



## Development of an Industrial-Scale Coffee Drying Technology: Energy Efficiency and Sustainability Assessment

Richard A Williams<sup>1\*</sup> , Maria V Sanchez-Delgado<sup>2</sup> , John M Dennis<sup>3</sup> , Eleanor C Sharp<sup>4</sup> , Samuel J Pettinger<sup>5</sup> 

<sup>1\*</sup>Department of Engineering; Chair in Sustainable Process Engineering, University of Manchester

<sup>2</sup>Cambridge Centre for Sustainable Energy & Resources (CCSER); Research Director for Thermal Systems.

<sup>3</sup>Department of Chemical Engineering and Biotechnology; Professor of Energy and Environmental Engineering.

<sup>4</sup>Department of Engineering; Lecturer in Thermofluids and Energy Systems.

<sup>5</sup>Cambridge Centre for Sustainable Energy & Resources (CCSER); Research Fellow in Agro-Industrial Decarbonization.

*Corresponding Autor\*:* [ra.williams@cam.ac.uk](mailto:ra.williams@cam.ac.uk)

<p><b>Article history</b> <i>Received Date:</i> 10 January 2026; <i>Accepted:</i> 19 April 2026; <i>Published:</i> 30 April 2026</p>	<p><b>Abstract</b> This study addresses the critical need for energy-efficient and sustainable technologies in industrial coffee processing by developing and evaluating a novel waste-heat recovery preheater integrated into a coffee roasting system. The research experimentally investigates the impact of preheating on the thermal dynamics, energy efficiency, and product quality of Robusta coffee beans at a laboratory scale. Results demonstrate that utilizing exhaust heat to pre-condition beans significantly enhances process performance, achieving a 62.33% reduction in overall energy consumption and a 60.65% decrease in LPG fuel use. The preheating mechanism accelerated the roasting kinetics, reducing the time to target roast level by 2–3 minutes and improving moisture removal efficiency, yielding a final bean moisture content of 1.6% compared to 3.1% in the conventional process. These findings validate the preheater as a highly effective intervention for optimizing heat and mass transfer. The study concludes that integrating such waste-heat recovery technology presents a viable, scalable pathway for decarbonizing industrial-scale coffee drying and roasting operations, directly contributing to enhanced energy efficiency, reduced carbon footprint, and improved economic viability within the global coffee supply chain.</p>
--	--

**Keywords:** *Energy Efficiency; Sustainable Coffee Processing; Waste-Heat Recovery; Preheating System; Thermal Performance*

© 2026 GIOEDUTECH-All rights reserved

### 1 Introduction

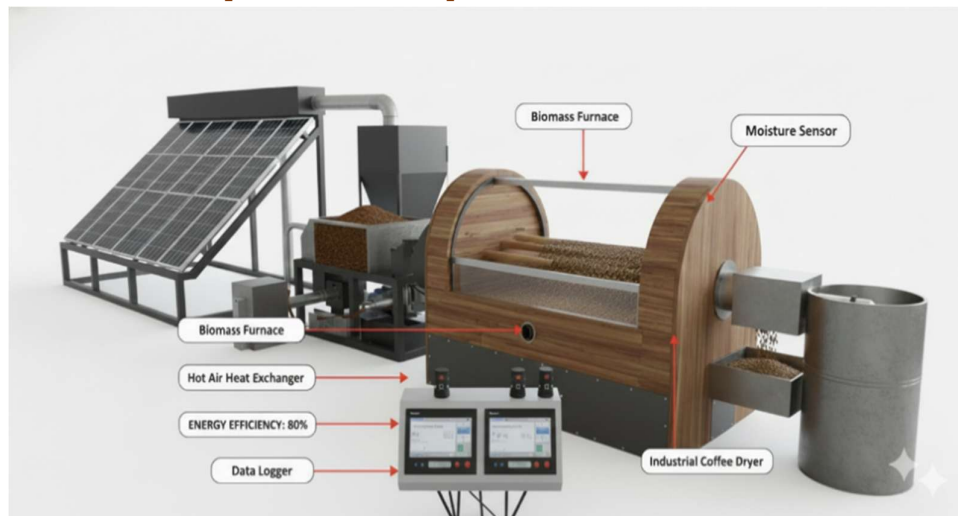
Global coffee production, exceeding 10 million tons annually, is an energy-intensive agro-industry where post-harvest processing, particularly drying and roasting, accounts for a substantial portion of its carbon footprint and operational costs [1],[2]. In an ideal paradigm, industrial coffee processing would operate within a circular economy framework, maximizing energy efficiency through integrated renewable systems and achieving near-zero waste emissions [3],[4]. However, the prevailing industrial reality is characterized by a heavy reliance on fossil fuels, with conventional hot-air dryers and roasters exhibiting high specific energy consumption and significant thermal losses, primarily through unharnessed exhaust gases [5],[6]. This represents a critical sustainability bottleneck, as the sector faces mounting pressure to mitigate its environmental impact while maintaining economic competitiveness and product quality [7].

