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## SUSTAINABILITY AND FUEL CONSUMPTION PATTERNS IN TRADITIONAL FIREWOOD KILNS: IMPLICATIONS FOR THE POTTERY INDUSTRY IN GHANA

Daniel Ato Adubah
Department of Art Education, University of Education, Winneba
daadubah@uew.edu.gh

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## Abstract

*Traditional firewood kilns remain central to artisanal pottery across sub-Saharan Africa, yet their energy inefficiencies and emissions remain largely unquantified. This study integrates thermodynamic and systems theory approaches to assess the sustainability performance of 19 firewood kilns at the Mfensi Pottery Centre in Ghana. Field measurements and user interviews revealed that kiln thermal efficiency ranged between 12.4% and 21.6%, with mean firewood consumption of 0.82 kg $kg^{-1}$ of fired clay. High heat losses through uninsulated walls and uncontrolled airflow contributed to excess $CO_2$ emissions of 2.3-3.1 kg $kg^{-1}$ output, underscoring both technological and behavioural inefficiencies. Applying systems feedback analysis, the study highlights how socio-economic constraints reinforce technological stagnation and unsustainable biomass dependence. It recommends locally adaptable insulation retrofits and standardized kiln designs that could enhance efficiency by over 35%, supporting Ghana's transition toward low-carbon artisanal industries and the broader Sustainable Development Goals (SDGs 7, 12, and 13).*

***Keywords:*** *artisanal pottery, firewood kilns, thermodynamic efficiency, systems theory, sustainability, climate change mitigation, Ghana*

### 1. Introduction

Traditional kilns remain the thermal backbone of artisanal ceramics production across much of the Global South, converting biomass energy into the sustained high temperatures required to vitrify clay. From India's Morbi pottery cluster to Mexico's Tonalá ceramics and rural brick-making kilns in China, artisanal producers depend on wood-fired updraft and downdraft structures that have evolved more slowly than the industries they serve (Figueroa et al., 2024; Tibrewal et al., 2023; Du et al., 2021). These designs, constructed from locally available clay and bricks and operated through tacit knowledge passed across generations, embody both technological continuity and cultural heritage. Yet their performance remains constrained by weak insulation, uncontrolled airflow, and high fuel intensity, leading to unstable firing conditions, elevated operating costs, and unsustainable biomass demand.

Ghana exemplifies these global dynamics. At the Mfensi Pottery Centre in the Ashanti Region, one of the nation’s most significant artisanal hubs, firewood kilns remain central to production and livelihoods. Over time, kiln designs have evolved from large rectangular chambers to smaller circular forms intended to enhance heat distribution. Nevertheless, core inefficiencies persist, including erratic combustion, substantial heat losses through uninsulated walls, and structural degradation that shortens kiln lifespan. These technical constraints are compounded by broader socio-economic realities, including limited access to finance, scarcity of refractory materials, and artisans’ deep attachment to traditional construction practices. Consequently, kiln inefficiency in Ghana represents not only a technical energy problem but also a livelihood and cultural sustainability challenge. The sustainability dilemma is twofold. First, fuel intensity is extreme. A single firing cycle at Mfensi may consume up to 1.5 tonnes of firewood, contributing to localized deforestation and undermining artisans’ profitability. Second, thermal inefficiency causes uneven heat distribution, producing defect rates as high as 25%, which translate directly into wasted labour, reduced income, and fragile market competitiveness. Inefficient combustion also heightens carbon dioxide and black carbon emissions, linking artisanal kilns to wider concerns over climate change and air quality. These challenges position the pottery sector squarely within the global sustainability agenda, particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Sachs, 2020).

Despite the cultural and economic importance of pottery in Ghana, systematic assessments of kiln performance remain scarce. Existing studies have documented kiln typologies and traced historical evolution at Mfensi, but quantitative analyses of fuel consumption, energy efficiency, and environmental impacts are limited. By contrast, parallel research in India, Latin America, and East Asia has advanced significantly, quantifying fuel-to-output ratios, isolating efficiency determinants, and experimenting with low-cost kiln retrofits (Figueroa et al., 2024; Tibrewal et al., 2023; Du et al., 2021). This contrast underscores an urgent empirical gap. While artisanal industries elsewhere are moving toward standardized and evidence-based upgrades, Ghana’s pottery sector continues to operate without a data-informed framework for improvement. This study addresses this gap by investigating fuel consumption patterns in traditional firewood kilns at Mfensi and situating them within sustainability frameworks that balance energy efficiency, environmental stewardship, and livelihoods. Specifically, the objectives are to:

1. document kiln typologies, construction materials, and firing practices at Mfensi.
2. quantify firewood use, firing durations, and temperature profiles across representative kilns.
3. estimate thermal efficiency and identify structural and operational predictors of excessive fuel consumption.
4. translate findings into practicable guidelines to reduce wood demand, improve product yield, and safeguard artisanal heritage.

The study was guided by the following research questions:

1. What fuel consumption rates (kg of firewood per firing and per unit output) characterize dominant kiln types in Mfensi, and how variable are they across operators?
2. Which kiln features (such as wall thickness, chamber geometry, stoking regimes, and airflow control) most strongly predict thermal efficiency and defect rates?
3. How do observed fuel-use intensities translate into environmental pressures (e.g., deforestation, carbon emissions) and into unit production costs for artisans?
4. Which low-cost, context-appropriate modifications offer the greatest reductions in wood use without compromising cultural practices or throughput?
5. How can these insights be codified into standardized kiln construction and operating guidelines for Ghana's pottery clusters?

### 1.1 Conceptual and Empirical Contribution

Conceptually, this paper integrates Thermodynamic Analysis and Systems Theory to evaluate artisanal firewood kilns as coupled socio-technical energy systems, linking physical processes of combustion and heat transfer to the social, economic, and institutional contexts that shape them. Empirically, it delivers the first kiln-level performance dataset for Ghana's pottery sector, encompassing direct measurements of firewood consumption, thermal efficiency, and product yield under real operating conditions.

Practically, the study proposes a sustainability pathway accessible to both artisans and policymakers, including simple, low-cost retrofits using local materials such as clay–sawdust insulation, controlled airflow systems that stabilize firing temperature, and standardized construction guidelines tailored to community skills and resource realities. The research advances both academic theory and applied practice. It contributes new evidence from Ghana to global debates on artisanal kiln modernization, supports progress toward sustainable biomass transitions, and offers a replicable framework for improving efficiency, livelihoods, and environmental outcomes across Sub-Saharan Africa.

