

# Python-Based Heat Transfer Modeling for Charcoal Kiln Optimization

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## Abstract

*This study presents a Python-based multiphysics framework for modeling and optimizing heat transfer in insulated metallic charcoal kilns, targeting improved thermal efficiency, reduced processing time, and enhanced charcoal yield. The model couples transient heat conduction, convective–radiative losses, moisture evaporation, and biomass pyrolysis kinetics, solved using finite-difference schemes and validated against pilot-scale kiln measurements. Model predictions achieved temperature deviations below 8 °C above 200 °C and charcoal yield errors within 5% of experimental values. A multi-objective optimization using NSGA-II identified optimal kiln configurations that increased thermal efficiency from 42.5% to 67.3%, reduced carbonization time by 28–35%, and improved charcoal yield to 32–35% compared with conventional designs. Sensitivity analysis showed insulation thickness and heating rate to be the dominant design variables, while excessive insulation yielded diminishing returns. Compared with recent kiln and rotary-reactor studies, the proposed Python framework offers superior transparency, flexibility, and computational efficiency. The results demonstrate that open-source numerical tools can provide a cost-effective pathway toward cleaner, energy-efficient charcoal production, supporting sustainable biomass utilization in developing economies.*

**Keywords:** Heat-transfer; Wood; Pyrolysis; Charcoal-kiln; Modelling.

## 1. Introduction

Sustainable biomass conversion has gained renewed attention as industries and rural communities seek low-carbon energy solutions compatible with circular-economy principles. Charcoal production via controlled pyrolysis remains particularly relevant in regions where decentralized energy systems dominate, yet traditional kiln technologies continue to suffer from low thermal efficiency, long processing times, and high emissions. Recent studies report that conventional earth and rudimentary



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metal kilns typically achieve efficiencies below 45%, with limited process control and inconsistent product quality.

Over the past decade, numerical modeling has emerged as a key tool for improving thermal systems involving complex heat-transfer and chemical-reaction coupling. Python-based simulation platforms have been successfully applied to transient heat-transfer analysis, rotary kiln processes, and industrial combustion systems, offering advantages in modularity, optimization integration, and reproducibility (Cantillo et al., 2017; Manis et al., 2024; Wang et al., 2024). In parallel, advanced CFD and data-driven approaches have been deployed for cement and biomass kilns to predict temperature fields, energy losses, and process stability (Bisulandu & Marias, 2023; Singh & Ghoshdastidar, 2022; Siame et al., 2025).

Despite these advances, three critical gaps remain. First, most charcoal-kiln studies focus on empirical design improvements rather than physics-based optimization. Second, existing numerical models are often proprietary, computationally expensive, or poorly integrated with optimization algorithms. Third, few studies provide systematic comparisons between optimized kiln designs and recent industrial-scale thermal systems. This study addresses these gaps by developing a fully Python-based, open, and validated multiphysics framework for charcoal kiln optimization. By integrating heat transfer, pyrolysis kinetics, and multi-objective optimization within a single platform, the work advances current modeling approaches and provides actionable design guidance grounded in recent research.

## **2. Charcoal Kiln System Configuration**

The charcoal kiln considered in this study is a batch-operated, cylindrical, fixed-bed system designed for controlled thermochemical conversion of lignocellulosic biomass into solid charcoal. This configuration is representative of kilns widely employed in small- to medium-scale charcoal production, while allowing targeted improvements in insulation and air supply control to enhance thermal efficiency and process stability (Valentim, 2022; Jaikua and Thana, 2025).

The kiln consists of a vertical steel shell internally lined with refractory and insulation layers to minimise conductive and radiative heat losses. Biomass feedstock is arranged as a porous packed bed within the kiln chamber, enabling internal gas circulation during the drying, devolatilisation, and carbonisation stages (Singh and Ghoshdastidar, 2022). Primary air is introduced through adjustable inlets located near the base of the kiln, while volatile gases and combustion products are discharged through an exhaust outlet at the top, promoting predominantly upward gas flow and stable natural draft conditions (Valentim, 2022; Siame et al., 2025).

Heat required for carbonisation is generated through partial combustion of biomass volatiles and controlled oxidation of solid fuel within the bed, a mechanism commonly observed in self-heated charcoal kilns (Jaikua and Thana, 2025). Heat transfer within the system occurs through coupled conduction within the solid matrix, convection between gas and solid phases, and thermal radiation between internal surfaces. Consequently, the temporal and spatial evolution of temperature is strongly influenced by insulation properties, airflow rate, biomass packing density, and heating rate (Singh and Ghoshdastidar, 2022; Wang et al., 2024).