Recent research has extensively explored pathways to improve the sustainability of thermal food processing, highlighting waste-heat recovery as a promising strategy [8], [9]. Studies on industrial dryers and roasters have quantified substantial exergy losses in exhaust streams, identifying this as a primary target for efficiency gains [10],[11]. Consequently, various heat recovery technologies, including heat exchangers and thermal wheels, have been modeled and tested in related agro-industrial applications, demonstrating potential fuel savings of 20-40% [12],[13]. Specifically for coffee, investigations have focused on optimizing drying air temperature and humidity [14] and assessing solar-assisted systems [15]. However, a significant research gap persists in the experimental development and holistic performance assessment of simple, retrofit-ready waste-heat recovery systems directly integrated into the coffee roasting process. Most prior studies are either theoretical, focused on large-scale complex systems, or applied to other agricultural commodities [16],[17]. There is a paucity of empirical, process-level data evaluating the simultaneous impact of exhaust heat recovery on the energy efficiency, roasting kinetics, and final product quality of coffee beans under controlled conditions [18].

To address this gap, this study aims to develop, implement, and rigorously evaluate a dedicated waste-heat recovery preheater for a laboratory-scale coffee roaster. The primary objective is to quantify the system's effectiveness in improving energy efficiency, reducing process time, and enhancing product dehydration compared to a conventional roasting baseline. By providing validated data on thermal performance and mass transfer, this research offers a practical and scalable technological solution, contributing directly to the development of more sustainable and energy-efficient industrial-scale coffee processing systems.

## 2 Materials and method

### 2.1 Materials and Experimental Setup



**Fig. 1** Experimental research facility

This study utilized Robusta green coffee beans as the primary raw material. A laboratory-scale rotating drum roaster was employed for the experiments. As illustrated in Fig. 1, the roaster's key component is a double-layer drum designed to enhance thermal stability. The outer layer is constructed from stainless steel (3 mm thickness), while the inner layer is composed of clay with a thickness of 10 mm and a thermal conductivity of 1.7218 W/mK. The system includes a combustion chamber, an airflow pathway incorporating a preheater and an air filter, and an exhaust for hot gases. Each experimental batch used 0.75 kg of green beans. Liquefied Petroleum Gas (LPG) served as the fuel source for heating, with its consumption meticulously recorded for energy analysis.

## 2.2 Experimental Design and Procedure

The research employed an experimental method with two distinct treatments: roasting with a preheater and roasting without a preheater (control). The operational parameters, established based on optimal laboratory-scale conditions to ensure controlled and repeatable results, are summarized in Table I. All thermal sensors were calibrated prior to experiments using ice (0 °C) and boiling water (100 °C) reference points, with validation against a certified digital thermometer. The procedure began by preheating the roasting machine until the combustion chamber reached the initial temperature of 200 °C. For the control treatment, beans with an initial moisture content of 11.4% were loaded directly into the drum and roasted for 900 seconds (15 minutes) at a constant airflow velocity of 3.1 m/s. For the preheating treatment, beans with a higher initial moisture content (13.6%) were first passed through the preheater. This step utilized waste hot air to reduce the bean moisture to 11.4% and increase their temperature to approximately 80 °C before transferring them to the roaster. This standardization of initial moisture content ensured that observed differences were attributable solely to the preheating effect. Each treatment was replicated three times to ensure data reliability.

