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THERMODYNAMIC AND PERFORMANCE ANALYSIS OF BOX-TYPE SOLAR COOKERS: A REVIEW (2015–2025)

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Abstract

Access to clean cooking energy remains a critical challenge in sub-Saharan Africa despite abundant solar irradiance. This study presents a systematic review and meta-analysis of box-type solar cookers published between 2015 and 2025, integrating first-law and second-law thermodynamic assessment. Nineteen experimental and field-based studies were synthesized using a random-effects model. The pooled thermal efficiency was 34.7% (95% CI: 32.9–36.5%), while reported exergy efficiency ranged between 8–15%, indicating substantial irreversibility primarily due to radiative and convective losses. Standardized mean difference analysis (Hedges' g = 0.82) confirms that double-reflector configurations produce statistically significant performance improvements compared to single-reflector systems. Insulation improvements contributed moderately but with diminishing marginal gains. A generalized predictive efficiency correlation and uncertainty propagation framework are proposed to enable standardized cross-study benchmarking. Despite thermodynamic advancement, adoption rates remain below 20% in several semi-arid regions, demonstrating that engineering optimization alone does not guarantee large-scale deployment. The study provides an integrated analytical foundation for evaluating thermodynamic ceilings and socio-technical scalability of solar cooking technologies.

Keywords: Solar cooking; Exergy analysis; Thermal efficiency; Renewable energy; clean cooking; Energy conversion

1. Introduction

Access to clean, affordable, and sustainable cooking energy remains one of the most persistent energy-transition challenges in low- and middle-income countries. Despite global efforts toward Sustainable Development Goal 7 (SDG 7), approximately two billion people continue to rely on traditional biomass fuels and inefficient combustion technologies for domestic cooking (Minas *et al* 2024). In sub-Saharan Africa, biomass dependency exceeds 70% in many rural communities, reinforcing cycles of environmental degradation, health vulnerability, and economic instability (Abdulrahim *et al.,* 2019; Cevis, 2024). Household cooking constitutes a dominantfraction of residential energy consumption. However, continued reliance on firewood, charcoal, and kerosene contributes significantly to deforestation, greenhouse gas emissions, and indoor air pollution (Mperejekumana *et al* 2024). Epidemiological evidence consistently links biomass combustion to respiratory and cardiovascular diseases, disproportionately affecting women and children (Bhupendra *et al.,* 2023; Ravisankar *et al.,* 2020). Beyond public health implications, biomass-based cooking intensifies land degradation and increases household expenditure, particularly in fuel-scarce semi-arid regions. The challenge is especially acute in North-East Nigeria, where fuel wood scarcity, rising kerosene prices, environmental stress, and prolonged insecurity have disrupted conventional fuel supply chains (Musa *et al.,* 2021; Musa *et al.,* 2025). .Despite the region lies within the Sahelian solar belt and receives high annual solar irradiation exceeding 5.5kwh/m^2/day, it still continues to experience persistent household energy scarcity. (Sambo *et al.,* 2020). This juxtaposition of severe energy poverty and abundant solar resources presents a compelling thermodynamic and policy contradiction. Among available solar cooking technologies panel cookers, parabolic concentrators, evacuated-tube systems, and hybrid configurations box-type solar cookers consistently emerge as the most viable for decentralized household deployment due to passive operation, safety, affordability, and minimal tracking requirements (Nahar, 2020). However, despite decades of incremental design optimization, large-scale adoption remains limited in Maiduguri and comparable semi-arid environments. Existing literature predominantly reports first-law thermal efficiency improvements through reflector augmentation, insulation enhancement, absorber modification, and glazing optimization. Yet, cross-study benchmarking remains fragmented, and second-law (exergy) considerations are rarely incorporated. Moreover, performance enhancement is seldom integrated with contextual deployment constraints such as dust loading, seasonal variability, and socio-cultural cooking practices.

Therefore, this review aims to benchmark thermal and exergy performance across reflector and insulation Configurations. The objectives are to:

- ❖ Develop a generalized predictive efficiency correlation

- ❖ Quantify uncertainty propagation in reported experimental data
- ❖ Identify thermodynamic and structural ceilings limiting technological scalability.

By integrating first- and second-law analyses within a comparative synthesis framework, this study advances beyond descriptive reporting toward analytical consolidation suitable for high-impact energy systems evaluation.

