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Structural and Thermodynamic Performance of Artisanal Firewood Kilns: Sustainability Evidence from the Mfensi Pottery Centre, Ghana

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PUBLIC INTEREST STATEMENT

This study evaluates firewood-fired downdraft kilns at Ghana's Mfensi Pottery Centre, linking structural degradation and operational behaviour to energy efficiency, offering sustainable manufacturing insights aligned with Ghana's climate goals and SDGs 7, 12 and 13.

Abstract

Purpose: This study evaluates the performance and energy efficiency of firewood-fired downdraft kilns at the Mfensi Pottery Centre in Ghana. It addresses critical gaps in the literature by linking structural degradation and operational behaviour to measurable energy performance outcomes.

Methodology/Design: A mixed-method approach was employed, integrating quantitative thermodynamic measurement and qualitative field insights, guided by systems theory and thermodynamic analysis. Data were gathered from a sample of 19 kilns through calibrated pyrometric measurements, structural inspections, yield assessments, and triangulated interviews to assess how structural, operational, and thermal interactions influence kiln efficiency. Thermal efficiency was estimated as the ratio of useful heat absorbed by the clay load to the total calorific energy input from firewood combustion.

Findings: Findings reveal extensive structural deterioration, the absence of insulation, and unregulated airflow, resulting in significant heat loss and a low average thermal efficiency (≈4.2%). Although kilns with cracks exhibited marginally higher efficiency (4.31% vs. 4.05%), this difference was not statistically significant ($p = 0.096$), with a small to moderate effect size (Cohen's $d = 0.53$), indicating that inefficiency is systemic rather than attributable to isolated structural defects. Thermodynamic computation, interpreted through a systems perspective, highlights the interaction between kiln design, operation, and energy transfer.

Practical and Social Implications: Improving kiln performance requires integrated interventions, including structural rehabilitation, airflow control, and operator training. The policy recommendations align with Ghana's sustainable energy and climate goals under SDGs 7, 12, and 13. The study offers a framework for sustainable energy interventions in traditional manufacturing sectors.

Originality: Beyond its technical findings, the study advances existing kiln efficiency models by integrating systems theory with thermodynamic measurement, revealing that inefficiency arises from feedback loops among structural, operational, and thermal subsystems, not isolated losses. The framework is transferable to other artisanal pottery centres in Ghana and Sub-Saharan Africa, as the core subsystems (insulation, airflow, structural integrity) are common to most wood-fired kilns, enabling cross-centre diagnosis and intervention design.

Keywords
Firewood kilns, thermal efficiency, systems theory, downdraft kilns, fuel efficiency, artisanal pottery, Ghana

1 | INTRODUCTION

Pottery production remains an integral part of Ghana's cultural heritage and rural economy, serving both functional and artistic purposes. In several pottery centres, including Mfensi in the Ashanti Region, pottery provides a primary source of livelihood, especially for women and low-income households (Kusimi et al., 2020). The craft not only sustains traditional knowledge and skills but also supports local employment and contributes to rural development. However, despite its socio-cultural and economic importance, the sector continues to rely predominantly on traditional firewood-fired kilns, which are often inefficient and environmentally unsustainable (Donkor et al., 2021). Energy use in artisanal pottery has become a critical concern because it directly influences production costs, environmental outcomes, and the long-term viability of artisanal enterprises. In Ghana and across Sub-Saharan Africa, firewood remains the dominant fuel source for pottery, accounting for a substantial

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share of total energy input in the sector (Sola et al., 2019). While biomass energy dependence is widespread across Sub-Saharan Africa, this broader trend differs from the specific energy use patterns in artisanal pottery production, where firewood is intensively utilised in kiln firing processes under largely uncontrolled thermodynamic conditions. The inefficiency of these kilns results in high fuel consumption, increased deforestation, and elevated production costs that erode profit margins for artisans (Arthur & Gikunoo, 2020). Enhancing kiln energy performance is therefore not only a technical necessity but also a socio-economic and environmental priority consistent with the United Nations Sustainable Development Goals, particularly SDG 7 on affordable and clean energy, SDG 12 on responsible production and consumption, and SDG 13 on climate action (United Nations, 2015; UNDP, 2017).

Despite this significance, the thermodynamic performance of artisanal pottery kilns remains poorly quantified, particularly in African contexts. Existing studies have largely focused on descriptive accounts of kiln structure and fuel use, with limited integration of measurable energy performance indicators such as heat transfer, combustion efficiency, and energy balance. This lack of quantitative evidence constrains both technological improvement and evidence-based policy formulation. At the global level, the thermodynamic performance of industrial kilns such as tunnel, rotary, and roller kilns is well documented, with reported thermal efficiencies exceeding 30% due to improved insulation, controlled airflow, and heat recovery systems (Çengel et al., 2019; Hussnain et al., 2021). In contrast, artisanal firewood-fired kilns common across Africa, Asia, and Latin America often record thermal efficiencies below 10%, largely due to poor design, inadequate insulation, and lack of airflow regulation (Valdés et al., 2020). These disparities highlight a persistent technological gap between industrial and artisanal kiln systems, which perpetuates fuel wastage, increases environmental stress, and limits the competitiveness of small-scale producers. This study addresses this gap by integrating thermodynamic analysis with a systems theory perspective to evaluate kiln performance within a real-world artisanal context. Unlike prior studies that examine kiln structure or energy use in isolation, the present research combines empirical measurement of thermal efficiency with an analysis of structural, operational, and socio-economic interactions. By doing so, it provides a more comprehensive understanding of kiln performance and sustainability in artisanal pottery systems.

1.1| Problem Statement and Research Gap

Although pottery production remains vital to rural livelihoods in Ghana and across Sub-Saharan Africa, the technological foundations supporting it, particularly kiln design and firing efficiency, have received limited scientific attention. Most existing studies have focused on the cultural significance, structural descriptions, or material composition of artisanal kilns without applying rigorous thermodynamic or systems-based analysis to evaluate their performance (Asante-Kyei, 2019; Sola et al., 2019). As a result, while the socio-cultural and economic roles of pottery are well documented, there is a lack of quantitative data on how kiln structure, airflow regulation, and insulation quality affect thermal efficiency and production outcomes in artisanal contexts (Arthur & Gikunoo, 2020; Donkor et al., 2021). In Sub-Saharan Africa, empirical research has largely remained qualitative or observational, offering descriptive accounts of kiln form and firing practices but omitting measurable indicators of energy flow, heat loss, and fuel-to-output ratios (Valdés et al., 2020). The few available thermodynamic analyses have been concentrated in industrial or semi-mechanised settings in Asia and Latin America, where efficiency metrics are far higher due to enhanced design, insulation, and airflow control (Khaliquzzaman et al., 2020; Hussnain et al., 2021). This imbalance has left a significant empirical void in the African artisanal kiln literature, where the interplay between structural degradation, operational behaviour, and energy inefficiency remains poorly quantified and insufficiently theorised.

Moreover, the absence of integrated systems theory and thermodynamic perspectives has limited academic and policy innovation in this field. Without understanding how kiln subsystems interact, including structural integrity, heat transfer dynamics, and operational feedback, efforts to enhance efficiency risk being piecemeal and unsustainable (Skyttner, 2005; Çengel et al., 2019). Consequently, the underlying systemic drivers of inefficiency across artisanal kiln structures are still not well understood, constraining the development of context-appropriate technological or policy interventions in Ghana and similar settings (see Table 1). This study therefore, addresses a critical knowledge gap by empirically evaluating the thermal, structural, and operational performance of firewood-fired downdraft kilns within a systems and thermodynamic framework. Through this integrated approach, the study aims to establish measurable baselines for efficiency, identify key determinants of performance, and contribute evidence-based insights for sustainable energy transitions in artisanal pottery production.