**Table 1.** Experimental Parameters

Parameter	Value
Drum Surface Area	0.094285 m <sup>2</sup>
Drum Diameter	0.2 m
Average Coffee Bean Surface Area	8.1 × 10 <sup>-5</sup> m <sup>2</sup>
Mass of Green Coffee Beans	0.75 kg
Initial Roasting Temperature	200 °C
Airflow Velocity	3.1 m/s
Volumetric Flow Rate	0.031428 m <sup>3</sup> /s
Roasting Time	900 s
Thermal Conductivity of Clay	1.7218 W/m·K

## 2.3 Data Collection and Analysis

The heat and mass transfer dynamics during roasting were analyzed based on the conceptual scheme in Fig. 2. The key energy flows were quantified using the following equations:

1. Convective Heat Transfer from Hot Gas to Bean Surface: This external heat input ( $Q_{conv}$ ) was calculated using Newton's law of cooling, considering the bean surface area, convective heat transfer coefficient, and temperature differential between the hot air and bean surface.

$$\dot{Q}_{conv} = \Delta Q_{conv} \times C_{p,conv}(T_{conv,i} - T_{conv,o})$$

2. Heat Generated from Exothermic Reactions: The internal heat release ( $Q_{gen}$ ) from chemical reactions (e.g., Maillard, pyrolysis) was estimated based on the mass of beans and the specific enthalpy change associated with these transformations.

$$\dot{Q}_{gen} = \Delta Q_{gen} \times m_{b(d,b)}$$

3. Heat Loss Due to Moisture Evaporation: The latent heat consumption ( $Q_{evap}$ ) for removing moisture was determined from the mass of water evaporated and its latent heat of vaporization.

Overall energy efficiency was assessed by comparing the total energy input (from LPG) to the effective energy utilized in the process, derived from the balance of the above components. Post-roasting, product quality was evaluated by measuring the

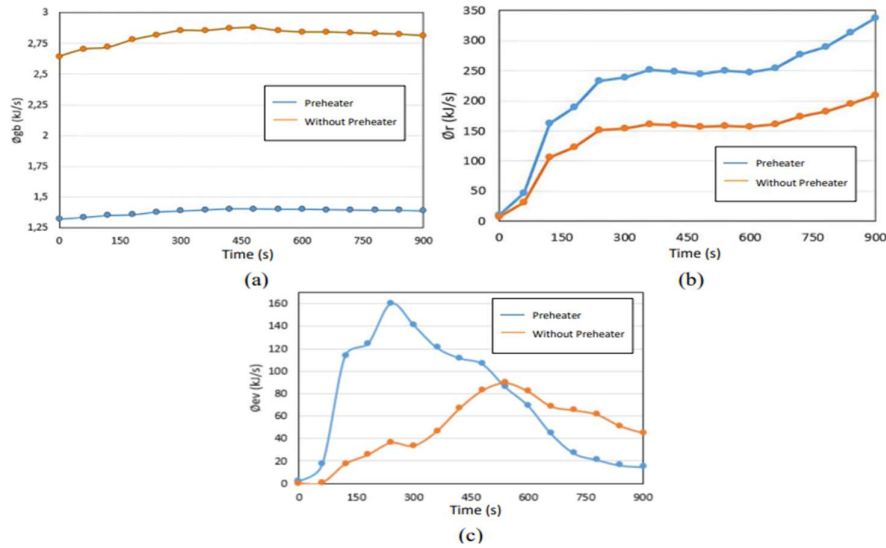
$$\dot{Q}_{ev} = \Delta H_v \left( -\frac{dx}{dt} \right) m_{b(d,b)}$$

## 3.4. Study Limitations

This research was conducted under controlled laboratory-scale conditions. Consequently, the thermal dynamics and scalability of the findings to industrial-scale systems with larger batch



Conversely, the exothermic heat released from internal bean reactions (Fig. 4b) was greater in the preheated treatment (average 204.17 J; total 2.65 kJ/s) compared to the control (average 143.12 J; total 2.289 kJ/s). This indicates that preheating more effectively triggers and sustains endothermic and exothermic chemical reactions like Maillard reactions and pyrolysis, leading to greater energy self-generation within the bean mass and aligning with findings on improved exergy efficiency [18]. The energy consumed for moisture evaporation (Fig. 4c) was also higher with preheating (average 86.4 J; total 1.12 kJ/s), reflecting a more rapid and effective dehydration phase due to the increased vapor pressure differential.