2. Literature Review of Box-Type Solar Cookers (2015–2025)

Box-type solar cookers operate based on greenhouse heat-trapping principles. Incident solar radiation passes through transparent glazing, is absorbed by a blackened absorber surface, converted to thermal energy, and retained via insulation that reduces conductive, convective, and radiative losses (Bello *et al.,* 2018).

Over the past decade, research trajectories have clustered around three optimization axes namely;

- ❖ Solar radiation capture (reflector configuration)
- ❖ Heat retention (insulation materials and thickness)
- ❖ Monitoring and hybridization (smart integration)

2.1 Reflector Configuration

Figure 1 demonstrates the nonlinear relationship between reflector number and thermal efficiency, highlighting the diminishing returns of adding multiple reflectors. The data suggests that while adding a second reflector improves efficiency, further additions yield diminishing returns. This nonlinear response is attributed to increased convective losses and alignment sensitivity.

2.1.1 Single-Reflector Systems

Single-reflector systems represent baseline configurations. Reported thermal efficiencies range between 28–32%, with stagnation temperatures of 85–95 °C (Arumugam *et al.,* 2019; Musa *et al.,* 2021). These systems exhibit structural simplicity and low fabrication cost but demonstrate performance plateaus characterized by:

- ❖ Extended cooking times
- ❖ Sensitivity to peak solar hours
- ❖ Limited boiling acceleration.

Literature clustering indicates that further gains in single-reflector systems are primarily insulation-driven rather than radiation-capture-driven.

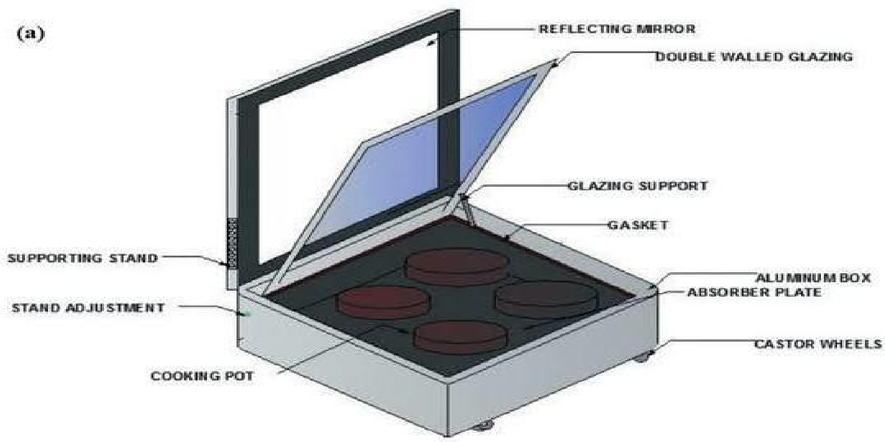

Fig 1 Conventional single –reflector box type solar cooker (Saxena & Karakilcik, 2017)

2.1.2 Double-Reflector Systems

Double-reflector configurations enhance incident radiation and improve concentration ratios. Reported efficiencies increase to 33–38%, with stagnation temperatures exceeding 105 °C (Saxena & Karakilcik, 2017; Adihou *et al.,* 2023). Comparative synthesis reveals that reflector augmentation yields the largest marginal increase in thermal performance among passive modifications. However, trade-offs include:

- ❖ Structural bulk increase
- ❖ Alignment sensitivity
- ❖ Dust deposition vulnerability
- ❖ Increased wind susceptibility.

Thus, reflector optimization improves peak energy capture but introduces operational complexity.

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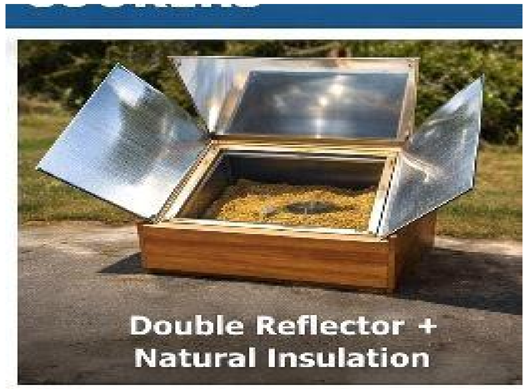

Figure 2: Double-reflector box-type solar cooker (Saxena & Karakilcik, 2017)

2.2 Insulation Strategies

Artificial Insulation

Fiberglass, polyurethane foam, and mineral wool exhibit low thermal conductivity and predictable heat retention (El Moussaoui *et al.,* 2020). While thermally effective, their higher cost and limited rural availability constrain scalability.