Table 1. Linking Mfensi kiln inefficiencies to SDGs and climate policy frameworks

Observed Inefficiency	Socio-Economic Impact	Relevant SDG / Climate Policy Alignment
Excessive firewood consumption due to poor insulation and uncontrolled airflow	High production costs; reduced artisan profits	SDG 7 - Affordable and Clean Energy (promotes energy efficiency in traditional sectors)
Structural deterioration (cracks, thin walls, lack of refractory materials)	Reduced kiln durability; unstable product quality	SDG 12 - Responsible Consumption and Production (encourages sustainable material use and reduced waste)
Lack of temperature monitoring and draft regulation	Prolonged firing cycles; low efficiency (≈4.2%)	SDG 9 - Industry, Innovation, and Infrastructure (supports technological adaptation in local industries)

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Rising firewood demand leading to deforestation	Local ecological degradation; carbon emissions	SDG 13 - Climate Action + Paris Agreement (targets biomass reduction and climate resilience)

1.2| Research Objectives and Questions

Guided by both systems theory and thermodynamic principles, this study seeks to analyse the performance of artisanal firewood-fired downdraft kilns at the Mfensi Pottery Centre within a holistic efficiency framework. Systems theory conceptualises the kiln as an interacting set of subsystems, including structural, operational, and environmental whose combined functioning determines overall system performance (Skyttner, 2005). Thermodynamic theory complements this view by quantifying the energy flows, losses, and conversion efficiencies that occur within these subsystems (Çengel et al., 2019). Integrating these theoretical perspectives provides a foundation for understanding how material integrity, airflow dynamics, and heat transfer collectively shape kiln outcomes in artisanal pottery production (Figure 1).

Accordingly, the study is guided by the following research questions:

- What is the thermal efficiency of firewood-fired downdraft kilns at the Mfensi Pottery Centre relative to global artisanal kiln benchmarks?
- How do structural and operational conditions such as wall integrity, insulation, and airflow regulation influence kiln efficiency and product yield?
- What are the socio-economic and environmental implications of kiln inefficiencies for artisanal livelihoods and sustainability transitions in Ghana?

To address these questions, the study is structured around the following specific objectives:

- To quantify the thermal efficiency and fuel-to-output ratios of firewood-fired downdraft kilns at Mfensi, establishing baseline performance levels against international artisanal and industrial benchmarks.
- To identify key structural and operational weaknesses including insulation deficits, airflow imbalances, and material fragility that contribute to systemic inefficiency, prolonged firing cycles, and high fuel consumption.
- To assess the socio-economic and environmental implications of kiln inefficiencies, focusing on their impact on artisan profitability, resource use, and alignment with the Sustainable Development Goals (SDGs) and Ghana's climate policy commitments (United Nations, 2015; MESTI., 2021).

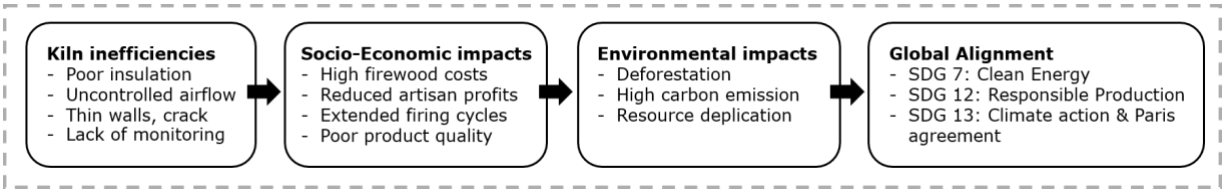


Figure 1. Kiln inefficiencies and their sustainability impacts. (Source: Author's construct, informed by systems theory (Skyttner, 2005) and thermodynamic principles (Çengel et al., 2019), and aligned with global sustainability frameworks (United Nations, 2015)).

1.3| Conceptual and Theoretical Anchors

This study is grounded in systems theory and thermodynamic theory, which together provide a holistic and quantitative lens for analysing kiln performance. Systems theory, as articulated by Skyttner (2005), views each kiln as a dynamic and interdependent system composed of structural, operational, and environmental subsystems. Within this framework, kiln efficiency emerges not from the function of isolated parts but from the coordinated interactions and feedback loops that sustain equilibrium across the system. The theory thus enables the identification of systemic inefficiencies that arise when one or more subsystems such as wall integrity, airflow control, or firing duration fail to function optimally within the whole. Thermodynamic theory complements this systems perspective by quantifying the physical processes of energy transfer, heat loss, and conversion efficiency within the kiln environment (Çengel et al., 2019; Hussnain et al., 2021). It provides the scientific basis for calculating thermal efficiency, assessing heat flow through conduction, convection, and radiation, and determining how structural and operational features influence overall energy utilisation. When applied together, these frameworks integrate the structural and operational realities of artisanal pottery with rigorous thermodynamic analysis, offering both conceptual coherence and empirical precision. Collectively, the systems and thermodynamic perspectives form the analytical foundation for assessing kiln performance and sustainability in this study. They facilitate a multidimensional understanding of how design characteristics, firing practices, and energy dynamics interact to shape both efficiency outcomes and broader environmental implications within the artisanal pottery sector (Valdés et al., 2020; United Nations, 2015).

2 | LITERATURE REVIEW

2.1| Global Perspectives on Kiln Efficiency and Sustainability

Globally, significant advances have been made in improving the thermal efficiency and environmental performance of kilns used in ceramic and brick production. It is important to distinguish between the different kiln categories discussed in the literature, as kiln type fundamentally influences thermodynamic behaviour, fuel

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consumption, and emission profiles. Brick kilns are typically used for large-scale construction material production and have been widely studied in the context of emission reduction and energy efficiency improvements (Khaliquzzaman et al., 2020; Valdés et al., 2020). Ceramic kilns, on the other hand, are employed in more controlled industrial or semi-industrial settings, often benefiting from advanced insulation, regulated airflow, and heat recovery systems that significantly improve thermal performance (Hussnain et al., 2021; Zhou et al., 2022). In contrast, pottery kilns in artisanal contexts are generally smaller, manually operated, and constructed from locally available materials with limited insulation and airflow control, resulting in lower and more variable thermal efficiency (Asante-Kyei, 2019; Arthur & Gikunoo, 2020). In industrialised settings, modern tunnel and roller kilns have achieved thermal efficiencies exceeding 30 percent through the incorporation of advanced refractory materials, optimised airflow regulation, and systematic heat recovery technologies (Çengel et al., 2019; Hussnain et al., 2021). These developments reflect the successful application of thermodynamic principles to reduce energy losses and increase productivity while simultaneously mitigating emissions.

In developing regions, particularly across South and East Asia, the evolution of artisanal and semi-industrial kiln technologies has yielded substantial progress in energy performance. In India and Bangladesh, for instance, the transformation of traditional Bull's Trench Kilns (BTKs) into improved fixed-chimney and zigzag configurations has raised thermal efficiency levels to between 10 and 15 percent while reducing particulate emissions by more than 40 percent (Khaliquzzaman et al., 2020). These gains have been primarily attributed to the introduction of improved draught control, enhanced insulation, and better fuel-to-air ratios, demonstrating that targeted design modifications can substantially increase energy efficiency even in low-technology contexts. In Latin America, similar initiatives have focused on upgrading artisanal kilns used in ceramic and brick production. Case studies in Chile and Mexico have shown that the adoption of thicker refractory walls, regulated chimney dampers, and optimised firing cycles has improved thermal performance by up to 8 percent while reducing firewood consumption (Valdés et al., 2020). Such incremental innovations have proven to be both technically feasible and economically accessible for small-scale producers, offering a viable pathway toward sustainability without compromising artisanal traditions. In China and parts of Southeast Asia, policy-led technological diffusion has further strengthened the link between kiln design efficiency and sustainable energy use. National energy policies promoting cleaner production techniques, combined with the dissemination of low-emission kiln models, have significantly improved the energy efficiency of traditional ceramic industries and reduced carbon footprints (Zhou et al., 2022). These interventions underscore the importance of regulatory support, knowledge transfer, and local adaptation in achieving sustainable transitions in thermally intensive industries. Collectively, these global cases demonstrate that even low-technology kilns can achieve meaningful efficiency gains when design and operational practices are optimised within a thermodynamic framework, although such improvements remain less developed in artisanal pottery contexts.