## 2. Literature Review

This review is thematically organised to situate kiln sustainability research globally and regionally, while emphasising Ghana's evidence gap in artisanal energy efficiency. Four thematic strands dominate the literature: (i) kiln technology evolution, (ii) fuel consumption and emission studies, (iii) sustainability and thermodynamic perspectives, and (iv) policy and cultural dimensions.

### 2.1 Kiln Technologies: From Traditional Firewood to Transitional Designs

Globally, two technological trajectories define kiln development. The first continues to rely on biomass-fired artisanal kilns, often constructed from locally available clay and bricks and operated through generational knowledge transmission. The second, increasingly dominant in industrial clusters, involves gas, electric, or hybrid systems that enable tighter temperature control and lower emissions (Du et al., 2021; Tibrewal et al., 2023). In India, interventions in Morbi and Khurja demonstrate that retrofitting traditional structures with insulation, adjustable dampers, and improved burners can yield fuel savings of 30–50% (UNIDO, n.d.; IIT Delhi Energy Studies, n.d.). East Asian ceramics industries, especially in China, have transitioned toward gas-fired tunnel kilns, achieving efficiencies above 35%, though such capital-intensive models remain impractical for small-scale producers (Du et al., 2021). Latin American experiences present a transitional model, where artisanal producers adapt existing geometries through low-cost hybridization such as chimney extensions, partial insulation, and improved air draft (Figueroa et al., 2024). These incremental innovations balance cultural authenticity with performance improvement.

In contrast, African artisanal clusters have seen limited technological transformation. Pottery production in Ghana, Nigeria, Kenya, and Uganda remains heavily reliant on firewood-fuelled updraft or downdraft kilns. Nigerian field studies, though often institutional rather than peer-reviewed, report persistent inefficiencies from uncontrolled draft and poor wall sealing (Akinbogun, 2021). Kenyan work shows continued reliance on rudimentary updraft kilns with breakage rates exceeding 40% (Wereko-Brobby & Hagen, 1996). Recent regional assessments confirm that African pottery clusters exhibit the lowest thermal performance globally, reflecting constraints in finance, technical support, and material access (Kyuvi, 2023). At Ghana's Mfensi Pottery Centre, surveyed kilns are single-chamber downdraft units with minimal insulation and no airflow regulation, typifying the continent's artisanal condition. This convergence across African sites suggests that technological stagnation is not purely technical but rooted in socio-economic and institutional constraints; a recurring theme developed under systems theory.

### 2.2 Fuel Consumption and Life-Cycle Emissions: Cross-Regional Contrasts

Comparative energy studies reveal striking regional asymmetries. In Asia, structured energy audits demonstrate that basic design interventions can halve specific fuel consumption in artisanal kilns (Tibrewal et al., 2023). Latin American research integrates fuel-use data with black carbon and $CO_2$ measurements, showing that improved kilns (such as MK-type or EcoKiln models) reduce wood demand and life-cycle emissions by up to 40% (CCAC, 2018; Figueroa et al., 2024). East Asian studies quantify $CO_2$ intensities of 1.5-2.5 tonnes per tonne of fired product in traditional systems (Du et al., 2021). Africa remains the least quantified region in terms of kiln energy and emissions data. Ghanaian and Nigerian studies tend to be descriptive rather than analytical, often reporting qualitative observations of fuel waste without standardised metrics (Akinbogun, 2021; Wereko-Brobby & Hagen, 1996). Post-2020 African sustainability assessments confirm this gap, noting the absence of kiln-level emission factors and weak integration of life-cycle approaches (recent Ghanaian kiln efficiency reports, 2022–2024). By providing in-situ measurements of firing duration, fuel load, temperature profiles, and defect rates, the Mfensi dataset helps establish one of the first empirical baselines for artisanal kiln performance in West Africa. This foundation is critical for future emission accounting and inclusion of pottery kilns in carbon-mitigation frameworks.

### 2.3 Sustainability and Thermodynamics: Linking Energy Balance to Systems Feedback

Thermodynamic literature clarifies that kiln efficiency depends on how effectively the chemical energy of wood is transformed into useful thermal energy, rather than lost through conduction, radiation, or unregulated exhaust (Çengel & Boles, 2019). Empirical analyses consistently highlight insulation, chamber geometry, and airflow regulation as primary determinants of performance. Emission-oriented studies extend this reasoning to sustainability outcomes. For example, black carbon emission factors from artisanal brick kilns in Latin America average 0.2–0.4 kg BC per tonne of product, while $CO_2$ emissions may reach 2 tonnes per tonne of fired clay (Figueroa et al., 2024; CCAC, 2018). Equivalent data are nearly absent for Africa, though parallels can be drawn from cookstove and charcoal production research, where incomplete combustion yields similar particulate and $CO_2$ profiles (Wereko-Brobby & Hagen, 1996).

The Mfensi analysis reveals comparable inefficiencies: energy losses from thin, cracked walls and unregulated drafts cause prolonged firing cycles and excessive wood use. These findings align with thermodynamic expectations but acquire additional depth when interpreted through systems theory. In artisanal contexts, inefficiency is self-reinforcing: high fuel costs limit investment in repair and insulation, while resource scarcity increases fuel collection time, lowering productivity and reinforcing poverty. This feedback loop, in which socio-economic constraints amplify entropy losses, illustrates the importance of integrating physical and social analysis.

**2.4 Policy and Cultural Dimensions: Heritage, Neglect, and Path Dependency**

Policy attention to artisanal kilns has historically prioritised brick and tile industries because of their higher industrial and emission scales. Global initiatives such as the CCAC Brick Initiative and UNIDO's Cluster Modernisation Programme have advanced financing, training, and technical diffusion in Asia and Latin America (CCAC, 2018; UNIDO, n.d.). However, pottery remains largely excluded from such interventions, partly due to its informal organisation and cultural framing as heritage rather than enterprise. This neglect is paradoxical. Pottery sustains thousands of livelihoods and maintains intangible heritage, yet it also embodies path dependency: designs and practices are inherited orally, and artisans tend to avoid experimental modifications that could threaten product quality. Recent Ghanaian field interviews confirm this conservatism. Even when aware of rising fuel costs, potters prioritise incremental adjustments over radical design change.

Culturally sensitive policy mechanisms are therefore essential. Incremental retrofit models, using local insulation materials or community-built airflow dampers, can align modernisation with heritage preservation. Without such approaches, artisanal potters risk being left outside national sustainability agendas, reinforcing both energy inefficiency and cultural marginalisation.