**Fig. 4** Heat transfer: (a) Hot gas to coffee bean, (b) Exothermic, (c) Moisture evaporation

### 3.3 Mass Loss, Moisture Reduction, and Process Implications

The enhanced heat transfer directly impacted mass loss and moisture kinetics, as summarized in Table III and Fig. 5. Beans roasted with the preheater exhibited a final mass of 0.580 kg, representing a 22.7% mass loss, compared to a 14.4% loss (final mass 0.642 kg) for the control. This correlates with a significantly faster reduction in moisture content (Fig. 5). While both batches started at 11.4% moisture, the preheated beans reached ~6% by 300 seconds and a final value of 1.6%, whereas the control beans retained ~7% at 300 seconds and finished at 3.1%. This demonstrates that preheating accelerates internal moisture migration, reducing the latent heat load during the primary roasting phase. The integration of a preheater, which utilizes waste exhaust heat to precondition beans, created a synergistic system that improved overall energy utilization. The observed reductions in LPG consumption (60.65%) and total energy savings (62.33%) validate this approach as a critical step towards sustainable coffee processing. By repurposing waste heat to reduce bean moisture and elevate initial temperature, the process shortens the main roasting duration, enhances uniformity, and improves thermodynamic efficiency, consistent with principles observed in other thermal systems [21],[22]. The results confirm that preheating is a viable method for optimizing laboratory-scale roasting, with promising implications for scaling energy-efficient practices in industrial applications.

**Table 2** Coffee Bean Mass Measurement Before And After Roasting

Test	Coffee Bean Mass (Kg)	
	Before Roasting	After Roasting
With Preheater	0.75	0.580
Without Preheater	0.75	0.642

## 4 CONCLUSION

This research provides empirical evidence that integrating a waste-heat recovery preheater is a highly effective strategy for advancing industrial-scale coffee drying technology, directly contributing to the dual goals of enhanced energy efficiency and sustainability. The laboratory-scale system demonstrated a 60.65% reduction in LPG consumption and 62.33% overall energy savings, primarily by utilizing exhaust heat to pre-condition beans. This significant decrease in primary energy demand validates a core thermodynamic principle scalable to industrial operations: recovering low-grade waste heat dramatically improves system efficiency and reduces both operational costs and greenhouse gas emissions. Furthermore, the accelerated drying kinetics—evidenced by a 51% reduction in convective energy input and a lower final bean moisture content (1.6% vs. 3.1%)—confirm that this approach enhances process throughput and product quality simultaneously, proving that sustainability and productivity are mutually achievable objectives in thermal processing.

The findings offer a practical and transferable blueprint for the development of sustainable industrial-scale drying systems. By demonstrating that a simple preheating mechanism can drastically improve exergy utilization and process control, this study bridges a critical gap between theoretical energy-saving concepts and viable industrial application. For the coffee industry, adopting such heat-recovery technologies represents a direct pathway to decarbonize one of its most energy-intensive post-harvest stages. Future work must focus on scaling this prototype, conducting comprehensive life cycle and techno-economic assessments at the industrial level, and integrating this approach with hybrid renewable thermal systems to fully realize its potential for creating a more sustainable and resilient global coffee value chain.

## ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by the Cambridge Centre for Sustainable Energy & Resources (CCSER) at the University of Cambridge under the Strategic Research Grant 2025 (Ref: CCSER-SRG/2025/ENG/03). We extend our sincere appreciation to our industrial partner, Sustainable Coffee Collective Ltd., for their technical collaboration and provision of materials. Special thanks are due to the technical staff of the Energy & Thermal Processes Laboratory, Department of Engineering, for their invaluable assistance in the experimental setup and data collection.