2.2| Thermodynamic and Systems-Based Approaches

Thermodynamic and systems-based approaches provide a robust theoretical framework for analysing kiln performance and energy efficiency in artisanal production settings. Thermodynamic theory focuses on the quantification of energy flow, conversion, and loss, emphasising the balance between heat input, energy utilisation, and dissipation through conduction, convection, and radiation (Çengel et al., 2019). Within this framework, kiln efficiency is determined by the proportion of total input energy effectively utilised in transforming clay materials into finished ceramic products. The magnitude of energy loss is influenced by multiple factors, including wall thickness, material conductivity, firing duration, and airflow dynamics (Hussnain et al., 2021). Consequently, thermodynamic analysis provides an essential basis for diagnosing the mechanisms of inefficiency and identifying strategies for energy conservation in thermal systems. In practice, empirical studies applying thermodynamic principles to kiln assessment have highlighted the crucial role of insulation, heat recovery, and airflow regulation in determining thermal efficiency. For example, Hussnain et al. (2021) demonstrated that the integration of heat exchangers and improved refractory linings in tunnel kilns significantly reduced energy losses and enhanced temperature uniformity. Similarly, Valdés et al., (2020) reported that modest structural modifications such as thicker kiln walls, controlled draft systems, and optimised combustion yielded measurable efficiency gains in artisanal brick kilns across Latin America. These findings affirm that thermodynamic optimisation can be achieved even in low-technology contexts when grounded in systematic design and operational improvements.

While thermodynamics offers quantitative insight into energy transformation, systems theory extends the analytical scope to encompass the complex interrelations among the structural, operational, and environmental components of kiln performance. As articulated by Skyttner (2005), systems theory views a kiln as an open socio-technical system in which energy flows, material integrity, and human operational practices interact dynamically. Kiln efficiency, therefore, is not solely a function of physical design but also of the balance and feedback among its subsystems, including fuel input regulation, temperature monitoring, and maintenance behaviour. Recent studies applying systems-based thinking to traditional production contexts emphasise that inefficiencies often emerge from the absence of feedback mechanisms and the fragmentation of subsystems rather than from single technical defects (Arthur & Gikunoo, 2020; Donkor et al., 2021). In artisanal kiln operations, for instance, the lack of real-time temperature monitoring and draft control can lead to compensatory behaviours such as extended firing times that inadvertently increase fuel consumption without improving output yield. By integrating systems and thermodynamic theories, researchers can therefore achieve a multidimensional understanding of kiln performance that captures both the physical dynamics of heat transfer and the organisational dynamics of artisanal production. This integrated framework provides the conceptual foundation for the present study, enabling a holistic

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assessment of how structural conditions, energy flows, and human practices interact to shape the thermal efficiency and sustainability of firewood-fired kilns in Ghana.

2.3| Empirical Studies in Sub-Saharan Africa and Identified Gaps

Recent empirical studies in African contexts further highlight the persistent challenges associated with biomass-based thermal systems. Analyses of wood fuel use and small-scale combustion systems across Sub-Saharan Africa reveal enduring inefficiencies, high fuel consumption, and weak regulatory frameworks governing biomass utilisation (Sola et al., 2019). More recent field-based and experimental studies reinforce these findings. For instance, field evaluations of traditional cookstoves and charcoal kilns have documented significant variability in field thermal efficiency and low wood-to-energy conversion rates, largely due to uncontrolled combustion conditions and inconsistent fuel quality (Urban, 2025). Similarly, broader assessments of biomass burning systems emphasise the continued dominance of inefficient combustion practices and the limited adoption of improved technologies across the region (Oloruntoba et al., 2025). At the applied systems level, emerging studies demonstrate that material properties, fuel characteristics, and kiln design significantly influence thermal performance. Experimental research on biomass briquettes in Ghana shows that variations in fuel density, moisture content, and calorific value can substantially affect combustion efficiency and heat output (Sekyere et al., 2025). In parallel, investigations into kiln-based thermal systems, including charcoal and hybrid drying kilns, indicate that inadequate insulation, poor airflow regulation, and lack of process control remain major constraints to achieving optimal energy efficiency (Nwigbo et al., 2025; Saniso et al., 2025). Even where technological improvements have been introduced, such as hybrid solar biomass kiln systems, performance gains are shown to depend heavily on system integration and local adaptation (Ferrari et al., 2024).

Within the specific context of pottery kiln systems in Sub-Saharan Africa, empirical research has largely concentrated on structural design, fuel consumption patterns, and material properties, with limited integration of thermodynamic or systems-based analyses. Several studies have explored the insulation potential of locally available materials, particularly clay-based compositions, in enhancing heat retention. For example, Arthur and Gikunoo (2020) demonstrated the suitability of Ghanaian anthill clays for high-temperature applications, highlighting their potential to improve kiln wall integrity and thermal resistance. Similarly, Donkor et al. (2021) identified important relationships between structural parameters and thermal performance in clay-based combustion systems, providing useful methodological insights for analysing heat transfer processes. In addition, Asante-Kyei (2019) showed that the use of locally sourced refractory materials in kiln construction can improve heat retention and reduce fuel dependency, although without extending the analysis to quantitative efficiency measurement. Despite these contributions, most studies within the African context remain largely descriptive, focusing on structure, fuel use, or material selection without applying thermodynamic computation or systems-based evaluation. Consequently, there is limited empirical evidence linking structural and operational characteristics to measurable energy performance outcomes. This gap is particularly evident in Ghana, where no study has systematically combined structural assessment with thermodynamic analysis to explain kiln efficiency. The present study addresses this gap by employing an integrated systems and thermodynamic framework to evaluate the thermal, structural, and operational performance of firewood-fired downdraft kilns at the Mfensi Pottery Centre.

To contextualise the methodological approaches adopted in previous studies, Table 2 presents a comparative summary of key kiln performance research, highlighting differences in analytical techniques, metrics, and limitations

Table 2: Comparative Summary of Previous Kiln Performance Studies

Study	Region	Kiln Type	Methodology	Key Metrics	Limitations
Çengel et al. (2019)	Global	Industrial kilns	Thermodynamic modelling	Heat balance, efficiency	Idealized assumptions, not field based
Zhou et al. (2022)	China	Ceramic kilns	Policy and energy systems analysis	Efficiency, emissions	Industrial focus
Hussnain et al. (2021)	Asia	Ceramic kilns	Experimental and modelling	Temperature distribution, efficiency	Limited socio-economic context
Khaliquzzaman et al. (2020)	South Asia	Brick kilns	Longitudinal field analysis	Emissions, efficiency	Region specific
Valdés et al. (2020)	Latin America	Brick and artisanal kilns	Field review and case studies	Fuel consumption, efficiency	Limited thermodynamic depth
Oloruntoba et al. (2025)	Sub-Saharan Africa	Biomass systems	Review and synthesis	Combustion efficiency, emissions	Limited kiln specificity
Sola et al. (2019)	Sub-Saharan Africa	Biomass energy systems	Policy and energy review	Fuel use patterns	No thermodynamic quantification
Urban (2025)	Sub-Saharan Africa	Cookstoves and charcoal kilns	Field-based measurement	Thermal efficiency,	Limited structural analysis

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				conversion factors	
Nwigbo et al. (2025)	Africa	Charcoal and hybrid kilns	Systematic review	Thermal performance, system design	Limited field validation
Saniso et al. (2025)	Developing regions	Charcoal kilns	Experimental case study	Yield, thermal performance	Not pottery specific
Ferrari et al. (2024)	DR Congo	Hybrid biomass kiln	Experimental system design	Energy efficiency, drying performance	Context specific
Sekyere et al. (2025)	Ghana	Biomass fuel systems	Experimental analysis	Calorific value, fuel properties	Not kiln specific
Donkor et al. (2021)	Ghana	Biomass combustion systems	Experimental analysis	Thermal efficiency, structural parameters	Focus on stoves
Arthur and Gikunoo (2020)	Ghana	Kiln materials	Material testing	Thermal conductivity, insulation	No system-level analysis
Asante-Kyei (2019)	Ghana	Pottery kiln	Design and fabrication	Structural performance	No efficiency quantification