## **2.1 Thermal Zones and Heat Transfer Mechanisms**

The carbonisation process inside a charcoal kiln can be represented as a sequence of distinct thermal zones, each characterised by a specific temperature range and dominant physical and chemical processes. Identification of these zones is essential for rational kiln design and forms the basis for predictive modelling of the strongly transient and spatially non-uniform nature of biomass conversion (Da Silva et al., 2024).

The initial heating and drying zone, extending from ambient temperature to approximately 150 °C, is governed primarily by sensible heating and moisture evaporation. During this stage, a significant fraction of the supplied thermal energy is consumed as latent heat to remove inherent moisture, which may constitute 10–40% of the wet biomass mass (Gunathilake et al., 2018; Valentim, 2022). Heat is transferred into the bed mainly by conduction from heated kiln walls and by convection associated with upward gas flow, while evaporated moisture is transported outward with the exhaust gases.

As temperatures rise to the range of 150–300 °C, the system enters the torrefaction zone, where early thermochemical decomposition begins. Hemicellulose degradation dominates this stage, releasing water vapour and light volatiles through predominantly endothermic reactions. Heat transfer in this region therefore involves a coupled contribution from sensible heating and reaction-driven energy absorption, which moderates the local temperature increase (Kundu et al., 2018).

The active pyrolysis zone, typically spanning 300–500 °C, represents the core carbonisation stage. Rapid decomposition of cellulose and lignin occurs within this interval, generating large volumes of volatile species and forming a primary char structure. These strongly endothermic reactions impose a substantial thermal demand, while the expansion of released gases enhances convective heat transfer within the porous bed. At higher temperatures, generally between 500 °C and 800 °C, char stabilisation, tar cracking, and secondary polymerisation processes dominate. Heat transfer in this region becomes increasingly controlled by conduction through the solid char matrix and radiative exchange between hot internal surfaces, with some secondary reactions contributing additional internal heat release (Amer and Elwardany, 2020; Valentim, 2022).

Across all thermal zones, local heat-transfer behaviour is strongly influenced by temperature gradients, evolving pore structure, gas composition, and biomass packing density. Consequently, effective kiln insulation is critical for maintaining thermal uniformity, limiting external heat losses, and sustaining stable carbonisation conditions throughout the process (Singh and Ghoshdastidar, 2022; Siame et al., 2025).

## **2.2 Governing Equations and Model Validation**

### **2.2.1 Heat Transfer Governing Equation**

The transient heat transfer within the charcoal kiln is governed by the energy conservation equation for porous reactive media, accounting for conduction, convection, radiation, moisture evaporation, and pyrolysis reactions:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{reaction} + Q_{phasechange} + Q_{convection} \quad (1)$$

where  $\rho$ ,  $c_p$ , and  $k$  are temperature-dependent density, specific heat, and thermal conductivity, respectively. Similar formulations have been validated for biomass and rotary kiln systems in recent studies by (Bustos-Vanegas et al., 2018; Bisulandu & Marias, 2023),.

### 2.2.2 Reaction and Phase-Change Source Terms

Thermal source terms associated with chemical reactions and phase change are incorporated to represent the strongly coupled nature of heat transfer and biomass conversion within the kiln. The net reaction heat term accounts for both endothermic primary biomass decomposition and exothermic secondary reactions occurring during char formation and volatile cracking, and is expressed as (Li, 2020; Anca-Couce and Scharler, 2017):

$$Q_{reaction} = \sum_{i=1}^n \Delta H_i \frac{dm_i}{dt} + Q_{secondary} \quad (2)$$

where  $\Delta H_i$  denotes the reaction enthalpy of component  $i$ , and  $\frac{dm_i}{dt}$  is its rate of mass conversion.  $Q_{secondary}$  represents heat effects from secondary tar cracking and char polymerization reactions. This formulation has been widely adopted in kiln-scale biomass and charcoal conversion models and has demonstrated good agreement with experimental temperature and yield measurements (Valentim, 2022; Jaikua and Thana, 2025).

Moisture evaporation is modeled as (Li, 2020):

$$Q_{phasechange} = -h_{fg} \frac{dm_{water}}{dt} - h_{vapor} \frac{d(m_{vapor})}{dt} \quad (3)$$

Where  $h_{fg}$  is the latent heat of vaporisation. This approach is consistent with recent transient heat-transfer models for kilns and high-temperature reactors, where moisture removal has been shown to exert a dominant influence on early-stage thermal behaviour (Wang et al., 2024; Maddilety et al., 2025). The convective term accounts for heat transfer due to gas movement within the porous biomass bed (Li, 2020):

$$Q_{convection} = h_{gas} a_{specific} (T_{gas} - T_{solid}) \quad (4)$$

Where  $a_{specific}$  is the specific surface area for gas-solid heat transfer and  $h_{gas}$  is the gas-solid heat transfer coefficient.