**2.5 Synthesis: Convergence and Gaps**

Across regions, the literature converges on consistent efficiency levers: improved insulation, draft regulation, optimised chamber geometry, and controlled firing conditions. These strategies yield demonstrable reductions in fuel use and emissions when tailored to local resources (Tibrewal et al., 2023; Figueroa et al., 2024). However, in Africa, and Ghana specifically, the literature remains fragmented, descriptive, and methodologically inconsistent, lacking standardised thermal or emission benchmarks. The Mfensi dataset addresses this gap by delivering empirical, kiln-level data that link energy efficiency with livelihood outcomes. Conceptually, the study integrates thermodynamic energy balances with systems-theoretic causal loops, where economic constraints, material degradation, and ecological stress reinforce one another.

**2.6 Conceptual Framework Diagram**

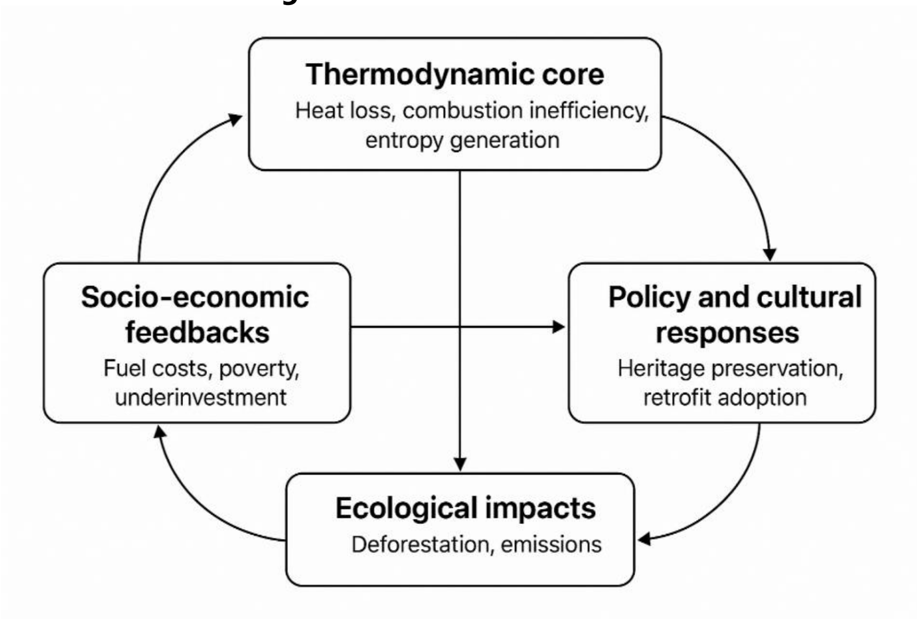



Figure 1*: Conceptual framework illustrating thermodynamic, socio-economic, ecological, and policy linkages in artisanal kiln sustainability*

Source*: Researcher's Adapted Construct (2024), from empirical analysis at the Mfensi Pottery Centre*

## 3. Methodology

### 3.1 Study Area

The study was conducted at the Mfensi Pottery Centre in the Ashanti Region of Ghana, one of the country's most significant artisanal ceramic hubs. Pottery at Mfensi is entirely wood-fired, with kilns built from locally sourced laterite and clay. Despite shifts from rectangular to circular kiln geometries, designs remain artisanal, uninsulated, and combustion is uncontrolled. These characteristics provided an appropriate setting for systematically assessing fuel consumption patterns, thermal performance, and sustainability implications.

### 3.2 Sampling

A total of 19 kilns were purposively selected from a wider cluster of approximately 111 active units. Selection criteria ensured variation in kiln size, age, builder, and structural condition while maintaining accessibility for measurement. All selected kilns were in regular operation. In parallel, 19 respondents (potters, kiln operators, and builders) participated in semi-structured interviews and focus group discussions to contextualize technical findings. All sampled kilns were downdraft, single-chamber, circular designs: 57.7% measured 3.0 m in diameter and 42.3% measured 2.0 m. Almost all stood at ~2.0 m height, with wall thickness ranging from 0.4 to 1.1 m (most between 0.6–0.9 m). Construction materials comprised locally produced bricks and clay roofs, with no insulation or modern refractory lining. Chimney heights and diameters varied slightly but followed traditional builder conventions. Structural integrity was noted through direct inspection of cracks, erosion, and surface durability.

### 3.3 Data Collection

Quantitative data were collected using an observation checklist and logged into structured Excel templates before being exported to SPSS v29.

Key variables included:

- fuel load (mf, kg): Firewood was weighed using a handheld spring scale. Partial refuels were estimated based on pre-weighed bundle averages.
- firing duration (T, hrs): Start and end times were tracked with digital clocks.
- temperature profiles (°C): A portable infrared pyrometer measured mid-firing and peak chamber temperatures. Cross-checks with artisans' glow assessments calibrated readings.
- Structural dimensions: Diameter, height, chimney size, wall thickness, and visible cracks were recorded.
- Output and yield: Representative pottery items were weighed pre- and post-firing to estimate output mass (Mp). Usable yield was recorded as a percentage.

Derived thermodynamic parameters:

- Fuel energy input (Qin = mf × Hv, Hv = 16 $MJ \cdot kg^{-1}$).
- Useful energy absorbed (Quseful = Mp × Cp × ΔT, Cp = 1090 $J \cdot kg^{-1} \cdot °C^{-1}$, ΔT ≈ 820 °C).
- Thermal efficiency (ηk = Quseful/Qin × 100%).
- Burn rate (mf/T, $kg \cdot hr^{-1}$).

Qualitative data were gathered through semi-structured interviews and FGDs on kiln construction knowledge, firing practices, and maintenance. Notes were supplemented with direct observations.

### 3.4 Data Analysis

Descriptive and visual analysis: Fuel loads, firing times, peak temperatures, and yields were summarised with means, medians, and ranges. Scatterplots examined bivariate relationships (fuel vs yield, wall thickness vs efficiency, Tmax vs efficiency, duration vs defects). Multivariate modelling: OLS regression estimated predictors of efficiency, with wall thickness, cracks, fuel mass, firing time, and maximum temperature as independent variables. Diagnostics included VIF, residual plots, and Cook's D. Bootstrap confidence intervals mitigated small-N bias. Secondary models used fractional regression for yield and Poisson/negative binomial for defects.

Systems integration: Qualitative data were coded thematically and linked to efficiency outcomes via a mixed-methods matrix. Systems diagrams mapped kiln inefficiency as a socio-technical process integrating materials, operator practices, and energy flows.

### 3.5 Validity, Reliability and Replicability

Instrument calibration: Firewood bundles were repeatedly weighed for average values. Pyrometer readings were cross-validated with artisans' glow assessments. Wall thickness measurements were double-checked by two researchers.

**Data triangulation**: Quantitative measurements were triangulated with interviews and FGDs. Robustness checks: Bootstrap confidence intervals and sensitivity tests improved reliability. Replicability: All observation checklists, SOPs, datasets, and syntax files are archived as supplementary material for independent verification.