2.4| Conceptual Framework

The present study is guided by an integrated conceptual framework that combines systems theory and thermodynamic theory to explain the determinants of kiln efficiency in artisanal pottery production. The framework (Figure 2) illustrates how efficiency outcomes in firewood-fired downdraft kilns emerge from the interaction of three interdependent subsystems, structural, operational, and thermodynamic, whose functions and feedback relationships collectively determine overall performance. The structural subsystem comprises the physical configuration of the kiln, including wall integrity, material composition, thickness, and insulation quality. These structural attributes influence the rate of heat transfer through conduction and radiation, thereby affecting energy retention and kiln durability (Arthur & Gikunoo, 2020; Donkor et al., 2021). Weaknesses such as cracks, thin walls, and the absence of refractory insulation increase heat losses and compromise temperature stability during firing (Valdés et al., 2020).

The operational subsystem encompasses the practices and procedures through which artisans manage kiln functions such as firing time, fuel loading rate, airflow control, and maintenance. These human and procedural factors regulate the balance between energy input and output. In artisanal settings, the absence of temperature monitoring and draft control often leads to compensatory behaviours, including prolonged firing durations, which inadvertently increase fuel consumption without enhancing product yield (Sola et al., 2019). The thermodynamic subsystem captures the energy processes occurring within the kiln, including the quantity and quality of energy input, the distribution of heat within the chamber, and the proportion of energy converted into useful work. It is within this subsystem that thermal efficiency is measured through the relationship between total heat input and the useful heat absorbed by the clay load (Çengel et al., 2019; Hussnain et al., 2021). Energy losses through conduction, convection, and radiation are key determinants of efficiency and directly relate to both structural and operational characteristics. These three subsystems interact dynamically, producing feedback loops that influence kiln performance. According to systems theory, as articulated by Skyttner (2005), system components must function in equilibrium for optimal performance; inefficiency arises when interconnections weaken or feedback mechanisms are absent. Within this study, kiln efficiency is treated as the dependent variable, influenced by the structural, operational, and thermodynamic subsystems (independent variables). Efficiency outcomes further affect secondary indicators such as pottery yield, fuel consumption, and broader sustainability implications related to resource use and emissions. This framework aligns with systems theory's emphasis on interdependence and thermodynamic theory's quantification of energy flow, providing both conceptual coherence and analytical rigour for assessing kiln performance. It serves as the foundation for the methodological design and empirical analysis presented in the next section.

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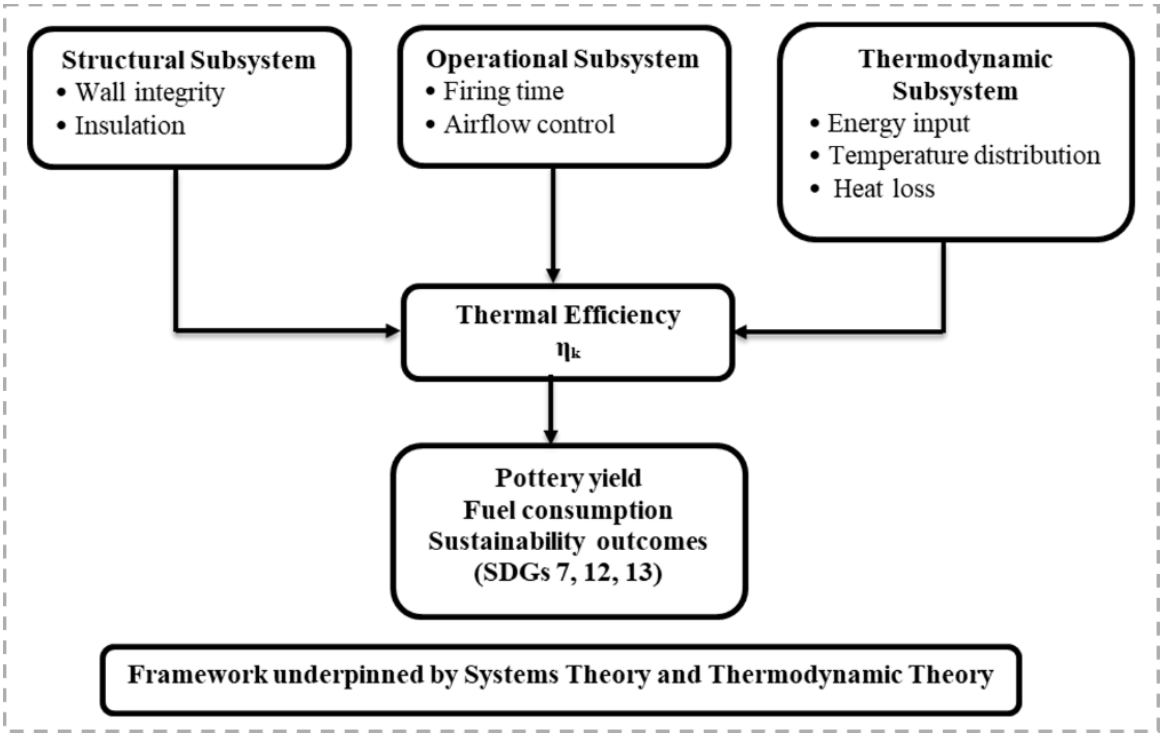


Figure 2. Conceptual Framework of Kiln Efficiency Analysis Based on Systems and Thermodynamic Theories. Source: Author's construct, adapted from Skyttner (2005) and Çengel et al. (2019).

3 | METHODOLOGY

Guided by the conceptual framework, the study employed a mixed-method approach integrating quantitative thermodynamic measurement with qualitative field insights. This design allowed for a holistic understanding of kiln performance, capturing both the physical parameters of thermal efficiency and the experiential perspectives of artisans. Such integration aligns with contemporary energy-efficiency research, where mixed-method approaches are used to triangulate empirical measurements with contextual realities (Creswell & Plano Clark, 2018; Hussnain et al., 2021).

3.1| Study site and sample

The study was conducted at the Mfensi Pottery Centre in the Ashanti Region of Ghana, a community hub with an estimated 200 artisans engaged in pottery production. A purposive sample of 19 functioning circular downdraft firewood kilns was selected. The choice of 19 kilns was guided by two considerations: (i) Structural and operational variation, the sample captured differences in wall integrity (intact vs. cracked), chimney presence, roof sealing, and firing/maintenance practices. (ii) Representativeness, the 19 kilns constituted approximately 60% of the actively used downdraft kilns at the site during the study period. Sampling at this proportion is considered adequate in artisanal kiln studies (cf. Valdes et al., 2020), as it balances feasibility with diversity while minimising sampling bias. Although all kilns followed the downdraft design, they varied in diameter, wall thickness, chimney draft function, and maintenance history, providing sufficient heterogeneity for comparative analysis.

3.2| Data collection procedures

Data were obtained using four complementary approaches:

- Direct measurement: firewood volumes were recorded per firing cycle (in m^3), firing durations measured in hours, and peak firing temperatures captured in °C using a calibrated digital pyrometer (±2 °C accuracy, K-type thermocouple) placed at multiple kiln points. Calibration was verified against a mercury-in-glass thermometer prior to field deployment.
- Structural inspection: visual and physical examination of kiln foundations, walls, roofs, chimneys, and insulation was conducted to assess presence/absence, degree of cracking, sealing effectiveness, and evidence of erosion.
- Output assessment: fired pottery products were quantified by calculating yield (%) as the proportion of defect-free items relative to total load, with defect categories including under-firing, warping, and cracking.
- Interviews and focus groups: semi-structured interviews with kiln operators and focus group discussions with artisans contextualised firing practices, fuel sourcing, and maintenance challenges. Reliability was ensured through cross-verification of responses across different groups and triangulation with observed practices.