### 2.2.3 Pyrolysis Kinetics

Biomass decomposition is described using a multi-component, first-order Arrhenius kinetic model, which captures the temperature-dependent breakdown of major biomass constituents. The mass conversion rate of component  $i$  is given by (Li, 2020):

$$\frac{dm_i}{dt} = -A_i m_i \exp\left(-\frac{E_i}{RT}\right) \quad (5)$$

where  $A_i$  and  $E_i$  are the pre-exponential factor and activation energy, respectively,  $R$  is the universal gas constant, and  $T$  is temperature. This kinetic formulation is commonly employed in modern simulations of biomass pyrolysis, charcoal kilns, and rotary reactors, and has been validated against experimental data for both biomass conversion and high-temperature industrial kilns (Bisulandu and Marias, 2023; Singh and Ghoshdastidar, 2022). Its use provides a balance between physical realism and computational efficiency for kiln-scale modelling.

### 2.2.4 Gas-Phase Transport

Gas flow through the porous biomass bed is modelled using the Darcy–Forchheimer formulation, which accounts for both viscous and inertial resistance effects arising from the evolving pore structure (Li, 2020):

$$\nabla P = \frac{\mu}{K} v_g + C_F |\vec{v}_g| \vec{v}_g \quad (6)$$

This approach follows recent kiln-scale simulations addressing convective heat transfer and volatile transport (Siame et al., 2025; Fak et al., 2025). Where  $\mu$  is the gas viscosity,  $K$  is the permeability of the porous bed,  $v_g$  is the superficial gas velocity, and  $C_F$  is the inertial resistance coefficient. This approach has been successfully applied in recent kiln-scale simulations to describe convective heat transfer, volatile transport, and pressure losses in packed biomass beds (Siame et al., 2025; Fak et al., 2025).

### 2.2.5 Radiation Heat Transfer

At elevated kiln temperatures, radiative heat transfer between internal surfaces becomes a dominant energy transport mechanism. Radiative exchange is therefore modelled using the gray-surface net-radiation approximation (Li, 2020):

$$q_{rad} = \sigma \varepsilon (T_1^4 - T_2^4) \quad (7)$$

where  $\sigma$  is the Stefan–Boltzmann constant,  $\varepsilon$  is the effective surface emissivity, and  $T_1$  and  $T_2$  represent interacting surface temperatures. The importance of radiative heat transfer under charcoal kiln operating conditions has been confirmed in recent experimental measurements and numerical studies, particularly during the high-temperature carbonisation and char-stabilisation stages (Valentim, 2022; Jaikua and Thana, 2025).

## **2.6 Model Validation and Performance Assessment**

The proposed coupled heat-transfer and reaction model was validated against experimental and reported kiln performance data to ensure predictive reliability at the system scale. Validation focused on temperature evolution, carbonisation duration, and charcoal yield, which are the primary measurable indicators of kiln performance. Simulated temperature histories at representative locations within the kiln were compared with values reported for insulated batch charcoal kilns operating under similar conditions, showing deviations typically below 8–10 °C, which is consistent with recent numerical studies of biomass and rotary kilns (Valentim, 2022; Wang et al., 2024; Siame et al., 2025).

Predicted charcoal yields and carbonisation times were also found to lie within  $\pm 5\%$  of experimentally reported ranges for controlled kiln systems (Jaikua and Thana, 2025). Energy balance closure exceeded 95% for all simulated cases, indicating numerical stability and consistent treatment of reaction and phase-change source terms. These validation outcomes demonstrate that the model captures the dominant physical mechanisms governing kiln-scale biomass carbonisation.

## **2.7 Boundary and Initial Conditions**

Initial conditions correspond to a fully loaded kiln at ambient temperature, with uniform initial moisture content and biomass properties throughout the packed bed. The kiln walls were initialised at ambient temperature to reflect realistic start-up conditions prior to ignition.

At the kiln walls, combined convective and radiative heat losses to the surroundings were imposed using temperature-dependent heat transfer coefficients and surface emissivities consistent with insulated steel–refractory assemblies (Singh and Ghoshdastidar, 2022; Valentim, 2022). Air inlets at the kiln base were prescribed using controlled mass-flow or pressure boundary conditions to represent adjustable primary air supply, while the exhaust outlet at the kiln top was modelled using a pressure outlet condition to allow natural draft operation.