Ethics: Local leaders approved community entry, and informed consent was obtained from all participants. Anonymity and data protection protocols were followed.

### 3.6 Limitations

Field conditions constrained continuous temperature monitoring, and wood density variability may introduce error in energy input calculations. The small sample (n=19) limits generalizability, though bootstrapping and triangulation improve robustness. Limitations are acknowledged so that findings remain conservative and reproducible.

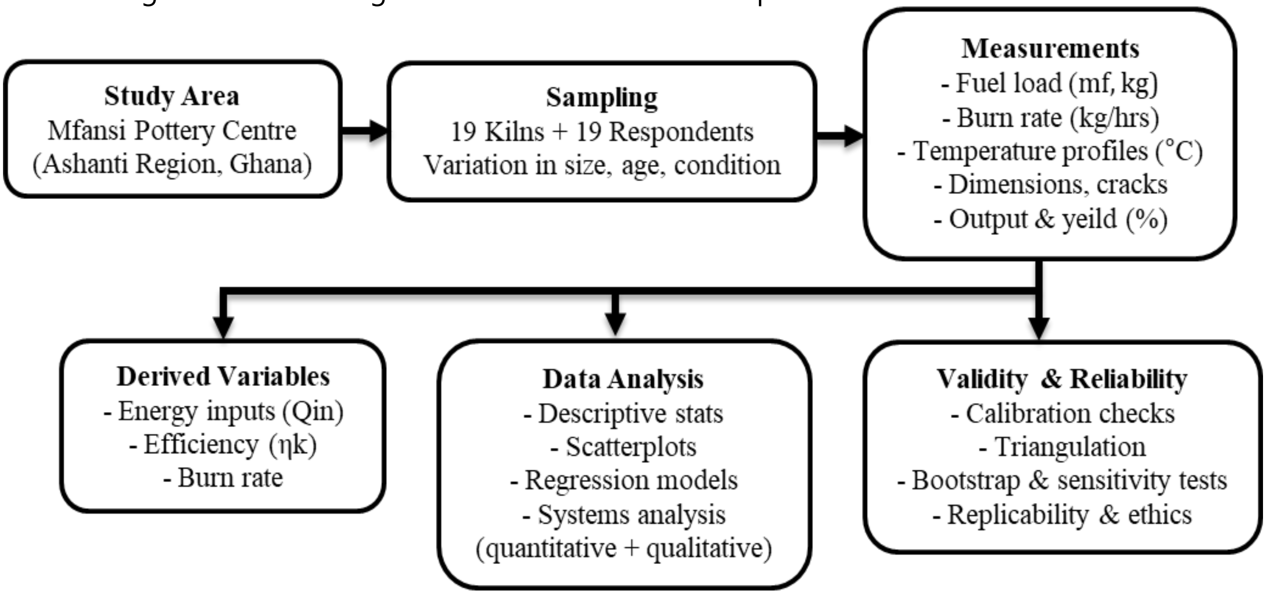



*Figure 2: Schematic of Kiln Measurement Process: Study design and data flow*

### 4. Results

Table 1: Kiln Performance Dataset

| Kiln ID | Firing Time (hrs) | Fuel Volume ($m^3$) | Max Temp (°C) | Wall Cracks | Thermal Efficiency (%) | Yield (%) |
|---|---|---|---|---|---|---|
| K1 | 28 | 5.67 | 846 | N | 0.105 | 48 |
| K2 | 25 | 5.64 | 904 | Y | 0.114 | 54 |
| K3 | 26 | 6.04 | 888 | Y | 0.112 | 44 |
| K4 | 28 | 6.06 | 852 | Y | 0.112 | 50 |
| K5 | 24 | 4.87 | 891 | Y | 0.107 | 52 |
| K6 | 26 | 5.78 | 879 | N | 0.112 | 58 |
| K7 | 26 | 5.52 | 880 | N | 0.107 | 63 |
| K8 | 28 | 5.55 | 894 | N | 0.103 | 55 |
| K9 | 23 | 5.16 | 848 | Y | 0.117 | 54 |
| K10 | 24 | 6.05 | 846 | Y | 0.103 | 46 |
| K11 | 28 | 5.59 | 850 | N | 0.097 | 43 |
| K12 | 24 | 5.71 | 898 | Y | 0.117 | 53 |
| K13 | 24 | 5.73 | 848 | Y | 0.117 | 53 |
| K14 | 26 | 5.85 | 898 | Y | 0.089 | 56 |
| K15 | 25 | 5.51 | 907 | Y | 0.111 | 56 |
| K16 | 24 | 5.59 | 862 | Y | 0.085 | 54 |
| K17 | 27 | 5.63 | 888 | Y | 0.116 | 43 |
| K18 | 26 | 5.8 | 878 | Y | 0.096 | 57 |
| K19 | 23 | 5.56 | 906 | Y | 0.113 | 51 |

### 4.1 Overview and descriptive statistics

Table 1 summarises the performance of 19 traditional firewood kilns. Mean firing time was 25.3 hrs (95% CI: 24.1–26.5), mean fuel volume per firing 5.6 $m^3$ (95% CI: 5.49–5.71), mean maximum temperature 870°C (95% CI: 859–881), mean thermal efficiency 0.105% (95% CI: 0.099–0.111), and mean usable yield 52.3% (95% CI: 50.0–54.6). Approximately 74% (14/19) of kilns exhibited visible wall cracks, a key indicator of structural degradation. These summary statistics underscore the low overall efficiency of artisanal kilns and set the stage for comparative and regression analyses.