## References

- [1] "Coffee Consumption by Country 2025." Accessed: Jan. 09, 2026. [Online]. Available: <https://worldpopulationreview.com/country-rankings/coffee-consumption-by-country>
- [2] O. Corigliano and A. Algieri, "A comprehensive investigation on energy consumptions, impacts, and challenges of the food industry," *Energy Convers. Manag. X*, vol. 23, p. 100661, Jul. 2024, doi: 10.1016/j.ecmx.2024.100661.
- [3] A. Ferretto, R. Matthews, R. Brooker, and P. Smith, "Planetary Boundaries and the Doughnut frameworks: A review of their local operability," *Anthropocene*, vol. 39, p. 100347, 2022.
- [4] J. F. Velasco-Muñoz, J. M. F. Mendoza, J. A. Aznar-Sánchez, and A. Gallego-Schmid, "Circular economy implementation in the agricultural sector: Definition, strategies and indicators," *Resour. Conserv. Recycl.*, vol. 170, p. 105618, Jul. 2021, doi: 10.1016/j.resconrec.2021.105618.
- [5] F. Majeed *et al.*, "Energy and exergy analysis of a solar coffee roaster using concentrating scheffler-reflector," *Therm. Sci. Eng. Prog.*, vol. 34, p. 101407, Sep. 2022, doi: 10.1016/j.tsep.2022.101407.
- [6] I. Muñoz *et al.*, "Comparison of different technologies (conventional thermal processing, radiofrequency heating and high-pressure processing) in combination with thermal solar

- energy for high quality and sustainable fish soup pasteurization," *Food Bioprocess Technol.*, vol. 15, no. 4, pp. 795–805, 2022.
- [7] C. Parmesan, M. D. Morecroft, and Y. Trisurat, "Climate change 2022: Impacts, adaptation and vulnerability," 2022.
- [8] H. Jouhara, N. Khordehghah, S. Almahmoud, B. Delpech, A. Chauhan, and S. A. Tassou, "Waste heat recovery technologies and applications," *Therm. Sci. Eng. Prog.*, vol. 6, pp. 268–289, Jun. 2018, doi: 10.1016/j.tsep.2018.04.017.
- [9] S. V. Sutar and G. D. Yadav, "Advancements in spray drying system for heat recovery, methodology, and economics: A review," *Dry. Technol.*, vol. 41, no. 16, pp. 2537–2565, Dec. 2023, doi: 10.1080/07373937.2023.2280641.
- [10] G. Theotokatos, A. Rentizelas, C. Guan, and I. Ancic, "Waste heat recovery steam systems techno-economic and environmental investigation for ocean-going vessels considering actual operating profiles," *J. Clean. Prod.*, vol. 267, p. 121837, Sep. 2020, doi: 10.1016/j.jclepro.2020.121837.
- [11] M. Alktrane, Q. Al-Yasiri, K. S. Mohammed, M. Arıcı, M. Szabó, and P. Bencs, "Energy, exergy, and economic analysis of indirect solar dryer integrated phase change material cans," *Energy Convers. Manag. X*, vol. 26, p. 100986, Apr. 2025, doi: 10.1016/j.ecmx.2025.100986.
- [12] P. L. Kumar, N. Beemkumar, M. S. Kumar, and D. Yuvarajan, "Performance evaluation of a multi-mode drying system with thermal energy storage for high-value agricultural products," *J. Energy Storage*, vol. 123, p. 116743, 2025.
- [13] X. Guan *et al.*, "Research on the performance of heat pump drying system with rock thermal energy storage," *Energy*, vol. 316, p. 134510, Feb. 2025, doi: 10.1016/j.energy.2025.134510.
- [14] F. Kulapichitr, C. Borompichaichartkul, I. Suppavorasatit, and K. R. Cadwallader, "Impact of drying process on chemical composition and key aroma components of Arabica coffee," *Food Chem.*, vol. 291, pp. 49–58, Sep. 2019, doi: 10.1016/j.foodchem.2019.03.152.
- [15] A. N. Mbakouop, H. Tchakounté, A. I. Ankungha, and C. B. Nzoundja Fapi, "Experimental performance analysis of a mixed forced convection solar dryer: Application to cocoa bean drying," *Sol. Energy*, vol. 257, pp. 110–124, Jun. 2023, doi: 10.1016/j.solener.2023.04.010.
- [16] A. Khouya, "Modelling and analysis of a hybrid solar dryer for woody biomass," *Energy*, vol. 216, p. 119287, Feb. 2021, doi: 10.1016/j.energy.2020.119287.
- [17] Ş. Atik, T. D. Aparisi, and R. Raslan, "Mind the gap: Facilitating early design stage building life cycle assessment through a co-production approach," *J. Clean. Prod.*, vol. 464, p. 142803, 2024.
- [18] F. Majeed *et al.*, "Energy and exergy analysis of a solar coffee roaster using concentrating scheffler-reflector," *Therm. Sci. Eng. Prog.*, vol. 34, p. 101407, 2022.