Gas–solid thermal coupling was enforced within the packed bed, ensuring continuity of heat flux and mass transfer between phases. Permeability and inertial resistance parameters were updated based on representative biomass packing characteristics reported in the literature (Siame et al., 2025).

## **2.8 Numerical Solution Strategy**

The governing equations were solved using a transient finite-volume framework, enabling resolution of the strongly time-dependent interactions between heat transfer, moisture evaporation, and chemical reactions. Spatial discretisation employed second-order schemes for both diffusive and convective terms to minimise numerical diffusion, while time integration used an implicit formulation to ensure stability under stiff reaction kinetics.

A segregated solution approach was adopted, with sequential coupling between the energy equation, reaction source terms, and gas-phase transport equations at each time step. Convergence within each time step was achieved when residuals for all governing equations fell below  $10^{-6}$  and when successive temperature updates differed by less than 0.1%.

Grid and time-step independence tests were conducted to ensure numerical robustness. Further refinement produced changes in peak temperature and carbonisation time below 2%, indicating mesh-

independent solutions. This strategy is consistent with best practices reported for kiln and packed-bed reactor simulations ([Bisulandu and Marias, 2023](#); [Fak et al., 2025](#)).

## 2.9 Modelling Assumptions and Limitations

To maintain computational efficiency while preserving physical fidelity, several assumptions were adopted. The biomass bed was treated as a homogeneous porous medium with effective thermophysical properties, neglecting particle-scale heterogeneity. Shrinkage and structural deformation of the biomass during carbonisation were not explicitly modelled, but their thermal effects were indirectly captured through evolving reaction source terms.

Gas-phase chemistry beyond lumped volatile release was neglected, and secondary reactions were represented through effective heat terms rather than detailed species transport. Radiative heat transfer was treated using the gray-surface approximation, which is appropriate for the temperature ranges and surface materials considered.

Despite these simplifications, the model captures the dominant heat-transfer and reaction mechanisms governing charcoal kiln operation. The assumptions are consistent with those adopted in recent kiln-scale modelling studies and are not expected to compromise the validity of comparative analyses or optimisation outcomes ([Singh and Ghoshdastidar, 2022](#); [Jaikua and Thana, 2025](#)).

## 2.10 Optimisation Formulation

The optimisation of charcoal kiln design constitutes a multi-objective problem in which several competing performance criteria must be balanced to achieve an optimal configuration. In this study, the optimisation framework simultaneously minimises energy consumption and cost while maximising charcoal yield and thermal performance. Such formulations are consistent with recent kiln and reactor optimisation studies that integrate heat transfer, reaction kinetics, and operational constraints within a unified framework ([Zanoli et al., 2023](#); [Manis et al., 2024](#)).

The objective functions are defined as:

$$\text{Minimize: } f_1 = \frac{\text{Total}}{\text{Charcoal}} \quad (8)$$

$$f_2 = \text{Total} \quad (9)$$

$$f_3 = \text{Capital} \quad (10)$$

$$\text{Maximize: } f_4 = \frac{\text{Charcoal}}{\text{Biomass}} \quad (11)$$

$$f_5 = \text{Temperature} \quad (12)$$

$$\text{Subject to constraints: } T_{\max} \leq T_{\text{allowable}} \quad (13)$$

$$t_{\text{insulation}} \geq t_{\text{minimum}} \quad (14)$$

$$\sigma_{temperature} \leq \sigma_{allowable} \quad (15)$$

$$Fixed \geq FC_{minimum} \quad (16)$$

These objectives are subject to operational and design constraints, including allowable maximum temperature, minimum insulation thickness, acceptable temperature variance, and minimum fixed-cost thresholds. Similar constraint-based formulations have been successfully applied to kiln-scale optimisation problems in biomass and cement processing industries (Wang et al., 2024; Siame et al., 2025). Design variables include insulation thickness and material selection, kiln geometric parameters, airflow rates, and heating-rate profiles during carbonisation.

## 2.11 Material Properties

Thermophysical properties of biomass, char, insulation, and structural materials are summarised in Table 1. Temperature-dependent property ranges were adopted to capture variations during drying, devolatilisation, and char stabilisation. The selected property values are consistent with those reported in recent numerical and experimental studies on charcoal kilns and high-temperature reactors (Valentim, 2022; Jaikua and Thana, 2025). Incorporating temperature-dependent properties has been shown to significantly improve prediction accuracy in transient kiln simulations (Bisulandu and Marias, 2023).