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3.3| Analytical framework

Three key thermodynamic indicators were applied:

- Thermal efficiency of the kiln (η_k) was computed as the ratio of useful heat absorbed by the clay load to the total energy input from fuel combustion. The useful heat (Quseful) was estimated based on the sensible heat required to raise the temperature of the clay load from ambient to peak firing temperature, expressed as:
  η_k = (Quseful / Qin) × 100
  where Quseful = Mp × Cp × ΔT, and Q_in = Vf × ρw × Hv × λ.

Here, Mp represents the mass of the clay load (kg), Cp is the specific heat capacity of clay (kJ/kgK), ΔT is the temperature rise from ambient to peak kiln temperature (K), Vf is the volume of firewood consumed (m^3), ρw is the density of firewood (kg/m^3), Hv is the calorific value of the firewood (kJ/kg), and λ is the combustion efficiency factor accounting for incomplete combustion. To ensure consistency and reproducibility, key thermodynamic parameters were defined using standard values from the literature. The specific heat capacity of clay (C_p) was assumed to be 0.84 kJ kg^{-1} K^{-1}, consistent with values reported for earthen materials in thermal systems (Çengel et al., 2019). The calorific value of firewood (H_v) was taken as 15,000 kJ kg^{-1}, reflecting typical energy content for air-dried hardwoods used in Sub-Saharan Africa (Donkor et al., 2021). Firewood density (ρw) was assumed to be 600 kg m^{-3} to convert measured volumetric fuel consumption into mass. A combustion efficiency coefficient (λ) of 0.70 was applied to account for incomplete combustion under field conditions, as commonly observed in traditional biomass systems (Sola et al., 2019). Ambient temperature was assumed to be 30°C, and temperature rise (ΔT) was computed relative to recorded peak kiln temperatures.

Firewood energy input was derived by converting measured fuel volume to mass using an assumed average density, followed by multiplication with the calorific value and combustion efficiency factor. This approach accounts for variability in fuel characteristics while maintaining consistency with established biomass energy estimation methods. Temperature measurements were obtained at the kiln chamber using a pyrometer positioned near the firing zone to capture peak thermal conditions. While these assumptions introduce minor uncertainties, consistent application across all kiln observations ensures comparability of results. The adopted approach is conceptually consistent with standard heat balance methods used in kiln efficiency studies. A detailed sample calculation and the full set of input parameters used in the thermal efficiency calculations is provided in Supplementary Material S1 and Supplementary Table S1, respectively.

- Fuel Efficiency Ratio (FER): FER = (mf × Hv × λ / Qin) × 100%: Where mf is the mass of firewood consumed (kg), Hv is the calorific value of firewood (kJ/kg), λ is the combustion efficiency coefficient, and Qin is the energy supplied.
- Heat loss (Fourier's Law): Qloss = (k × A × ΔT) / d: Where k is the thermal conductivity of kiln wall material (W/m·°C), A is the surface area of heat transfer (m^2), ΔT is the temperature difference between kiln interior and exterior (°C), and d is wall thickness (m).

It is important to note that the thermodynamic measurements are subject to inherent uncertainties associated with field-based data collection. Temperature readings may be affected by sensor placement, temporal fluctuations during firing, and limitations in measurement resolution. Similarly, the estimation of fuel consumption based on volumetric firewood measurements introduces uncertainty due to variations in wood density, moisture content, and stacking configuration. While standardised procedures were applied consistently across all kiln observations to minimise systematic bias, these factors may contribute to minor deviations in the calculated thermal efficiency and fuel energy inputs. Nonetheless, the consistency of measurement conditions across the sampled kilns ensures that the results remain suitable for comparative analysis.

3.4| Analytical tools and data treatment

Descriptive statistics (means, standard deviations, and ranges) were computed to summarise quantitative data. Group comparisons between cracked and intact kilns were conducted using independent-samples t-tests, while zero-order correlations explored associations among thermal efficiency, yield, firing duration, and fuel consumption. Statistical significance was assessed at $p < 0.05$. Qualitative data from interviews and focus groups were analysed thematically to identify recurring operational patterns, challenges, and local adaptation strategies. Integration of quantitative and qualitative findings followed a convergent mixed-method design, where both datasets were interpreted together to enhance explanatory depth (Creswell & Plano Clark, 2018). Given the relatively small sample size (n = 19), particularly for the subgroup of kilns without cracks (n = 5), the results of independent-samples t-tests should be interpreted with caution. While the tests provide indicative comparisons between groups, the limited sample size reduces statistical power and may affect the detection of significant differences. In addition, the assumption of normality was not formally tested due to sample constraints; however, the t-test was retained as an exploratory analytical tool appropriate for small-sample comparative analysis. These limitations are acknowledged and further discussed in the limitations section. Potential sources of uncertainty, including variability in fuel properties and measurement constraints, are discussed in the limitations section.

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4 | RESULTS AND DISCUSSION

4.1| Structural condition

The structural integrity of the kilns was generally poor. Approximately 68% of kiln foundations were rated fair, with visible signs of erosion. Wall and roof assessments revealed that only 21% were in good condition, whereas 74% exhibited cracks of varying severity, and 5% were rated poor. Notably, none of the kilns possessed any form of insulation, and airflow regulation mechanisms such as dampers or vents were absent, leaving all chimneys unregulated. These deficiencies indicate widespread susceptibility to heat loss and operational inefficiency (Table 3 and Figure 3).

4.2| Thermodynamic performance

Thermodynamic measurements further confirmed low efficiency across the sample. Mean thermal efficiency was ≈4.2%, with the most efficient kiln reaching only ~5.1%. The average firing cycle lasted 25.3 hours (range: 21-32 hours). Firewood consumption averaged 5.6 m³ per firing, while mean peak temperature reached 901 °C. The mean product yield was 52.3%, with high defect rates dominated by under-firing, warping, and cracking.

4.3| Comparative patterns

When comparing cracked (n = 14) and intact (n = 5) kilns, cracked kilns consumed slightly more firewood (5.76 m³ vs. 5.31 m³) and produced lower yields (50.9% vs. 56.3%). Although cracked kilns showed marginally higher thermal efficiency (4.31% vs. 4.05%), independent-samples t-tests indicated that none of the observed differences in efficiency, yield, firing time, or fuel consumption were statistically significant ($p > 0.05$). Independent-samples t-tests further confirmed that differences in thermal efficiency were not statistically significant ($t = -1.76$, $p = 0.096$), with a small to moderate effect size (Cohen's $d = 0.53$). The 95% confidence interval for the mean difference (−0.58 to 0.06) includes zero, further confirming that the observed variation is not statistically meaningful. This suggests that inefficiency was systemic rather than attributable to single structural features such as wall cracking. These findings correspond to the conceptual expectation that structural and operational subsystems jointly determine overall thermal efficiency, as outlined in the conceptual framework (see Figure 3). Although no statistically significant differences were observed between cracked and non-cracked kilns, the small sample size of the non-cracked subgroup limits the statistical power of the analysis. As such, the absence of statistical significance should be interpreted with caution and does not necessarily imply the absence of a true effect.

Table 3. Performance summary by wall condition (derived from per-kiln dataset).

Wall Condition	n	Mean η_k (%)	SD (η_k)	Mean Yield (%)	Mean Firing Time (h)	Mean Fuel (m³)	t-value	p-value	Cohen's d	95% CI (Mean Diff)
No cracks	5	4.05	0.07	56.3	25.5	5.31				
Cracks	14	4.31	0.07	50.9	25.2	5.76	−1.76	0.096	0.53	[−0.58, 0.06]

Note: p-values indicate no statistically significant differences across groups (ns = not significant).