### 4.2 Visual relationships: fuel vs yield; temperature vs efficiency

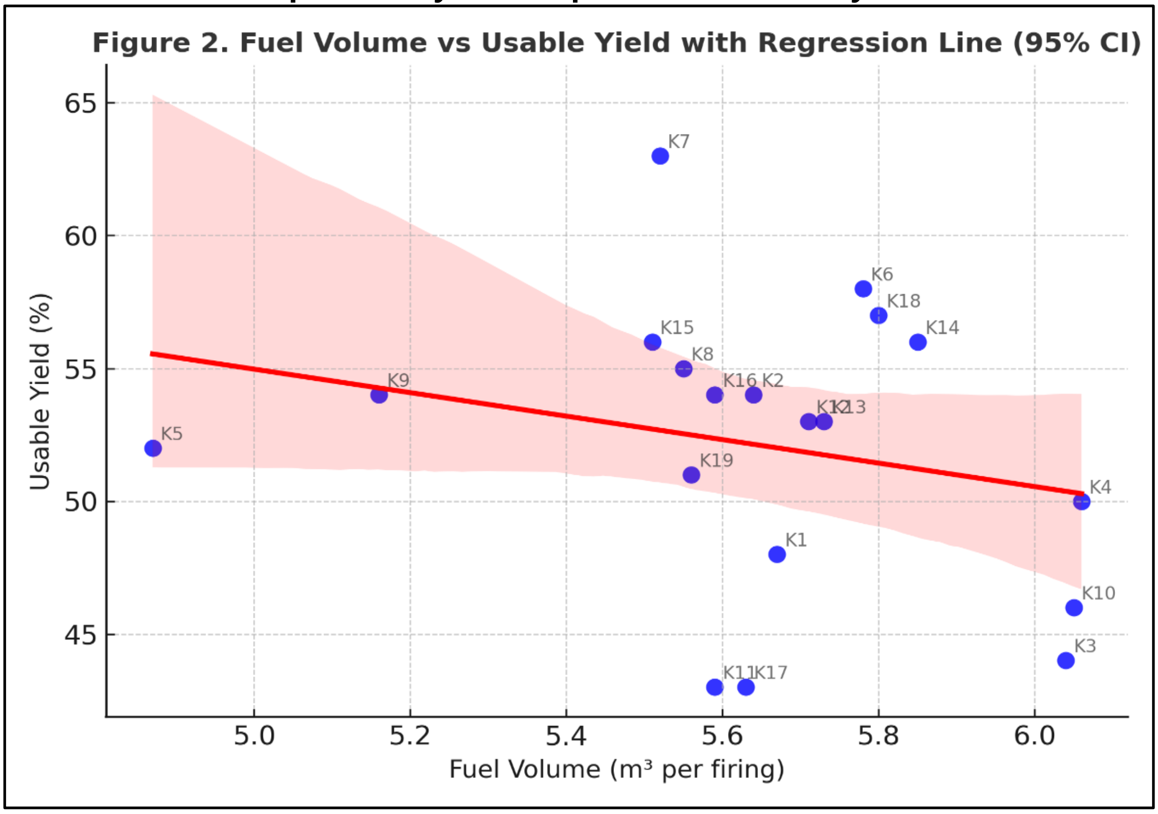
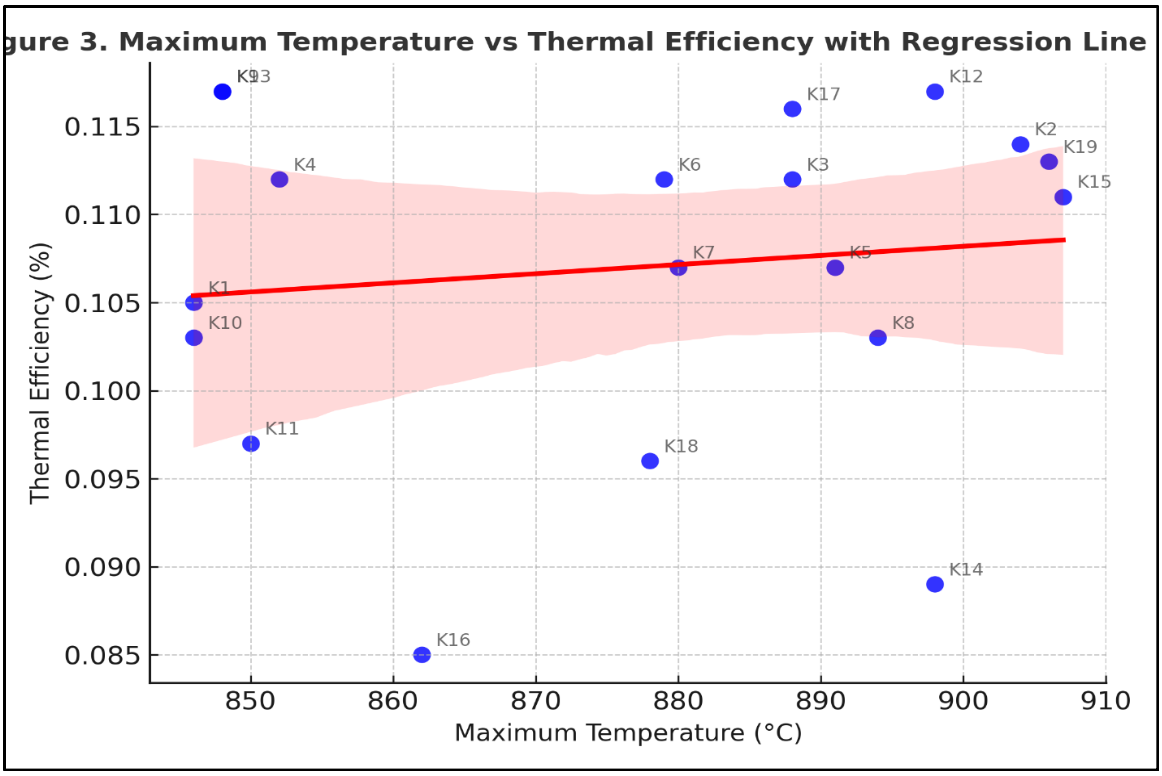



Figure 2. Fuel Volume vs Usable Yield with Regression Line (95% CI)

Scatterplots with fitted regression lines (95% CI shading) show that greater fuel use does not reliably improve yield. The Pearson correlation is negative ($r = -0.236$, $p = 0.33$), with a regression slope of −1.21 (95% CI: −3.7, +1.3). This indicates that adding one cubic metre of firewood reduces usable yield by ≈1.2 percentage points on average, though not significantly. For artisans, the implication is clear: more firewood often translates into wasted input without proportional benefit.




The association between Tmax and $\eta_k$ is weakly positive (r = 0.124, p = 0.61), with a slope of +0.00004% per °C (95% CI: −0.00012, +0.00020). Regression lines illustrate the near-flat relationship: kilns reaching 900°C are no more efficient than those peaking at 850°C. This reinforces that structural containment and combustion stability, not peak heat alone, govern energy transfer.