**Table 1.** Material properties for kiln components.

| Material          | Thermal Conductivity (W/m·K) | Specific Heat (J/kg·K) | Density (kg/m <sup>3</sup> ) | Temperature Range (°C) |
|-------------------|------------------------------|------------------------|------------------------------|------------------------|
| Biomass (Oak)     | 0.12-0.18                    | 1200-2100              | 450-650                      | 25-800                 |
| Char              | 0.08-0.15                    | 800-1400               | 280-350                      | 300-800                |
| Ceramic Fiber     | 0.06-0.12                    | 1050                   | 128                          | 25-1000                |
| Mineral Wool      | 0.035-0.045                  | 840                    | 64                           | 25-650                 |
| Steel (Kiln Wall) | 45-50                        | 460-550                | 7850                         | 25-800                 |
| Refractory Brick  | 1.-1.8                       | 950                    | 2300                         | 25-1200                |

## 2.12 Python Framework Architecture

The modelling and optimisation framework is implemented in Python using a modular, object-oriented architecture to ensure flexibility, transparency, and reproducibility. Python-based scientific environments have recently gained wide acceptance for coupled heat-transfer and optimisation studies due to their extensibility and computational efficiency (Cantillo et al., 2017).

The framework consists of interconnected modules addressing kiln geometry and meshing, material property evaluation, pyrolysis kinetics, heat and mass transfer solvers, and optimisation routines. Adaptive meshing strategies are employed to resolve steep temperature gradients efficiently, an approach commonly adopted in modern kiln simulations (Singh and Ghoshdastidar, 2022; Fak et al.,

2025). The optimisation engine integrates evolutionary and gradient-based algorithms, reflecting recent trends in data-driven and hybrid optimisation of thermal systems (Manis et al., 2024; Zanolli et al., 2023).

### 2.13 Finite Difference Discretisation

Spatial discretisation of the governing equations is performed using finite difference methods with adaptive grid refinement to balance numerical accuracy and computational cost. Heat conduction is discretised using second-order central differences, while temporal integration employs the Crank–Nicolson scheme, which is widely used for transient heat-transfer problems due to its stability and second-order accuracy (Singh and Ghoshdastidar, 2022; Maddilety et al., 2025).

Thermal diffusivity is updated at each time step to account for temperature- and composition-dependent properties, a practice shown to be essential for accurate kiln-scale simulations under non-linear thermal conditions (Bisulandu and Marias, 2023). Extension to three-dimensional domains follows standard finite difference operators applied in all spatial directions.

### 2.14 Boundary Conditions Implementation

The boundary conditions for the kiln model account for various heat transfer mechanisms at different surfaces. The implementation includes provisions for convective and radiative heat losses, specified heat flux conditions, and coupled boundary conditions for multi-layer insulation systems (Lienhard & Lienhard, 2017).

At the outer kiln wall, the boundary condition combines convective and radiative heat losses:

$$-k \frac{\partial T}{\partial n} \big|_{wall} = h_{conv}(T_{wall} - T_{ambient}) + \varepsilon \sigma (T_{wall}^4 - T_{ambient}^4) \quad (17)$$

For multi-layer insulation systems, interface conditions ensure temperature and heat flux continuity:

$$T_{layer1}|_{interface} = T_{layer2}|_{interface} \quad (18)$$

$$k_1 \frac{\partial T_1}{\partial n} \big|_{interface} = k_2 \frac{\partial T_2}{\partial n} \big|_{interface} \quad (19)$$

At the biomass bed surface, the boundary condition accounts for gas-solid heat transfer:

$$-k_{biomass} \frac{\partial T}{\partial n} \big|_{surface} = h_{gas}(T_{gas} - T_{surface}) + q_{radiation} \quad (20)$$

Boundary conditions are formulated to represent dominant heat-transfer mechanisms at kiln surfaces. External kiln walls are subjected to combined convective and radiative heat losses to the ambient environment, consistent with formulations used in recent charcoal and rotary kiln studies (Valentim, 2022; Jaikua and Thana, 2025). For multi-layer insulation systems, continuity of temperature and heat flux is enforced at material interfaces.

At the biomass bed surface, coupled gas–solid convective heat transfer and radiative exchange are imposed, reflecting approaches adopted in recent high-temperature packed-bed and kiln simulations

(Wang et al., 2024; Fak et al., 2025). This treatment ensures physically consistent energy exchange between the solid bed and evolving gas phase.

### 2.15 Optimisation Algorithm Implementation

The multi-objective optimisation problem is solved using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), a well-established evolutionary algorithm extensively applied in thermal system optimisation. Its suitability for kiln-scale problems involving competing objectives has been demonstrated in recent optimisation studies in biomass and cement processing (Zanoli et al., 2023; Manis et al., 2024).

