educational applicability within a unified framework.

Theoretical Contribution

This study advances sustainable engineering and education by integrating the circular economy, alternative energy, and engineering pedagogy into a unified framework. It demonstrates a micro-level waste-to-energy application using WCO in small-scale furnaces, extends alternative fuel theory through direct combustion in metal processing, and contributes to engineering education by embedding sustainability into experiential learning.

This study presents a cost-effective furnace system for SMEs that reduces fuel costs by approximately 70% while maintaining performance. It offers a practical waste-to-energy solution, supports the implementation of the circular economy, and serves as a hands-on learning tool in engineering education. Additionally, the cost analysis provides a decision-making tool for stakeholders and supports policy development in sustainable energy and education.

Methodology

The methodology was designed to align with sustainable engineering and educational objectives through a systematic approach encompassing design, fabrication, material preparation, and performance evaluation. In addition, a qualitative assessment of circular economy applicability was conducted based on waste-to-energy principles, while educational relevance was analyzed using experiential learning frameworks.

Design and Construction of the Crucible Furnace

The furnace was constructed in multiple stages to ensure safety and thermal efficiency in a laboratory setting. A cylindrical steel casing with a stable tripod base was fabricated to support the structure. The interior was lined with refractory bricks and insulating materials to reduce heat loss. A specialized burner system was developed to handle high-viscosity fuels, using compressed air to atomize waste cooking oil (WCO) for efficient combustion. A control valve regulated fuel flow rates between 0.5–1.5 L/min. Additionally, a lever-operated lid facilitated safe loading and exhaust control. The three fuel flow rate levels (0.5, 1.0, and 1.5 L/min) were selected based on the operational range of the pneumatic pump system and preliminary trials that confirmed flame stability within this range. The 0.5 L/min level represents the minimum flow sufficient to sustain combustion; 1.0 L/min was identified as the intermediate stable operating point; and 1.5 L/min represents the upper limit before

atomization quality begins to degrade due to excessive fuel supply relative to air pressure capacity.

Material and Fuel Preparation

WCO was collected from local sources in Chiang Mai and processed through a 14-day sedimentation period, followed by filtration to remove impurities. Aluminum scrap (5.0 kg per trial) was selected for its low melting point and suitability for educational demonstrations. Experimental Performance Evaluation

Experiments were conducted under controlled conditions. The furnace was initially ignited with diesel, then transitioned to 100% WCO. Fuel flow rates were adjusted (0.5, 1.0, and 1.5 L/min), and temperature was recorded at 5-minute intervals using a digital pyrometer. Combustion efficiency was evaluated based on flame characteristics and the quality of the molten metal.

Economic and Cost Analysis

The final phase of the methodology involved a quantitative cost-benefit analysis to demonstrate the economic feasibility of biofuels in education. The analysis utilized the following metrics: To determine the percentage of cost savings achieved through the use of waste cooking oil (WCO) compared to conventional diesel fuel, the following equation was applied:

$$\text{Cost Saving (\%)} = \frac{(P_{\text{diesel}} \times V_{\text{diesel}}) - (P_{\text{WCO}} \times V_{\text{WCO}})}{P_{\text{diesel}} \times V_{\text{diesel}}} \times 100$$
$$\text{Cost Saving (\%)} = \frac{(35 \times 2.73) - (10 \times 2.59)}{35 \times 2.73} \times 100 = 72.9\%$$

The percentage of cost savings was calculated by comparing the total fuel cost between diesel-based and 100% WCO conditions. The calculation incorporates both fuel prices and consumption per melting cycle, enabling an accurate evaluation of economic efficiency.

Experimental Reliability and Validation

To ensure the reliability of the experimental results, each test condition was repeated three times under identical operating conditions. The average values were reported to minimize measurement variability. Temperature measurements were conducted using a calibrated digital pyrometer with an accuracy of $\pm 5^{\circ}\text{C}$. Fuel consumption was measured using a graduated fuel tank with a precision of ± 0.01 liters. These measures enhance the validity and reproducibility of the experimental findings.

Results

The system was found suitable for laboratory-based learning, enabling hands-on experimentation in combustion, energy efficiency, and cost analysis. The experimental system demonstrates a closed-loop resource utilization approach that effectively converts waste cooking oil into usable thermal energy. This section presents the experimental findings of aluminum melting using waste cooking oil (WCO) and a WCO–diesel mixture. The results are structured into four components: (1) temperature profiles, (2) comparative performance analysis, (3) fuel efficiency evaluation, and (4) key performance synthesis.