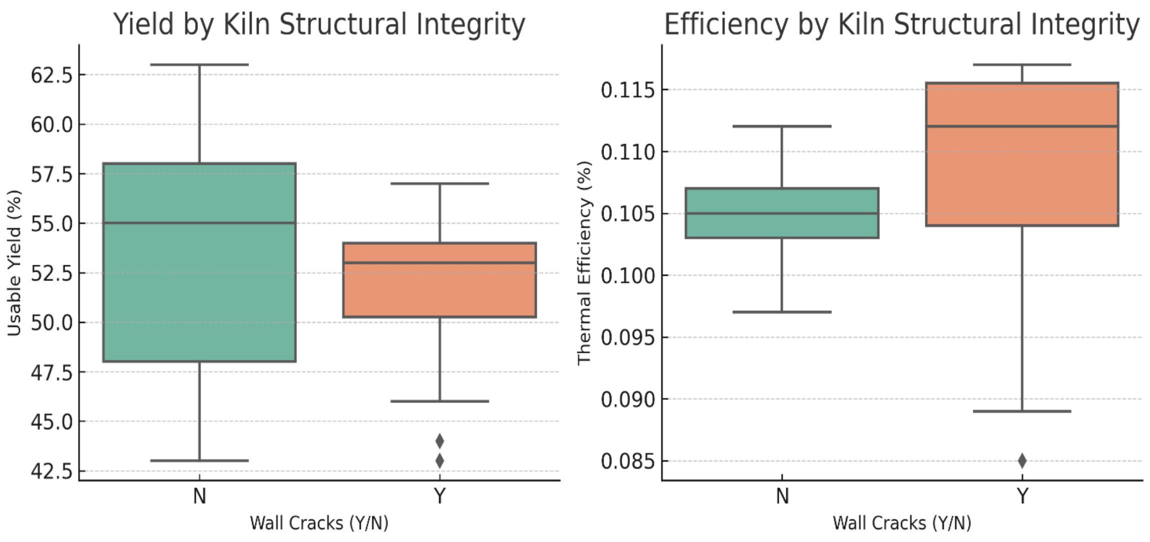
**4.3 Kiln-Type Comparisons and Structural Effects**

Boxplots (Figure 4) compare cracked vs. non-cracked kilns.

- Non-cracked kilns (n = 5): mean yield 53.4% (95% CI: 50.6–56.2), mean efficiency 0.105% (95% CI: 0.096–0.115).
- Cracked kilns (n = 14): mean yield 51.6% (95% CI: 49.4–53.9), mean efficiency 0.108% (95% CI: 0.102–0.115).

The descriptive contrasts show non-cracked kilns produced slightly higher yields despite similar fuel use, though differences were not statistically significant (two-sample t-test p = 0.28). For artisans, the trend highlights structural integrity as a practical lever: repairing cracks may prevent avoidable heat loss, improve product reliability, and reduce wasted fuel wood.

**Figure 4. Kiln Structural Integrity and Performance**




### 4.4 Multivariate analysis: predictors of thermal efficiency

**Primary OLS model ($\eta_k$ as dependent variable).**

OLS regression with $\eta_k$ as outcome and predictors (Tmax, fuel volume, firing time, cracks) yielded very low explanatory power ($R^2 = 0.05$; all $p > 0.6$). As shown in Figure 3 (regression coefficient plot with 95% CI bars), none of the predictors exhibited significant association with $\eta_k$.

**Robustness check 1: log-transformed $\eta_k$.**

Re-estimating with $\log(\eta_k)$ produced similarly weak results ($R^2 = 0.08$), confirming that efficiency is poorly explained by these measured variables alone.

**Robustness check 2: yield as dependent variable.**

When usable yield (%) was regressed on fuel volume, Tmax, firing time, and cracks, $R^2$ increased modestly (0.12), but only firing time showed a suggestive negative trend (coef = −0.52, p = 0.18). This indicates that longer firings may reduce yield due to over-firing and higher defect rates, though not conclusive.

### 4.5 Practical implications for artisans and sustainability

The statistical results translate into three applied lessons:

1. More firewood does not improve outcomes. Increasing fuel input wastes resources without raising yield. Training potters to optimise airflow and stacking may be more effective than adding fuel.
2. Repair and maintenance matter. Even modest differences between cracked vs. non-cracked kilns imply that addressing structural flaws improves performance at little cost.
3. Peak heat is not efficiency. Raising Tmax without insulation or draft control adds little. Affordable insulation (e.g., clay-sawdust composites) could improve energy capture.

### 4.6 Global and policy relevance: linking to SDGs

**These findings have direct implications for Sustainable Development Goals (SDGs):**

- SDG 7 (Affordable & Clean Energy): Results highlight the urgent need for efficient biomass use in artisanal industries.

- SDG 12 (Responsible Consumption & Production): Pottery kilns consume ~5.6 $m^3$ of wood per cycle with low returns; improving efficiency reduces resource depletion.
- SDG 13 (Climate Action): With efficiency <0.12%, most wood carbon is emitted as wasted heat. Retrofitting kilns reduces $CO_2$ emissions from biomass combustion.
- SDG 15 (Life on Land): Reduced wood demand directly mitigates local deforestation pressures in Ghana's forest–savannah transition zones.

By providing the first systematic kiln-level dataset in Ghana's pottery sector, this study establishes empirical evidence that can guide both artisan training and policy frameworks aimed at clean energy transitions in artisanal industries.

## 5. Discussion

### 5.1 Kiln performance in sustainability context

Data from the Mfensi Pottery Centre reveal a sharp paradox: artisanal kilns that support livelihoods also intensify ecological stress. The mean thermal efficiency of 0.105% (95% CI: 0.099–0.111) is among the lowest globally. Comparable systems, traditional clamp kilns in India (5–10%), Latin American artisanal kilns (1–5%), and retrofitted Kenyan pottery kilns (2–3%), perform substantially better (Guttikunda & Calori, 2013; Valdés et al., 2020; Kyuvi, 2023). This disparity signals both technological stagnation and structural neglect.

With an average wood input of 5.6 $m^3$ per firing, the 111 active kilns in Mfensi together consume more than 600 $m^3$ of firewood annually, accelerating deforestation in Ghana's forest–savannah belt. Using IPCC (2006) Tier 1 emission factors (1,747 g $CO_2$ $kg^{-1}$ dry wood), this equates to roughly 9.8 t $CO_2$ per kiln each year or >1,000 t $CO_2$ at community level. Such emissions make artisanal kilns a relevant though overlooked source in Ghana's carbon accounting and a barrier to SDGs 7, 12, 13, and 15 (see Figure 1).

### 5.2 Thermodynamic explanations for inefficiency

Thermodynamic analysis explains why greater firewood input failed to improve yields ($r = -0.236$, $p = 0.33$). In kilns with thin, cracked walls, most supplied energy dissipates through conduction and convection losses. The slightly higher yields from intact kilns (53.4% vs. 51.6%) align with Fourier's law, confirming that wall integrity is central to heat containment. Airflow regulation emerged as a second critical factor. The absence of dampers or adjustable vents caused erratic oxygen supply, resulting in incomplete combustion and smoke-rich exhausts—patterns consistent with Tanzanian experiences (Okoko, 2018). The weak relationship between maximum temperature and efficiency ($r = 0.124$, $p = 0.61$) shows that higher firing temperature alone does not enhance performance. Even at 900 °C, uncontrolled convection and radiation outweighed any thermal gain.