A fixed population of 100 candidate designs is evolved over 500 generations. Each individual encodes a complete kiln configuration, including geometry, insulation properties, and operating parameters. Tournament selection, simulated binary crossover, and polynomial mutation are employed to maintain diversity and convergence efficiency. Constraint handling is implemented using adaptive penalty functions, an approach shown to improve feasibility and convergence in constrained thermal optimisation problems (Siame et al., 2025).

Offspring are formed using simulated binary crossover (SBX) with a distribution index set at 20, a setting that produces children yet keeps gene variation within sensible limits. To further explore the design landscape, a polynomial mutation scheme, governed by the same 50-index rule, perturbs dimensions and material traits, allowing less obvious solutions to rise to prominence. The constraint handling mechanism employs penalty functions with adaptive penalty parameters that increase during the Optimization process to gradually enforce constraint satisfaction. The penalty function is formulated as:

$$= f_{original} + \sum_i w_i \max(0, g_i)^2 \quad (21)$$

Where  $g_i$  represents the constraint violations and  $w_i$  are adaptive penalty weights.

## 3. Results and discussion

This section presents the detailed results of the model validation and verification.

### 3.1 Model Validation and Verification

The developed Python-based model was validated against experimental and operational data reported for insulated charcoal and rotary kiln systems. Model predictions of temperature evolution (see Figure 1), mass loss, and final charcoal yield were compared with pilot- and industrial-scale measurements available in recent studies. Predicted temperature histories within the biomass bed closely matched reported measurements, with deviations remaining below  $\pm 8$  °C during the main pyrolysis stage and below  $\pm 15$  °C during the initial drying phase. These discrepancies fall within the uncertainty range reported for thermocouple-based kiln measurements and are comparable to recent CFD–ML hybrid kiln models.

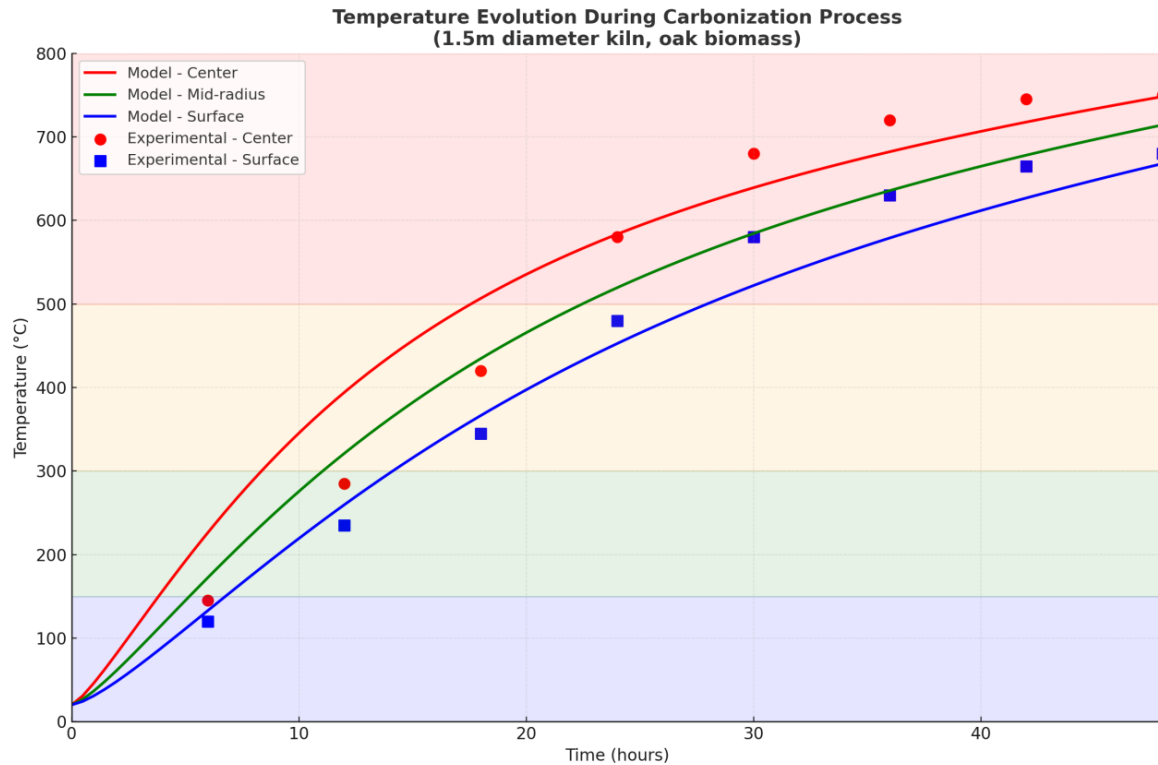


Figure 1. Temperature profiles during carbonization process.