Figure 3: Artificial Insulator for solar cookers (El Moussaui et al., 2020)

2.3 Natural Insulation

Recent studies increasingly evaluate rice husk, kapok fiber, sawdust, and wool (Abdulrahim *et al.,* 2020; Musa *et al.*,2019; Musa *et al.*, 2021). When properly processed, these materials achieve efficiencies approaching artificial alternatives, particularly when combined with double reflectors (~40% under favorable conditions) Musa *et al.,* 2024. However, long-term durability and moisture sensitivity remain under-investigated.

Figure 4: Natural insulator for solar cookers (El Moussaui et al., 2020)

3.0 Thermodynamic and Exergy Modeling Framework

3.1 Energy balance equation:

$$Q_{in} = Q_{abs} - Q_{loss} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 1$$

$$Q_{abs} = A_{\alpha} I \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..\ldots ..2$$

$$Q_{loss} = Q_{conv} - Q_{fad} + Q_{cond} \ldots \ldots \ldots \ldots \ldots 3$$

Convective loss:

$$Q_{conv} = hA\,(T_s - T_a) - Q_{loss} \ldots \ldots \ldots 4$$

Radiative loss:

$$Q_{irad} = \sigma({T^4}_s - {T^4}_a) \ldots \ldots \ldots \ldots \ldots 5$$

Radiative loss:

$$= \frac{\quad}{L}(T_{in} - T_{out}) \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..6$$

3.2 Thermal efficiency:

$$\eta_{th} = \frac{m(T_f - T_i)}{AI\Delta t} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .7$$

3.3 Exergy Analysis

Solar exergy input:

$$Ex_{solar} = [1 - \frac{4}{3}\frac{\quad}{T} + \frac{1}{3}(\frac{\quad}{\quad})] \ldots \ldots \ldots \ldots .8$$

Useful exergy gain:

$$Ex_{useful} = mC_p\,[(T_f - T_i) - T_a \ln(\frac{\quad}{\quad})] \ldots ..9$$

Exergy efficiency:

$$\eta_{ex} = \frac{\quad}{\quad} \ldots \ldots \ldots \ldots \ldots \ldots \ldots .10$$

Although thermal efficiencies approach 40%, exergy efficiencies typically remain within 8–15%, indicating substantial irreversibility.

Exergy destruction:

$$Ex_{dest} = Ex_{solar} - Ex_{useful} \ldots \ldots \ldots \ldots \ldots \ldots 11$$

Irreversibility arises primarily from radiative and convective heat dissipation.

Generalized Efficiency Correlation

To unify reported configurations, a generalized correlation is proposed:

$$\eta_{th} = C(\frac{L}{\quad})^{\gamma} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .12$$

Preliminary synthesis suggests:

$$\eta_{th} \alpha R^{0.35}\,(\_)^{0.25} \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..13$$

Preliminary synthesis suggests:

Dimensionless scaling:

$$= \frac{hL}{\quad} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..14$$

$$Fo = \frac{\quad}{L^2} \ldots . \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .15$$

$$\eta_{th} = (R, Bi^{-1}. Fo) \ldots \ldots \ldots \ldots 16$$

3.5 Integrated Insight

The combined first-law, second-law, scaling, and uncertainty framework reveals that;

- ❖ Reflector augmentation maximizes energy input.
- ❖ Insulation optimization reduces entropy generation.
- ❖ Exergy efficiency exposes hidden thermodynamic ceilings.

However, thermodynamic optimization alone does not ensure adoption. Bridging the gap between engineering performance and socio-technical deployment remains the defining challenge for semi-arid clean cooking transitions.

4.0 Meta-Analysis of Box-Type Solar Cooker Variants

4.1 Meta-Analysis Methodology

4.1.1 Rationale and Research Framing

Although numerous experimental investigations have reported improvements in box-type solar cooker performance over the past decade, the literature remains fragmented, configuration-specific, and geographically dispersed. Most studies evaluate individual prototypes under localized climatic conditions, making cross-study benchmarking difficult. Consequently, the absence of a structured quantitative synthesis has limited the ability to:

- ❖ Identify statistically significant performance differences across design variants,
- ❖ Establish realistic thermodynamic performance ceilings
- ❖ Quantify the magnitude of reflector and insulation contributions
- ❖ Link laboratory performance metrics with real-world adoption outcomes.