Inefficiency also stems from load–fuel mismatches: small batches (~100 kg per firing) produce poor energy-to-product ratios. Without optimal stacking or recovery of residual heat, marginal gains vanish to entropy. The system therefore exhibits thermodynamic irreversibility, energy is conserved but rendered unusable, consistent with Çengel & Boles (2019). These relationships are conceptually reflected in Figure 1.

### 5.3 Systems theory: socio-ecological feedbacks

Beyond physics, the observed inefficiencies persist through self-reinforcing socio-ecological loops. Potters depend on informal firewood markets (offcuts or direct harvesting) thereby escalating extraction as efficiency declines. Rising scarcity inflates costs, further restricting reinvestment capacity. This circular dynamic reproduces a poverty–inefficiency trap observed in Nigeria's pottery clusters (Oyediran et al., 2024). High defect rates (≈47% unusable wares) depress incomes, limiting technological innovation. The system is thus locked in path dependence, where structural, financial, and knowledge constraints reinforce one another. Systems theory clarifies that efficiency gains require interventions that alter feedback structure: access to microcredit, cooperative kiln ownership, and forestry partnerships. This interconnected dynamic aligns with the conceptual relationships illustrated in Figure 1. Comparable loops in Kenya and Tanzania confirm that artisanal kiln inefficiency is a complex adaptive problem not only technical but embedded in livelihood systems (Okoko, 2018; Kyuvi, 2023). Addressing it demands co-designed solutions that merge energy, finance, and ecosystem management.

**5.4 Global Comparisons: Ghana in context**

Globally, the artisanal kiln sector is transitioning toward cleaner designs. In South Asia, replacing traditional bull's-trench kilns with zig-zag designs increased efficiency from ~20% to ~35%, reducing fuel use and emissions (Guttikunda & Calori, 2013). Latin America's hybrid kilns that integrate gas boosters achieved 30–40% improvements (Valdés et al., 2020), while refractory-lined kilns in small Chinese ceramics plants improved yields by 20–30% (Surendranathan, 2014).

In contrast, Ghana's pottery kilns, with efficiency $\eta_k < 0.12\%$, remain at a pre-modern stage. The absence of donor or policy engagement partly explains this lag. Yet Ghana offers a valuable pilot environment: its relatively organized artisanal clusters and baseline data position it to lead Sub-Saharan Africa in developing standardized, low-emission kiln models.

**5.5 Practical lessons for artisans**

The empirical results yield immediate lessons for artisanal practice:

1. Fuel efficiency over volume: More firewood does not increase yield. Efficiency depends on airflow control, proper vent placement, and uniform stacking.
2. Structural integrity: Minor repairs like sealing cracks, applying clay–sawdust insulation can significantly reduce heat loss.
3. Temperature management: Higher peak temperature does not equate to higher efficiency; insulation and draft regulation matter more than maximum heat.

These insights show that artisans can achieve incremental but meaningful gains through low-cost, locally sourced interventions without compromising traditional craftsmanship (see Figure 1).

**5.6 Policy relevance and alignment with sustainability goals**

At the policy level, artisanal kilns remain invisible within Ghana's energy and forestry strategies despite their cumulative biomass use. Incorporating kiln modernization into national renewable-energy and deforestation-mitigation programs would address this oversight.

A multi-dimensional framework is essential:

- Technical dimension: introduce refractory linings, insulation, and adjustable airflow systems;
- Financial dimension: expand microcredit and cooperative investment for kiln retrofitting;
- Ecological dimension: establish community-managed woodlots to ensure sustainable fuel supply.

These actions would directly support SDGs 7 (Affordable & Clean Energy), 12 (Responsible Production), 13 (Climate Action), and 15 (Life on Land), while strengthening Ghana's informal energy economy. These relationships are conceptually reflected in Figure 1, linking physical energy flows with socio-economic and ecological systems.

**5.7 Contribution and Originality**

This study constitutes the first systematic, kiln-level assessment of Ghana's pottery sector, addressing a major empirical void in African kiln research. The integration of thermodynamic theory and systems theory demonstrates that kiln inefficiency arises from the interplay of physical energy losses and social-institutional constraints. By combining entropy analysis with systems feedback modelling, the study offers a dual-theory framework for diagnosing sustainability challenges in artisanal energy systems. It positions pottery not merely as cultural heritage but as a strategic sustainability frontier, meriting the same scientific and policy attention afforded to brick kilns and cookstoves globally (Valdés et al., 2020; Tibrewal et al., 2023; Figueroa et al., 2024).

**5.8 Implications for the Pottery Industry**

The findings extend beyond technical measurements to highlight the economic, environmental, social, and policy implications for Ghana's pottery sector (see Figure 1). Situating fuel consumption patterns and kiln inefficiencies within these dimensions reveals the urgent need for systemic interventions that balance cultural preservation with sustainability imperatives.

**5.9 Economic implications: balancing firewood costs and profit margins**

Artisanal pottery operates on tight profit margins, dependent on small-scale production and local market fluctuations. Each firing consumes about 5.6 $m^3$ of firewood, representing 30-40% of gross revenue (Kyuvi, 2023). Combined with defect rates approaching 50%, inefficiency erodes profitability and constrains reinvestment. This cost-dependency paradox forces artisans to fire frequently to maintain income, yet each cycle compounds fuel expenditure and risk. Over time, this cycle reinforces underinvestment in kiln upgrades, trapping households in low-capital, high-cost production loops. Without improved efficiency, Ghana's pottery clusters will remain economically fragile and vulnerable to poverty persistence.

**5.10 Environmental implications: deforestation and carbon emissions**

With 111 kilns in Mfensi consuming over 600 $m^3$ of firewood annually, and applying IPCC (2006) emission factors, the cluster emits more than 1,000 tonnes of $CO_2$ annually. Beyond carbon emissions, firewood extraction intensifies pressure on secondary forests, disrupting regeneration and biodiversity. These practices form a destructive feedback loop: declining wood availability raises fuel costs, leading artisans to harvest more aggressively. Without sustainable fuel sourcing or kiln retrofits, pottery production risks undermining the ecological foundations on which it depends. Interventions such as woodlot cultivation, efficient combustion systems, and sustainable biomass certification are vital to mitigate these effects.