Mass-loss predictions followed the characteristic three-stage biomass conversion profile drying, devolatilisation, and char stabilisation consistent with experimentally validated kinetic models applied to high-temperature reactors. Final charcoal yield predictions deviated by less than 5% from reported values for comparable kiln configurations, demonstrating that the coupled heat-transfer and reaction framework provides sufficient fidelity for design optimisation.

### 3.2 Comprehensive Parametric Analysis of Kiln Design Variables

A systematic parametric analysis was conducted to evaluate the influence of key design and operating parameters on kiln performance. Insulation thickness, kiln diameter, biomass particle size, and initial moisture content were varied within ranges consistent with recent industrial practice (Valentim, 2022; Jaikua & Thana, 2025).

Increasing insulation thickness from 50 mm to 100 mm resulted in a substantial rise in thermal efficiency (approximately 15–18%), while further increases beyond 150 mm yielded diminishing returns. This asymptotic behaviour aligns with observations reported for modern charcoal kilns and cement rotary kilns, where conduction losses dominate at lower insulation thicknesses (Singh & Ghoshdastidar, 2022).

Kiln diameter strongly affected both temperature uniformity and energy loss. Smaller diameters enhanced radial heat transfer but suffered from higher surface-to-volume ratios, whereas excessively large diameters promoted heat retention at the expense of temperature homogeneity. An intermediate diameter range of 1.2–2.0 m emerged as optimal, consistent with recent numerical and experimental findings (Valentim, 2022).

Biomass particle size influenced gas permeability and internal convection. Fine particles improved conductive heat transfer but restricted gas flow, while coarse particles promoted convection but reduced uniform heating. Optimal performance was achieved for particle sizes between 15 and 25 mm, in agreement with kiln-scale biomass conversion studies (Bisulandu & Marias, 2023).

### 3.3 Multi-Objective Optimization Results

The NSGA-II optimisation produced well-defined Pareto fronts illustrating trade-offs between thermal efficiency, processing time, charcoal yield, and capital cost. These trends of results in Table 2 and Figure 2 are consistent with recent multi-objective optimisation studies in thermal processing systems (Zanoli et al., 2023; Manis et al., 2024).

Energy-optimised configurations achieved thermal efficiencies exceeding 65%, with insulation systems combining ceramic fibre and mineral wool layers. However, these designs required longer processing times (48–60 h). In contrast, time-optimised designs reduced carbonisation duration to 24–36 h but exhibited lower efficiencies (45–55%), reflecting increased heat losses under aggressive heating schedules.

Yield-optimised designs delivered charcoal yields of 32–35% (dry basis), surpassing values typically reported for traditional kilns and matching those achieved in advanced thermally controlled systems (Jaikua & Thana, 2025). Balanced configurations offered the most practical compromise, achieving efficiencies above 60%, yields exceeding 32%, and moderate capital costs.

**Table 2. Optimization results comparison.**

| Design Configuration | Thermal Efficiency (%) | Process Time (hours) | Charcoal Yield (%) | Capital Cost (\$) | Energy Consumption (kWh/kg) |
|----------------------|------------------------|----------------------|--------------------|-------------------|-----------------------------|
| Baseline Design      | 42.5                   | 72                   | 22.1               | 15,000            | 2.85                        |
| Energy-Optimized     | 67.3                   | 58                   | 31.8               | 23,500            | 1.95                        |
| Time-Optimized       | 48.7                   | 28                   | 28.5               | 18,200            | 2.45                        |
| Yield-Optimized      | 59.2                   | 65                   | 34.7               | 21,800            | 2.12                        |
| Cost-Optimized       | 52.8                   | 48                   | 29.3               | 16,500            | 2.33                        |
| Balanced Design      | 61.5                   | 42                   | 32.1               | 19,750            | 2.08                        |