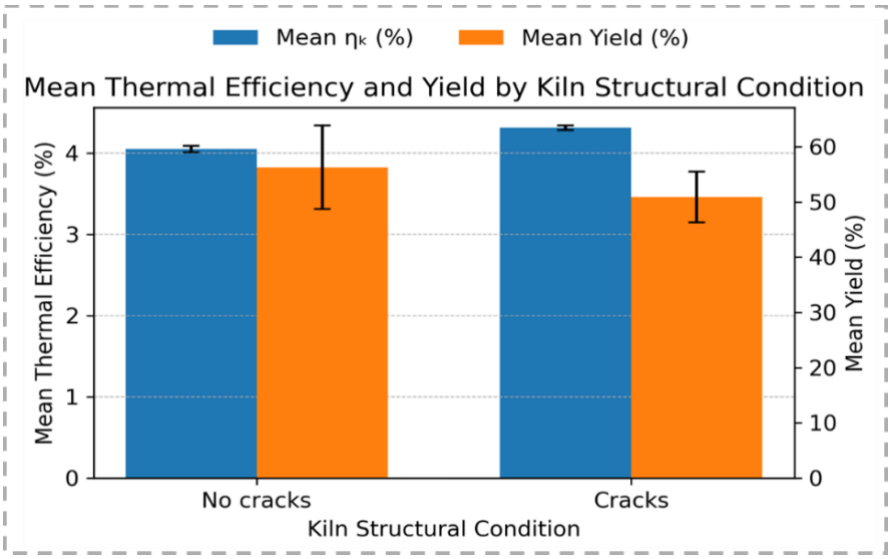


Figure 3. Comparative Thermal Efficiency and Product Yield by Kiln Structural Condition

This figure presents mean thermal efficiency (η_k) and product yield for kilns with and without cracks. Although cracked kilns show slightly higher efficiency, they record lower yields, indicating that structural degradation affects production outcomes. The small variability in efficiency compared with the wider dispersion in yield further suggests

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that energy performance is consistently constrained across kilns, while production outcomes are more variable. Differences between groups are not statistically significant at p greater than 0.05.

4.4| Correlation Analysis

Zero-order correlations between efficiency, yield, and operational variables revealed only weak associations (Table 4). The correlation between thermal efficiency and yield was positive but negligible (r = +0.03, p = 0.89). Similarly, efficiency showed weak, statistically insignificant negative associations with fuel consumption (r = -0.07, p = 0.74), firing time (r = -0.21, p = 0.39), and maximum temperature (r = -0.03, p = 0.92). These results reinforce the interpretation that kiln inefficiencies arise from interrelated systemic weaknesses rather than direct, linear relationships between individual performance variables.

Table 4. Zero-order correlations (N=19)

Variable Pair	r	p-value
η_k vs. Yield	+0.03	0.89
η_k vs. Max Temp	-0.03	0.92
η_k vs. Fuel	-0.07	0.74
η_k vs. Firing Time	-0.21	0.39

5 | DISCUSSION

5.1| Interpretation within Thermodynamic Context

The measured thermal efficiencies of 4%–5% indicate low but realistic energy conversion rates relative to both industrial and improved artisanal kiln benchmarks, which typically range from 10% to 30% (Valdés et al., 2020; Hussnain et al., 2021). This efficiency gap confirms that most of the heat generated during firing is lost through conduction and radiation, consistent with thermodynamic expectations where uninsulated walls and unregulated airflow increase energy dissipation (Çengel et al., 2019). Figure 3 presents the mean thermal efficiency and yield by kiln structural condition, with error bars indicating variability within each group. The relatively small standard deviations observed in thermal efficiency, compared to the wider variability in yield, further indicate that energy performance is consistently constrained across kilns, whereas production outcomes are more variable. The marginally higher efficiency observed in cracked kilns should be interpreted with caution. Although the difference suggests a slight variation in heat transfer dynamics, statistical analysis indicates that it is not significant and exhibits only a small to moderate effect size. This reinforces the argument that structural defects, such as wall cracking, do not independently determine kiln performance. The long firing durations (21–32 hours) further highlight poor energy retention and suboptimal combustion rates. According to thermodynamic theory, inefficient combustion and heat retention directly reduce the useful energy (Quseful) absorbed by the clay load relative to total energy input (Qin) (Çengel et al., 2019). The observed high fuel consumption and low yields thus validate the theoretical premise that without proper insulation, energy equilibrium within the kiln cannot be maintained

5.2| Justification of the Reported Thermal Efficiency (≈4.2%)

The efficiency reported in this study (≈4.2%) is based on a strict calculation boundary representing the ratio of useful heat absorbed by the clay load to the total calorific energy input from firewood combustion, a "product-only" approach. For context, the Chinese national standard GB/T 23459-2009 for industrial ceramic kilns mandates a full heat balance accounting for heat stored in kiln structures, flue gas losses, and exterior radiation. Applying the logic of GB/T 23459-2009 to the Mfensi kilns, which lack insulation, have cracked walls (74% of kilns), and feature unregulated chimneys, would yield very high heat loss terms, resulting in an equally low net efficiency. Furthermore, research by Prof. Zeng Lingke (South China University of Technology), a leading expert in ceramic kiln energy efficiency, demonstrates that advanced features such as lightweight insulation materials and optimised burner systems are essential for achieving high thermal performance. The Mfensi kilns possess none of these features, making the observed ≈4.2% efficiency a plausible and defensible reflection of their severely compromised structural and operational state.

5.3| Structural and Operational Drivers

The study's results reveal that kiln structure and operation jointly determine performance outcomes. Cracked walls, absent insulation, and unregulated chimneys permit uncontrolled heat escape, while poor fuel stacking and draft management worsen combustion efficiency. Such interactions between physical degradation and procedural inefficiency exemplify the interdependence of structural and operational subsystems identified in the conceptual framework (see Figure 2). Kilns with sound walls and controlled firing exhibited shorter cycles and higher yields, aligning with Arthur and Gikunoo's (2020) findings, which demonstrated that wall integrity and material density significantly influence thermal resistance. Similarly, effective airflow control has been shown to enhance flame uniformity and reduce temperature fluctuation in small-scale combustion systems (Donkor et al., 2021; Hussnain et al., 2021). The absence of such control mechanisms at the Mfensi Pottery Centre explains much of the inefficiency observed.

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5.4| Systems Perspective on Interdependent Subsystem Failures

From a systems theory perspective, the inefficiencies identified in the Mfensi kilns stem from the breakdown of equilibrium and feedback regulation among structural, operational, and thermodynamic subsystems. Systems theory emphasises that the effectiveness of a system depends not only on the performance of individual components but also on their coordination and feedback loops (Skyttner, 2005). In this context, the lack of mechanisms to monitor temperature or adjust draft flow represents the absence of negative feedback, leading to uncontrolled energy loss and unstable firing conditions. The weak correlations observed among efficiency, yield, and fuel use (see Table 4) further support this interpretation, indicating that kiln performance cannot be explained by isolated variables but must be understood as the outcome of complex subsystem interactions. This reinforces the study's conceptual stance that artisanal kiln performance is a systems problem, not merely a technical one. The absence of statistically significant differences between kiln categories, despite observable structural variation, further supports the systems perspective that performance outcomes arise from the interaction of multiple subsystems rather than any single structural parameter.

5.5| Global Parallels and Contextual Lessons

The challenges documented at Mfensi are not unique to Ghana; they mirror those faced by traditional ceramic communities across the Global South and even within industrialising economies. In China, for instance, the vast ceramic industry is undergoing a profound "green transition," shifting from coal to natural gas and increasingly to electricity ("gas-to-electric"). While the technological solutions differ markedly from what is feasible at Mfensi, the core tension among balancing tradition, production costs, and environmental sustainability is shared. Notably, research in central China has documented traditional dragon kiln (longyao) communities that continue to operate using ancestral firing techniques. These communities face similar pressures of modernisation and economic decline, yet they persist as vital repositories of intangible cultural heritage and indigenous technical knowledge (Zhou et al., 2022). The lesson is that technological upgrading must be context-sensitive; preserving artisanal knowledge while improving efficiency is a delicate but essential balance.