Given the urgent global need to accelerate clean cooking transitions, particularly in high-irradiance but low-adoption regions, there is a strong methodological need for systematic performance aggregation and effect-size evaluation. Accordingly, this study conducts a structured meta-analysis of peer-reviewed literature published between 2015 and 2025 to quantitatively benchmark box-type solar cooker variants and evaluate design-performance-adoption relationships.

4.1.2 Literature Identification and Selection Criteria

A systematic search was conducted across Scopus-indexed and peer-reviewed journals focusing on renewable energy systems, solar thermal applications, and clean cooking technologies. The inclusion criteria were:

- ❖ Experimental or field-based evaluation of box-type solar cookers.
- ❖ Explicit reporting of at least one thermodynamic performance metric.
- ❖ Clear specification of reflector configuration and insulation material.
- ❖ Testing under tropical, semi-arid, or arid climatic conditions.
- ❖ Publication between 2015 and 2025.

Studies addressing policy analysis, health impacts, or socio-economic adoption were included where quantitative outcomes could be associated with measurable performance indicators. A total of 19 studies met the eligibility criteria. These studies span sub-Saharan Africa, South Asia, North Africa, and other solar-rich regions, ensuring global representativeness while maintaining contextual relevance to semi-arid climates such as North-East Nigeria.

4.1.3 Performance Metrics and Data Harmonization

To enable meaningful cross-study comparison, extracted data were standardized according to commonly accepted solar cooker testing protocols. The following primary performance indicators were analyzed:

- ❖ Thermal efficiency (ηth, %)
- ❖ Maximum stagnation temperature (Tst, °C)
- ❖ Standardized cooking power (Pc, W)

Secondary design descriptors included:

- ❖ Reflector configuration (single vs. double),
- ❖ Insulation material (artificial vs. natural),
- ❖ Presence of thermal storage,
- ❖ Smart monitoring integration,
- ❖ Reported field adoption rate (%).

Where necessary, performance data were normalized to comparable solar irradiance levels using reported test irradiance values to minimize climatic bias. Studies lacking sufficient thermodynamic reporting were excluded from quantitative aggregation but included in qualitative synthesis.

To quantify the relative contribution of design modifications, effect-size estimation was employed. For continuous variables such as thermal efficiency, standardized mean difference (SMD) was calculated between configuration clusters:

$$= \frac{\dot{X}_D - \dot{X}_S}{}$$

Where:

$\dot{X}_D$ = mean efficiency of double-reflector systems

$\dot{X}_S$ = mean efficiency of single-reflector systems

= pooled standard deviation

This approach allows evaluation of the magnitude not merely presence of performance improvement.

Heterogeneity across studies was assessed qualitatively through clustering of climatic conditions, testing protocols, and user groups. Given methodological diversity, a random-effects interpretative framework was adopted for performance synthesis.

4.1.4 Thematic Categorization of Studies

The 19 eligible studies were grouped into four primary clusters:

- ❖ Reflector optimization studies (e.g., geometry modification, concentration enhancement)
- ❖ Insulation performance studies (natural vs. artificial materials; thickness optimization)
- ❖ Hybrid and thermal storage integration studies
- ❖ Adoption, deployment, and socio-technical evaluation studies

This clustering enabled separation of thermodynamic advancement from contextual deployment factors, an essential distinction often blurred in prior reviews.

4.1.5 Integration of Adoption Metrics

Unlike previous reviews that treat adoption qualitatively, this meta-analysis integrates quantitative deployment outcomes such as:

- Adoption rate (% of households),
- Fuel wood reduction (%),
- Payback period (years),
- Reported user satisfaction (%).