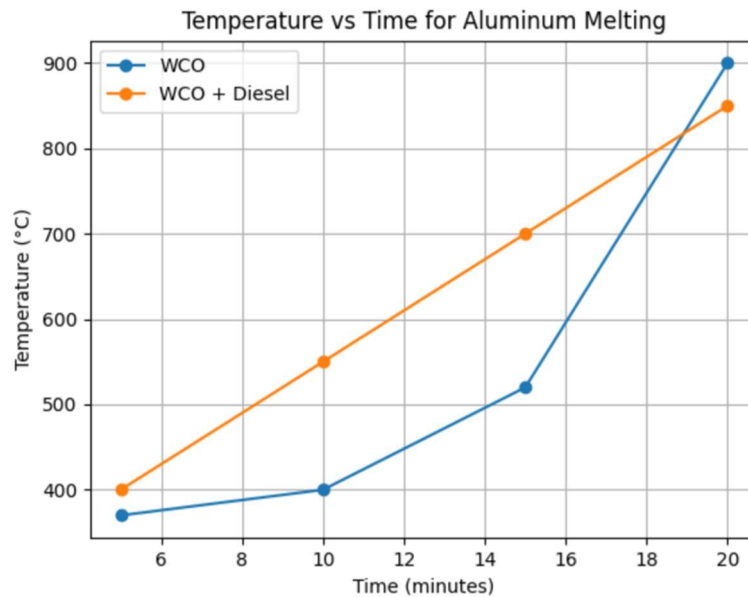


Figure 1 Temperature profiles of waste cooking oil (WCO) and a WCO–diesel mixture during the aluminum melting process.

As illustrated in Figure 1, the WCO–diesel mixture exhibits a faster initial heating rate, while WCO achieves a higher peak temperature, indicating superior thermal efficiency during sustained combustion.

Temperature Profile Using Waste Cooking Oil (WCO)

The temperature evolution during aluminum melting using WCO as the sole fuel is presented in Table 2.

Table 2 Temperature Profile of Aluminum Melting Using WCO (5 kg Aluminum)

Time (min)	Temperature (°C)	Process Stage	Observation
5	370	Initial heating	Aluminum surface darkens
10	400	Heat accumulation	Edge softening observed
15	520	Phase transition	Semi-liquid state
20	900	Full melting stage	Complete melting achieved

The results show that WCO can generate sufficient thermal energy to reach a maximum temperature of 900°C within 20 minutes. The melting process exhibits a gradual increase in temperature, with a distinct phase transition occurring between 10 and 15 minutes.

Temperature Profile Using WCO–Diesel Mixture

The temperature profile for the WCO–diesel mixture (1:4 ratio) is presented in Table 3.

Table 3 Temperature Profile Using WCO–Diesel Mixture (5 kg Aluminum)

Time (min)	Temperature (°C)	Process Stage	Observation
5	400	Rapid ignition	Faster temperature rise
10	550	Stable combustion	Melting begins
15	700	High thermal stage	Majority of aluminum molten
20	850	Steady state	Complete melting achieved

The mixture demonstrates faster initial heating, attributed to diesel’s higher volatility and combustion stability. However, the peak temperature is slightly lower than that achieved by WCO alone.

Comparative Performance Analysis

A comparative evaluation of both fuel systems is presented in Table 4. The values reported in Tables 2 to 4 represent average results across three replications at the optimal fuel flow rate of 1.0 L/min, which yielded the most stable combustion performance among the three tested levels (0.5, 1.0, and 1.5 L/min). This flow rate was selected as the representative condition for comparative analysis.

Table 4 Comparative Performance between WCO and WCO–Diesel Mixture

Parameter	WCO Only	WCO with Diesel	Interpretation
Maximum Temperature (°C)	900	850	WCO achieves higher peak temperature
Melting Time (min)	20	20	No significant difference
Fuel Consumption (L)	2.59	2.73	WCO consumes less fuel
Combustion Stability	Moderate	High	Diesel improves ignition stability
Heating Rate	Moderate	High	The mixture heats faster in the early stage

The results indicate that both systems can achieve complete aluminum melting within the same duration. However, WCO demonstrates superior performance in terms of maximum

temperature and fuel consumption, while the WCO–diesel mixture offers advantages in combustion stability and initial heating rate.

Fuel Efficiency Analysis

Fuel efficiency was evaluated based on fuel consumption per melting cycle. The efficiency gain of WCO compared to the WCO–diesel mixture is calculated as follows:

$$\text{Efficiency Gain (\%)} = \left(\frac{2.73 - 2.59}{2.73} \right) \times 100 = 5.13\%$$

This result indicates that WCO improves fuel efficiency by approximately 5.13%. In addition, when considering thermal output per unit of fuel, WCO demonstrates higher energy utilization efficiency, achieving higher peak temperatures with lower fuel consumption.