In Latin America, incremental innovations in artisanal brick kilns have achieved measurable efficiency gains (8–10%) through modest structural modifications such as thicker refractory walls, chimney dampers, and optimised firing cycles (Valdés et al., 2020). These interventions are affordable and technically accessible to small-scale producers, offering a realistic model for Mfensi. Similarly, in South Asia, the transformation of traditional Bull's Trench Kilns into zigzag configurations increased thermal efficiency to 10–15% while reducing emissions by more than 40% (Khaliquzzaman et al., 2020). Although brick kilns differ from pottery kilns, the underlying principles of draft control, insulation, and combustion optimisation are transferable. What distinguishes the Mfensi case is the systemic nature of inefficiency: structural degradation, absent insulation, and unregulated airflow operate together as interacting failures. This finding aligns with systems theory (Song, 2018) and suggests that piecemeal interventions (e.g., repairing cracks alone) will likely fail. Instead, an integrated approach – combining structural rehabilitation, airflow regulation, and operator training – is necessary (Valdés et al., 2020). The global parallels do not imply a one-size-fits-all solution, but they provide inspiration and evidence that low-cost, high-impact improvements are possible even in resource-constrained settings (Cordeiro et al., 2016).

Positioning the Mfensi study within this wider global narrative does not diminish its contextual specificity. Rather, it highlights that artisanal kiln inefficiency is a pervasive but solvable challenge. By learning from successes elsewhere – from Chinese dragon kiln communities preserving tradition while adapting, from Latin American brickmakers adopting simple dampers, and from South Asian zigzag innovations – Ghanaian policymakers and artisans can design locally appropriate pathways toward sustainable pottery production. This study provides the empirical baseline and systemic diagnosis needed to begin that journey.

5.6| Socio-Economic and Sustainability Implications

The identified inefficiencies have critical socio-economic and environmental implications. Prolonged firing durations and high fuel consumption increase production costs and labour intensity, reducing profitability for artisans whose livelihoods depend on small-scale ceramic sales. From an environmental standpoint, inefficient combustion contributes to deforestation and elevated greenhouse gas emissions, contravening Ghana's commitments to sustainable energy use and climate resilience (United Nations, 2023). Improving kiln efficiency, therefore, supports Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (UNDP, 2017). Interventions such as promoting insulation using locally available refractory clays, introducing draft regulation devices, and providing technical training could significantly enhance both economic and environmental outcomes. These recommendations align with regional strategies for sustainable woodfuel use in artisanal industries (Sola et al., 2019).

5.7| Theoretical and Empirical Contributions

This study contributes to both theory and practice. Conceptually, it operationalises systems theory within a thermodynamic context, demonstrating how interdependent kiln subsystems collectively influence energy performance. By integrating systems dynamics and energy balance principles, it provides an explanatory model that links structural and operational variables to measurable thermodynamic outcomes. Empirically, it offers the first quantified efficiency assessment of artisanal downdraft kilns in Ghana, establishing a baseline for comparative

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research and technical optimisation. The study's mixed-method approach also exemplifies how physical measurement can be combined with field-level insights to produce a comprehensive understanding of artisanal energy systems. This dual contribution advances both academic discourse and practical innovation in sustainable pottery production.

5.8| Limitations and Directions for Future Research

While this study offers valuable empirical and theoretical insights, several limitations should be acknowledged. First, the thermodynamic efficiency computations were based on short-term field measurements that may not capture seasonal variations in fuel moisture, firing frequency, and ambient temperature. Second, the absence of advanced instrumentation, such as real-time combustion analysers or infrared thermography, constrained precision in quantifying total heat loss. Third, the sample was geographically limited to the Mfensi Pottery Centre, which, although representative of Ghanaian artisanal practice, may not reflect variations across other pottery clusters with differing kiln designs and fuel types. Fourth, qualitative observations relied on artisan self-reports, which may contain recall bias. A further limitation relates to the small sample size of the non-cracked kiln subgroup, n equals 5, which reduces the statistical power of comparative analyses and increases the likelihood of Type II error. Consequently, the inability to detect statistically significant differences between kiln conditions should not be interpreted as definitive evidence of equivalence. In addition, measurement uncertainties related to temperature recording and firewood energy estimation may introduce minor variations in calculated efficiency values. Despite these constraints, the triangulation of data sources and the integration of systems and thermodynamic perspectives enhance the robustness of the findings. Future studies should employ long-duration monitoring, comparative regional sampling, and computational fluid dynamics modelling to further validate and generalise the results. Regarding generalisability, other Ghanaian centres (e.g., Sirigu, Vume) may use different kiln designs (updraft or beehive) or fuels (agricultural waste, charcoal). Thus, the specific efficiency value (≈4.2%) should not be directly generalised without local measurement. However, the analytical framework, which combines thermodynamic measurements with systems-based subsystem diagnosis, is fully transferable, as the core inefficiencies (lack of insulation, unregulated airflow, structural degradation) are likely common across wood-fired artisanal kilns in Sub-Saharan Africa. Future multi-site studies are needed to validate the framework across diverse contexts.

6 | CONCLUSION

This study evaluated the performance and energy efficiency of firewood-fired downdraft kilns at the Mfensi Pottery Centre, with particular emphasis on the interaction between structural, operational, and thermodynamic subsystems. Empirical findings revealed widespread structural degradation, absence of insulation, and limited airflow regulation, all of which contributed to substantial heat loss and low thermal efficiency, with mean values of approximately 4.2%. Although minor variations in performance were observed between cracked and non-cracked kilns, these differences were not statistically significant, confirming that inefficiency is systemic rather than attributable to isolated structural defects. From a thermodynamic perspective, the results demonstrate that poor heat retention and uncontrolled combustion significantly reduce the proportion of useful energy transferred to the clay load, leading to extended firing durations, increased fuel consumption, and variable production outcomes. Beyond these empirical insights, the study makes a clear theoretical contribution by advancing an integrated systems thermodynamic framework for analysing artisanal kiln performance. Unlike conventional approaches that assess efficiency primarily through isolated thermal indicators, this framework conceptualises kiln performance as an emergent property of interacting structural, operational, and thermodynamic subsystems. In doing so, it provides a more comprehensive explanatory model for inefficiency in traditional production systems and offers a transferable analytical basis for evaluating energy performance in other small-scale, resource-constrained manufacturing contexts. While the findings provide robust insights, certain limitations should be acknowledged. The study is geographically confined to a single pottery centre, which may limit generalisability to other artisanal settings with different kiln configurations, fuel types, and environmental conditions. In addition, thermodynamic calculations were based on field measurements and assumed parameters, which may introduce some degree of uncertainty. The relatively small sample size, particularly for kilns without structural defects, also limits statistical power and the ability to detect subtle performance differences. Nevertheless, the consistency of the observed inefficiencies and the robustness of the systems-based interpretation suggest that the core findings are indicative of broader patterns across similar artisanal contexts. Importantly, the insights generated from this study are transferable to other artisanal pottery centres in Ghana and across Sub-Saharan Africa, where kiln designs, fuel dependence, and operational practices exhibit comparable characteristics. The integrated analytical framework developed here can therefore serve as a diagnostic and evaluative tool for identifying efficiency constraints and guiding context-specific interventions in similar settings.