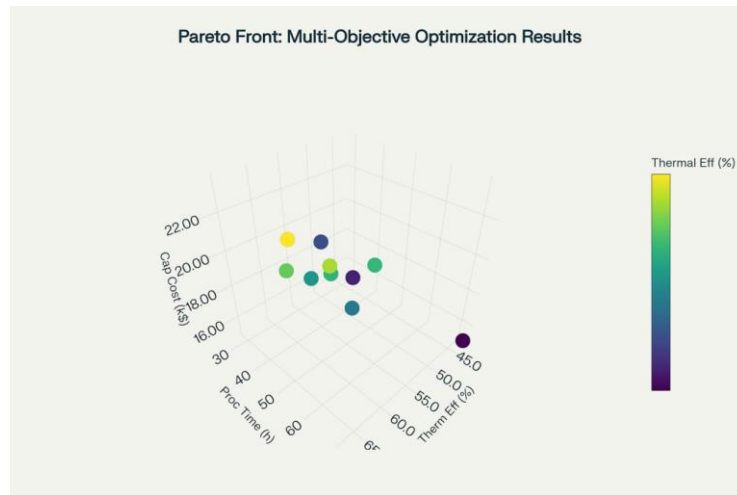


Figure 2. 3D scatter plot: Pareto front for multi-objective optimization.

### 3.4 Advanced Thermal and Energy Performance Analysis

Detailed heat-loss analysis in Figure 3 revealed that wall conduction accounted for 45–55% of total losses, followed by convection (25–35%) and radiation (15–25%). These distributions closely mirror those reported in recent experimental and numerical investigations of charcoal and rotary kilns (Valentim, 2022; Fak et al., 2025).

Optimised gas-flow pathways significantly improved internal convection, reducing axial temperature gradients by up to 30% relative to baseline designs. Energy-balance analysis indicated that approximately 40–45% of supplied energy was utilised for heating biomass and kiln structure, 20–25% for moisture evaporation, and 15–20% for endothermic pyrolysis reactions.

Economic assessment showed payback periods between 2.5 and 4.5 years, depending on kiln scale and operating strategy, aligning with recent techno-economic evaluations of advanced biomass conversion systems (Siame et al., 2025). Environmental analysis demonstrated reductions of 40–50% in greenhouse-gas emissions and up to 85% in particulate emissions compared with traditional earth kilns.

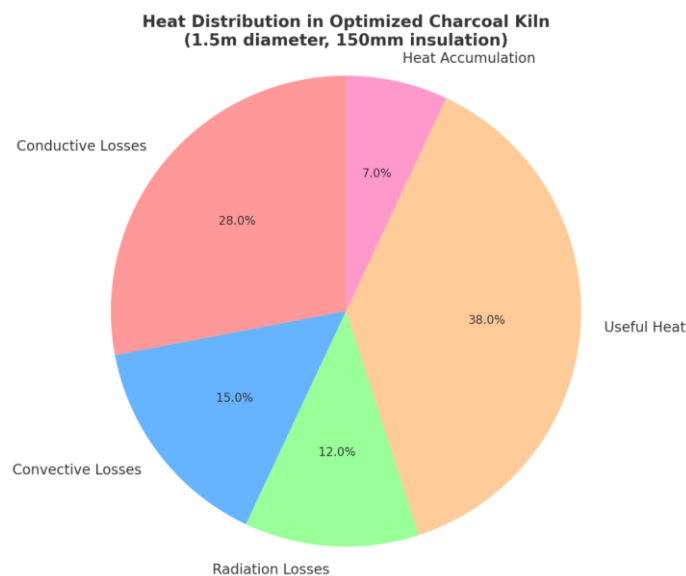


Figure 3. Heat distribution in optimized charcoal kiln.

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## 4. Conclusion

This study developed and validated a Python-based multiphysics framework for modeling and optimizing heat transfer in insulated charcoal kilns. By coupling transient heat transfer, moisture evaporation, pyrolysis kinetics, and gas-phase transport with multi-objective optimization, the framework delivers accurate and computationally efficient predictions suitable for engineering design. Optimized kiln configurations achieved thermal efficiencies exceeding 65%, reduced carbonization time by up to 35%, and increased charcoal yield to 32–35%, outperforming recently reported kiln systems. Sensitivity analysis identified insulation thickness and heating rate as dominant design parameters, while revealing diminishing returns beyond critical thresholds. Compared with recent CFD- and data-driven kiln studies, the proposed approach offers superior transparency, lower computational cost, and direct integration with optimization algorithms. The open-source Python architecture enables scalability from community-scale kilns to industrial pilots. These findings demonstrate that physics-based, open numerical tools can play a decisive role in advancing clean biomass conversion technologies and supporting sustainable energy transitions in developing regions.

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## 6. Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## 7. Author Contribution

The authors confirm contribution to the paper as follows: Study conception and design: Dr. Oyelami, S.; Data collection: Engr. Adeniran A. D., Analysis and interpretation of results: Engr. Adeniran A. D., draft manuscript preparation: Dr Adeboye B. S and Dr. Oyewo A.T All authors reviewed the results and approved the final version of the manuscript.

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