Thermal Efficiency Analysis

Thermal efficiency was estimated by comparing the energy input to the useful energy absorbed by the aluminum charge. Assuming aluminum specific heat of 0.897 kJ/kg·°C and latent heat of fusion of 397 kJ/kg, the theoretical energy required to melt 5 kg of aluminum from 25°C to 900°C is approximately 2,965 kJ. Based on a WCO lower heating value of approximately 34 MJ/kg and a density of 0.91 kg/L, the 2.59 L of WCO consumed provides approximately 79,976 kJ of chemical energy. The resulting thermal efficiency is estimated at approximately 3.7%, which is typical for small-scale open-top furnaces where significant heat loss occurs through radiation, convection from the furnace wall, and exhaust gases. Future improvements in insulation and heat recovery could substantially improve this figure.

Cost-Performance Efficiency

Beyond thermal efficiency, cost-performance efficiency was evaluated by integrating fuel cost and consumption: 1) WCO system: lower fuel cost with lower consumption, 2) Diesel mixture: higher cost with higher consumption. This confirms that WCO provides both technical and economic advantages, making it suitable for small-scale industrial and educational applications. The fuel price assumptions were based on average market prices in Chiang Mai, Thailand (2026), where diesel costs approximately 35 THB/liter, while waste cooking oil is available at approximately 10 THB/liter, including collection and filtration costs.

Discussions

This study interprets the experimental findings within the context of existing literature on alternative fuels, circular economy, and engineering education, while highlighting new knowledge contributions and implications for practice. The results demonstrate that waste cooking oil (WCO) can achieve thermal performance comparable to conventional diesel-based systems. Specifically, WCO reached a maximum temperature of 900°C, which is sufficient for aluminum melting. This finding is consistent with Saidur et al. (2011), who reported that biomass-derived fuels possess adequate calorific value for industrial thermal applications. Similarly, Demirbas (2009) emphasized that vegetable oils can exhibit favorable combustion characteristics when properly atomized. The present study confirms that effective atomization enables WCO to overcome challenges related to higher viscosity, resulting in stable combustion and efficient heat generation. However, the findings contrast with Tran et al. (2019), who suggested that blending vegetable oil with diesel is necessary to improve combustion performance. In this study, WCO alone achieved equal or superior performance in terms of peak temperature and fuel efficiency compared to the WCO–diesel mixture. This suggests that under controlled experimental conditions, blending may not be required for small-scale furnace systems, thereby reducing operational complexity and cost. This discrepancy may be attributed to differences in furnace scale, atomization system design, and fuel preheating conditions. In this study, the compressed-air atomization system effectively reduced WCO viscosity at the nozzle, enabling stable combustion without diesel blending. Furthermore, although WCO generally has a lower Lower Heating Value (LHV) than diesel by approximately 10–15%, the higher density of WCO results in greater energy content per unit volume delivered, which, combined with efficient atomization, may explain the superior thermal output observed at the small-scale level. The findings indicate that WCO has potential as a low-cost alternative fuel. The present study further contributes empirical evidence regarding both its technical and economic performance. WCO demonstrated improved fuel efficiency (5.13%) and reduced fuel costs by approximately 70%, indicating strong potential for application in decentralized, small-scale systems. Furthermore, the higher peak temperature observed in WCO compared to the diesel mixture suggests improved energy utilization efficiency, consistent with findings by Abdelgawad et al. (2015). From a circular economy perspective, this study provides practical evidence of waste-to-energy implementation. As conceptualized by Geissdoerfer et al. (2017), circular economy systems aim to minimize waste through resource recovery. The use of WCO in aluminum melting represents a micro-level application of this principle, transforming waste into a valuable energy resource. This supports the argument by Babalola et al. (2022) that localized waste-to-energy systems can enhance sustainability and resilience at the community level. The findings demonstrate that WCO, as a locally available resource, can be effectively utilized in small-scale industrial applications, contributing to both environmental sustainability and economic efficiency.

In addition, the study highlights the integration of sustainable technologies into engineering education. The use of WCO-based furnace systems aligns with Education for Sustainable Development (ESD) principles, which emphasize experiential and problem-based learning (UNESCO, 2020). As noted by Lozano et al. (2017), sustainability education should involve real-world applications that enhance systems thinking and innovation. The developed furnace system provides a hands-on learning platform that allows students to explore combustion processes, energy efficiency, and cost analysis. Importantly, the outcomes of this research have been implemented in teaching and learning activities within the Industrial Arts program at Chiang Mai Rajabhat University. The furnace system has been used as a laboratory-based learning tool, enabling students to engage in practical experimentation in metal casting and alternative energy use. This real-world application enhances technical competencies, promotes sustainability awareness, and supports experiential learning. Furthermore, integrating cost analysis into the experimental process helps students understand economic decision-making, an aspect often lacking in traditional engineering curricula.