7 | RECOMMENDATION

Improving the performance and sustainability of artisanal kilns requires coordinated technical, institutional, and research-driven interventions. At the structural level, kiln walls should be reinforced using appropriate refractory materials, and basic insulation layers should be introduced using locally available clays with proven thermal resistance, thereby enhancing heat retention and durability (Arthur & Gikunoo, 2020). In addition, the installation of simple airflow regulation mechanisms, such as dampers or vents, can improve draft control, stabilise

internal temperatures, and reduce uncontrolled heat loss, leading to more efficient combustion (Donkor et al., 2021). Operational improvements are equally critical. Targeted capacity building initiatives should be implemented to train artisans in fuel stacking techniques, draft management, and routine maintenance practices, all of which are essential for improving combustion efficiency and extending kiln lifespan. At the institutional level, policy integration is required to support the upgrading of artisanal kiln systems. Relevant agencies, including the National Board for Small Scale Industries and the Energy Commission, should incorporate kiln improvement strategies into broader renewable energy and climate adaptation programmes, in alignment with Ghana's commitments to Sustainable Development Goals 7, 12, and 13 (United Nations, 2023). Finally, further research should extend the present framework through comparative studies across multiple regions and by incorporating advanced energy modelling techniques to support design optimisation and scalability. By bridging theoretical thermodynamics with practical kiln design, the integrated framework developed in this study provides a foundation for sustainable energy interventions and cross-country applications in artisanal manufacturing sectors

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DATA AVAILABILITY STATEMENT

Data sharing applies to this study upon an acceptable request from the corresponding authors.

ETHICAL APPROVAL STATEMENT

There is no ethical approval for this study.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this article.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the authors used Grammarly and QuillBot to polish and refine the language. All research design, data collection, analysis, interpretation of findings, and conclusions were developed by the authors. After using these tools, the authors carefully reviewed and edited all suggested text and take full responsibility for the accuracy and integrity of the manuscript.

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SUPPLEMENTARY MATERIALS

The authors provide a detailed sample calculation and the full set of input parameters used in the thermal efficiency calculations in the Supplementary Material.

REFERENCES

Arthur, E. K., & Gikunoo, E. (2020). Property analysis of thermal insulating materials made from Ghanaian anthill clay deposits. *Cogent Engineering*, 7(1), Article 1827493. https://doi.org/10.1080/23311916.2020.1827493

Asante-Kyei, K (2019). Design and fabrication of gas kiln using local materials to compose its refractory bricks and mortar. *Journal of Arts and Humanities*, 8(3), https://theartsjournal.org/index.php/site/article/view/1584

Çengel, Y. A., Boles, M. A., & Kanoğlu, M. (2019). Thermodynamics: An engineering approach (9th ed.). New York, NY: McGraw-Hill Education.

Cordeiro Mota, S., Mazarelo Maciel Pacheco, K., & Hernandis Ortuño, B. (2016). O Design Sistêmico como método de inovação aplicado a fornos tradicionais de cerâmica vermelha no Amazonas-Brasil. In Systems&design: beyond processes and thinking (pp. 793-806). Editorial Universitat Politècnica de València. https://doi.org/10.4995/IFDP.2016.3696

Creswell, J. W., & Plano Clark, V. L. (2018). Designing and conducting mixed methods research (3rd ed.). SAGE Publications.

Donkor, K., Obeng, G. Y., Opoku, R., & Agyei-Agyemang, A. (2021). Production processes and statistical analysis of ceramic liner-hole parameters for sustainability and improved thermal efficiency of clean biomass stoves. *Renewable Energy and Environmental Sustainability*, 6, Article 23, 1–10. https://doi.org/10.1051/rees/2021023

Ferrari, S., Cuccui, I., Cerutti, P., & Allegretti, O. (2024). A hybrid solar/biomass active indirect kiln dryer for timber in the Democratic Republic of Congo. *International Journal of Ambient Energy*, 45(1), https://doi.org/10.1080/01430750.2024.2367109

MESTI. (2021). Updated nationally determined contributions (NDCs) under the Paris Agreement (2020-2030). Environmental Protection Agency, Ministry of Environment, Science, Technology and Innovation, Accra, Ghana. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx

Hussnain, S. A., Farooq, M., Amjad, M., Riaz, F., Tahir, Z. U. R., Sultan, M., Hussain, I., Shakir, M. A., Qyyum, M. A., Han, N., & Bokhari, A. (2021). Thermal analysis and energy efficiency improvements in tunnel kiln for sustainable environment. *Processes*, 9(9), Article 1629. https://doi.org/10.3390/pr9091629

Khaliquzzaman, M., Harinath, A. S., Ferdousi, S. A., & Khan, S. M. M. H. (2020). Thirty years' quest for emission reduction and energy efficiency improvement of brick kilns in Bangladesh. *International Journal of Environmental Monitoring and Analysis*, 8(1), 11–22. https://doi.org/10.11648/j.ijema.20200801.12

Kusimi, BA, Donkor, AK, Ayivor, JS, Kyeremeh, K, & Kusimi, JM (2020). The Lifecycle of Pottery Art Processes and Production in Mpraeso, Ghana. *De Arte*, 55(3), 70–94. https://doi.org/10.1080/00043389.2020.1805849

Nwigbo, O., Nwoko, C., Emerie, S., & Onyenanu, I. (2025). Optimizing Agricultural Drying Technologies: A Systematic Review of Charcoal, Gas, and Hybrid Kilns for Sustainable Food Preservation. *Journal of Sustainable Engineering & Renewable Energy (JSERE)*, 1(1), 37-51.

Oloruntoba, A., Omoniyi, A., Olaseinde, O., Nkoh, J., Okeke, E., Ajibade, F., Adeniran, O., Kolawole, S. & Adekanye, K. (2025). Biomass burning and biochar: developments in Sub-Saharan Africa. *Physical Sciences Reviews*, 10(7-9), 723-766. https://doi.org/10.1515/psr-2023-0016

Saniso, E., Sueni, L., Hayibaka, M., & Suttikan, M. (2025). Enhancing charcoal Production: Improvements in the traditional brick kiln and product properties. *Case Studies in Thermal Engineering*, 73, 106634. https://doi.org/10.1016/j.csite.2025.106634

Sekyere, C. K. K., Opoku, R., Asaaga, B., Baah, B., Andoh, P. Y., Obeng, G. Y., & Agbogla, J. (2025). Techno-environmental assessment of the fuel properties of a variety of briquettes for biomass boiler applications. *Cleaner Energy Systems*, 10, https://doi.org/10.1016/j.cles.2025.100185

Skyttner, L. (2005). General systems theory: Problems, perspectives, practice (2nd ed.). World Scientific.

Sola, P., Schure, J., Eba'a Atyi, R., Gumbo, D., Okeyo, I., & Awono, A. (2019). Woodfuel policies and practices in selected countries in Sub-Saharan Africa – a critical review. *Bois et Forêts des Tropiques*, 340(2), 27–41. https://doi.org/10.19182/bft2019.340.a31690

Song, B. (2018). The research on energy-saving reconstruction of ceramic kiln based on engineering system theory. *Chemical Engineering Transactions*, 66, 601-606. https://doi.org/10.3303/CET1866101

United Nations Development Programme. (2017). Sustainable Development Goals: SDG 7 – Affordable and clean energy. UNDP. https://www.undp.org/sustainable-development-goals

United Nations Development Programme. (2017). Sustainable Development Goals: SDG 12 – Responsible consumption and production. UNDP. https://www.undp.org/sustainable-development-goals

United Nations Development Programme. (2017). Sustainable Development Goals: SDG 13 – Climate action. UNDP. https://www.undp.org/sustainable-development-goals

United Nations. (2015). Paris Agreement. United Nations Treaty Collection. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development. United Nations. https://sdgs.un.org/2030agenda

United Nations. (2023). The Sustainable Development Goals report 2023: Special edition. United Nations Publications. https://unstats.un.org/sdgs/report/2023/

Urban, J.P. (2025). Evaluating traditional cookstove and charcoal kiln performance in Sub-Saharan Africa: quantifying in-field thermal efficiency and wood-to-charcoal conversion factors. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/hh63t534k

Valdés, H., Vilches, J., Felmer, G., Hurtado, M., & Figueroa, J. (2020). Artisan brick kilns: State-of-the-art and future trends. *Sustainability*, 12(18), 7724. https://doi.org/10.3390/su12187724

Zhou, Y., Wang, X., & Li, Q. (2022). Energy efficiency and emission reduction in China's ceramic kiln industry: Policy evolution and technological progress. *Energy Policy*, 164, 112892. https://doi.org/10.1016/j.enpol.2022.112892

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