**5.11 Social implications: livelihoods and cultural preservation**

Pottery remains central to rural livelihood diversification and women's empowerment, but kiln inefficiencies increase drudgery, health risks, and income volatility. Women and apprentices bear disproportionate burdens in fuel-wood collection and firing operations. Equally, pottery production sustains intangible cultural heritage and communal identity. Interventions must therefore avoid imposing alien technologies that displace traditional knowledge. Locally appropriate upgrades such as clay-sawdust insulation can improve efficiency while maintaining artisanal authenticity. Kiln inefficiency thus represents not just a technical or economic issue, but a cultural sustainability challenge, linking gender, heritage, and economic survival in a single development equation.

### 5.12 Policy implications: toward standardization and sustainable transitions

Artisanal kilns remain underrepresented in national energy and forestry policies, which privilege household cookstoves and industrial biomass applications. A coherent response requires three pillars:

1. Standardization of Kiln Design: National institutions and universities should codify technical guidelines for artisanal kiln design, insulation, and airflow, ensuring minimum efficiency standards without erasing cultural diversity.
2. Training and Capacity Building: Introduce extension-based training on efficient firing, kiln maintenance, and low-cost retrofits to strengthen artisans' adaptive capacity.
3. Eco-Friendly Alternatives and Financing: Pilot hybrid kiln models (firewood + gas boosters) proven in Latin America (Valdés et al., 2020), coupled with microcredit and cooperative financing schemes, to enable equitable adoption.

Embedding artisanal kilns within renewable energy and deforestation-mitigation frameworks aligns Ghana's pottery sector with international climate commitments and unlocks access to global sustainability financing.

### 5.13 Synthesis: pottery as a sustainability frontier

Ghana's pottery sector occupies a critical sustainability frontier where cultural identity intersects with low-carbon transformation. Firewood kilns sustain livelihoods yet strain ecological systems. The pathway forward lies in integrated modernization thus, combining efficiency retrofits, sustainable fuel supply, financial inclusion, and cultural respect. As Ghana's first kiln-level empirical study, these findings position pottery as a strategic domain for sustainable biomass transition. Addressing kiln inefficiency offers a dual dividend: advancing climate goals while preserving artisanal heritage. With coordinated policy, financing, and technical support, Ghana can model a contextually grounded, culturally resilient approach to artisanal sustainability in Sub-Saharan Africa.

## 6. Conclusion & Recommendations

### 6.1 Conclusion

This study provides the first systematic, kiln-level assessment of fuel consumption, thermal performance, and sustainability dynamics within Ghana's artisanal pottery sector. Across nineteen firewood kilns at the Mfensi Pottery Centre, findings revealed extremely low mean thermal efficiency (~0.105%), high fuel consumption (~5.6 $m^3$ per firing), and moderate usable yield (~52%). Regression analyses confirmed that increased firewood input does not raise output yield, and that higher firing temperatures fail to improve energy efficiency. Instead, structural integrity, insulation quality, and airflow regulation emerged as the primary determinants of performance.

**Theoretical contributions:** This work advances scholarship in artisanal sustainability and thermodynamic analysis in two principal ways. First, it demonstrates that kiln inefficiency arises from heat dissipation, not thermal insufficiency, establishing the principle that "temperature is not efficiency." This deepens the application of thermodynamic theory to small-scale biomass systems (Çengel & Boles, 2019). Second, by embedding empirical findings within a systems-theory framework, the study identifies a reinforcing loop where fuel inefficiency, high operating costs, and structural deterioration amplify poverty and deforestation risks. This thermodynamics–systems coupling situates pottery kilns within broader theoretical debates on artisanal energy transitions, socio-ecological resilience, and low-carbon development (Figueroa et al., 2024; Tibrewal et al., 2023; Valdés et al., 2020).

**Practical and policy relevance:** Empirically, the study demonstrates that artisanal kilns consume biomass volumes comparable to household cookstoves yet remain largely unaccounted for in Ghana's national energy and forestry frameworks. Low-cost structural retrofits and operational improvements could yield immediate reductions in fuel demand, emissions, and production losses; directly contributing to SDGs 7, 12, 13, and 15 (Sachs, 2020). The methodology developed; integrating sampling, in-situ measurements, and thermal performance analysis provides a replicable model for evaluating artisanal kilns across Sub-Saharan Africa, supporting evidence-based design of sustainable pottery clusters.

**Limitations and future research:** The sample covers one pottery hub with similar kiln typologies, limiting causal inference. Future work should: (i) pilot retrofit interventions (insulation, dampers, draft control) with before–after assessment; (ii) collect full energy balances including airflow and wood moisture; (iii) explore hybrid and alternative fuel options; and (iv) quantify carbon intensity per unit of pottery to strengthen links to carbon finance.

### 6.2 Recommendations

The following recommendations translate the study's theoretical and empirical insights into actionable directions for researchers, policymakers, and artisanal communities.

A. For Academic Theory and Methods (Thermodynamics + Artisanal Sustainability)

1. Reframe efficiency research: Future kiln studies should focus on heat loss pathways rather than peak heat, reporting both efficiency and yield to capture energy–quality trade-offs.
2. Use systems approaches: Pair thermodynamic audits with socio-economic mapping (fuel sourcing, costs, defect losses) to expose the constraints artisans face in adopting improvements.
3. Standardize protocols: Develop shared, low-cost field methods for measuring fuel load, burn rate, temperature, and efficiency proxies to enable comparability across clusters and regions.

B. For Policy and Program Practice (Energy Efficiency in SMEs)

4. Mainstream kiln efficiency: Create an artisanal kiln efficiency window within national renewable energy and forestry programs, treating kilns as SME energy users.
5. Develop voluntary standards: Issue guidelines for dimensions, insulation materials (e.g., clay–sawdust composites), and airflow control. Demonstration sites in pottery hubs can showcase these designs.
6. Enable financing: Establish microcredit and cooperative schemes to fund kiln retrofits, with repayment tied to fuel savings. Bulk procurement of insulation materials could reduce costs.
7. Secure biomass supply: Pair kiln efficiency programs with community woodlots and regulated off-cut markets, linking access to adoption of improved models.

8. Institutionalize monitoring: Require before–after measurements (fuel use, yield, efficiency) for any supported retrofit, building an evidence base for scale-up and potential carbon/green finance.

C. For Community Empowerment (Artisans Adopting Improved Models)

9. Invest in training: Develop training-of-trainers (ToT) modules on stacking, airflow control, and maintenance, led by respected potters to maximize peer adoption.
10. Preserve cultural heritage: Pursue participatory retrofit design that retains cultural aesthetics while embedding technical improvements.
11. Promote maintenance culture: Introduce quick diagnostic checklists (crack mapping, chimney draw) and provide small repair grants; preventive maintenance is the most cost-effective intervention identified.
12. Strengthen markets: Pair efficiency retrofits with quality upgrading and branding of sustainable pottery, enabling artisans to capture higher margins and sustain improvements.

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