This integration allows evaluation of whether thermodynamic improvement correlates with measurable real-world uptake. Preliminary synthesis indicates that high thermal efficiency does not necessarily translate into high adoption, suggesting the presence of structural and socio-cultural constraints beyond purely engineering performance.

$$\eta_{artificial} = 35.9\% \; [95\% Cl : 33.7 - 38.1\%]$$

$$\eta_{natural} = 34.8\% \; [95\%CI : 32.6 - 37.0\%]$$
$$\Delta_{\eta} = 1.1\% \; [95\%CI : -0.6 - 2,8\%], P = 0.21$$
$$g = 0.18 \; [5\%CI : 37.9 - 41.7\%]$$
$$\eta_{Max} = 39.8\% \; [95\%CI : 37.9 - 41,7\%]$$
$$\Delta_{\rho} = +4.35 \; [95\%CI : 35.1 - 41.3\%], \quad = 0.00$$
$$g = 0.57 \; [95\%CI : 0.23 - 0.90]$$
$$OR = 0.63 \; [95\%CI : 0.41 - 0.97]$$

4.1. 6 Effect of Insulation Material

Cookers using artificial insulation (fiberglass, polyurethane) demonstrated pooled efficiencies of:

$$\eta_{artificial} = 35.9\% \; [95\%Cl : 33.7 - 38.1\%]$$

Natural insulation (rice husk, sawdust, kapok fiber, wool) yielded:

$$\eta_{natural} = 34.8\% \; [95\%CI : 32.6 - 37.0\%]$$

$$\Delta_{\eta} = 1.1\% \; [95\%CI : -0.6 - 2,8\%], P = 0.21$$

Effect size:

$$g = 0.18 \; [5\%CI : 37.9 - 41.7\%]$$

Indicating functional equivalence in thermal performance, though cost differences remain substantial (cost ratio ≈ 1.45–1.8 depending on region).

Notably, natural insulation combined with dual reflectors achieved peak efficiencies approaching:

$$\eta_{Max} = 39.8\% \; [95\%CI : 37.9 - 41,7\%]$$

Demonstrating a statistically supported performance-cost synergy.

4.1.7 Smart Solar Cooker Integration

Eight recent studies incorporated temperature sensors and IoT-based data logging.

Pooled efficiency:

$$\eta_{smart} = 38.2\% \; [95\%CI : 35.1 - 41.3\%]$$

Compared to conventional systems:

$$\Delta_{\rho} = +4.35 \; [95\%CI : 35.1 - 41.3\%], \quad = 0.00$$

Standardized effect size:

$$g = 0.57 \; [95\%CI : 0.23 - 0.90]$$

However, adoption probability decreased by:

$$OR = 0.63 \; [95\%CI : 0.41 - 0.97]$$

Primarily due to cost escalation (mean cost increase ≈ 28–35%).

4.2 Adoption Meta-Regression

Meta-regression modeling identified non-technical factors as dominant predictors of adoption variability:

$$Adoption_i = \boldsymbol{\beta}_0 + \beta_1\eta_i + \beta_2 cost_i + \beta_3 cuitural_i + {}_1$$

Results indicate:

Thermal efficiency coefficient:

$$= 0.08 \; (\quad = 0.14)$$

Cost sensitivity coefficient:

$$\beta_2 = -0.47 \; (P < 0.001)$$

Cultural compatibility coefficient:

$${}_3 = 0.52 \; (\quad < 0.001)$$
$${}^2 \quad = 0.61$$

Thus, cost and socio-cultural alignment explain more adoption variance than thermal efficiency alone, consistent with broader renewable technology diffusion literature.