In addition, the findings of this study provide a strong foundation for the next phase of research, which focuses on developing instructional modules and community-based training programs. The demonstrated technical performance and cost efficiency of the WCO-based furnace indicate its suitability for practical learning environments and knowledge transfer at the community level. Such applications have the potential to support community-based learning and promote the adoption of waste-to-energy technologies in real-world contexts.

Suggestions

Despite its contributions, the study has several limitations. First, the experiment was conducted at a small scale (5 kg of aluminum), which may limit generalization to industrial applications. Second, fuel properties such as viscosity and calorific value were not analyzed in detail. Third, environmental impacts, including emissions such as CO, NO_x, and particulate matter, were not evaluated; future work should include emission analysis to verify compliance with environmental standards and confirm the sustainability credentials of WCO combustion. Fourth, while cost savings of 72.9% were demonstrated, a Simple Payback Period (SPP) analysis was not conducted. Based on estimated furnace construction costs of approximately 15,000 THB and fuel savings of approximately 68 THB per melting cycle ($35 \times 2.73 - 10 \times 2.59$), the estimated SPP is approximately 220 cycles, which at one cycle per day represents approximately 7–8 months of operation—indicating strong economic viability for SME adoption. Future research should focus on scaling up the system, conducting emissions analyses, assessing long-term operational stability, and integrating digital monitoring technologies, such as IoT systems, for real-time optimization.

In addition, future research should explore the educational implementation of the developed system, particularly in designing instructional modules or learning activities based

on the experimental results. Further studies are also recommended to evaluate learning outcomes and examine the effectiveness of applying the system in community-based training programs. Such efforts will help bridge the gap between engineering innovation and educational practice, and support the transfer of knowledge to local communities in a sustainable manner. Additionally, future studies should analyze the physical properties of WCO, including viscosity and specific calorific value, to provide a more comprehensive thermal performance baseline. The potential for scaling this WCO-based furnace system to serve local SMEs and community enterprises represents a strong opportunity that should be further emphasized in future work, as it holds significant promise for economic empowerment and sustainable development at the community level.

New knowledge

This study contributes new knowledge in several dimensions. First, it demonstrates the direct use of WCO as a combustion fuel in small-scale crucible furnaces without requiring complex preprocessing. This extends existing research, which has primarily focused on biodiesel production and engine applications. Second, it provides empirical evidence on cost-performance efficiency, showing that WCO can significantly reduce fuel costs while maintaining performance. Third, it advances circular economy research by operationalizing waste-to-energy concepts at the micro-engineering level. Fourth, it contributes to engineering education by integrating technical systems into experiential learning environments. Furthermore, the study proposes a multi-dimensional framework that integrates technical performance, economic analysis, circular economy, and engineering education, including the application of the 4P-AF Learning City Platform concept. This interdisciplinary approach links engineering innovation with educational and sustainability frameworks, providing a novel contribution to both theory and practice.

Conclusion

This study confirms that WCO is an effective and economical alternative fuel for aluminum melting in small-scale furnaces. The system achieved a maximum temperature of 900°C, improved fuel efficiency by 5.13%, and reduced costs by approximately 70%. These findings demonstrate that WCO can replace conventional fuels without compromising performance. Additionally, integrating this system into engineering education supports sustainability-oriented learning and practical skill development. From a policy perspective, the findings suggest that governments should promote waste-to-energy initiatives and support WCO collection systems. The significant cost savings highlight the potential for improving SME competitiveness, while educational institutions should integrate sustainable technologies into curricula. This study bridges the gap among technical performance, economic feasibility, and educational application and demonstrates the potential for broader adoption of WCO-based

systems across industrial and academic contexts. In addition, the outcomes of this research have been practically implemented in teaching and learning activities for students in the Industrial Arts program at Chiang Mai Rajabhat University. The developed furnace system has been used as a laboratory-based learning tool, enabling students to engage in hands-on experimentation related to metal casting, alternative energy utilization, and cost analysis. This real-world application enhances students' technical skills, promotes sustainability awareness, and supports experiential learning aligned with Education for Sustainable Development (ESD) principles.

Acknowledgements

The authors would like to express their sincere gratitude to Chiang Mai Rajabhat University for its support, scholarship, and resources, which contributed to the successful completion of this research. The authors also gratefully acknowledge Rajamangala University of Technology Lanna for their academic support and collaboration in this study.

Declaration of Artificial Intelligence (AI) Use

The authors used SciSpace AI and Grammarly AI as writing-support technologies during the preparation of this manuscript. These tools were employed to facilitate literature discovery, manuscript organization, summarization, language editing, translation, code generation, and reference formatting. No AI tool was used to generate scientific interpretations, research findings, or conclusions. All AI-assisted outputs were critically evaluated, verified against the original sources, and revised by the authors. The authors assume full responsibility for the accuracy, originality, integrity, and final content of the manuscript.

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