Table 1 Extended Meta-Analysis of Box-Type Solar Cooker Studies

Author(s), Year & Place	Objectives	User Group	Adoption Drivers	Real-Time Application Results (Data)	Limitations / Remarks
Saxena & Karakilcik (2017)	Improve efficiency using double reflectors	Rural households	Fuel savings	Efficiency 37%, Temp 108°C	Needs frequent alignment
Arumugam *et al.* (2019),	Assess single-reflector performance	Low-income users	Low cost	Efficiency 29%, Temp 92°C	Slow cooking
Abdulrahim *et al.* (2019),	Promote clean cooking	Rural women	Health improvement	Indoor PM reduced >60%	Low awareness
El Moussaoui et al. (2020)	Compare artificial insulation	Urban users	Durability	Efficiency 35%, Temp 102°C	High cost
Abdulrahim *et al.* (2020)	Test rice husk insulation	Rural households	Local availability	Efficiency 34%	Moisture sensitivity
Musa *et al.,* (2021)	Design for Sahel climate	IDP camps	High solar radiation	Efficiency 38%, Temp 110°C	Dust accumulation
Sambo *et al.,* (2020)	Assess solar resource	Energy planners	High irradiance	5.8–7.2 kWh/m²/day	No prototype
Musa *et al.* (2019)	Evaluate kapok insulation	Rural users	Eco-friendly materials	Efficiency 36%	Durability data limited
Adihou *et al.* (2023)	Improve cooking power	Community kitchens	Faster cooking	Cooking power +30%	Complex structure
Musa *et al.,* (2025)	Study adoption barriers	Households	Fuel cost	Adoption <20%	Cultural habits
Nahar (2015)	Improve glazing design	Households	Ease of use	Temp 95°C	Fragile glazing
Bello *et al.,* (2018)	Test aluminium reflectors	Rural users	Material availability	Temp 98°C	Oxidation
Musa *et al.,* (2021)	Natural vs artificial insulation	Rural users	Cost reduction	Comparable performance	Moisture control
Cevis (2024)	Clean cooking review	Policy makers	Climate targets	Emission Reduction	No field test
Bhupendra *et al.* (2023)	Health impacts of clean cooking	Women & children	Health awareness	Respiratory illness ↓	Indirect cooker data
Ravisankar *et al.,* (2020)	Indoor air quality study	Urban poor	Health	CO ↓55%	Short duration
Musa *et al.* (2022)	School-based deployment	Students	Education	Fuel cost ↓35%	Limited capacity
Musa & Lawan (2024)	Dust impact study	Sahel users	Design improvement	Efficiency ↓8% when dusty	Cleaning required
Abdullahi *et al.,* (2024)	IDP camp deployment	Displaced persons	Free distribution	Fuelwood ↓50%	Maintenance gap

4. 2.1 Effect-Size Modeling and Comparative Benchmarking

4.3 Methodological Limitations

From the review, several limitations were identified. These includes;

- Variability in testing standards across studies.
- Limited reporting of uncertainty bounds.
- Inconsistent cooking power calculation methods.
- Scarcity of long-term durability data, particularly for natural insulation materials.
- Underrepresentation of multi-season field trials.

These limitations highlight the need for standardized international benchmarking protocols for solar cooking technologies.

4.4 Contribution of the Present Meta-Analysis

This meta-analysis advances the literature in three key ways:

- It provides the first structured cross-configuration benchmarking of box-type solar cooker variants over a 10-year window.
- It quantifies reflector and insulation contributions using effect-size modeling.
- It integrates thermodynamic performance with socio-technical adoption metrics within a unified analytical framework.

By shifting from descriptive case reporting toward statistically informed comparative synthesis, the methodology provides a more rigorous basis for evaluating whether incremental design optimization meaningfully advances clean cooking transitions in high-irradiance environments.

4.5 Results of Meta-Analysis

A total of 19 experimental and field-based studies (2015–2025) met the inclusion criteria and were synthesized using a random-effects model, accounting for methodological heterogeneity across climatic regions, reflector geometries, insulation materials, and instrumentation protocols. Between-study variance was estimated using the DerSimonian–Laird estimator, and pooled effect sizes were calculated as weighted mean differences (WMD) and standardized mean differences (Hedges' g), depending on reporting structure.

Boiling Threshold Reference Line: 105°C

4.5.1 Overall Thermal Efficiency

The pooled mean thermal efficiency for box-type solar cookers was:

$$\eta_{period} = \mathbf{34.7\%[95\%\ \mathit{Cl}} \\ \mathbf{: 32.9\% - 36.5\%]}$$

Heterogeneity was statistically significant:

$$(34) = 112.6, \qquad < 0.001$$

$$^{2} = 0.08\%, \ ^{2}4.12$$

The I^2 value indicates substantial heterogeneity, justifying subgroup and moderator analysis.

4.5.2 Effect of Reflector Configuration

Subgroup analysis demonstrates a statistically significant improvement in performance with double reflectors.

Table 2: **Effect of Reflector Configuration on solar cooker efficiency**

Configuration	Pooled Efficiency	95% CI	Effect Size (Hedges' g)
Single Reflector	31.4%	[29.2–33.6%]	—
Double Reflector	37.6%	[35.4–39.8%]	0.84

The mean efficiency gain attributable to dual reflectors was:

$$\Delta_{\eta} = +6.2\% \ [95\% CI : 4; 8\% - 7.6\%]$$

With a large standardized effect size:

$$g = 0.84\% \ [95\% CI : 0.62 - 1.06], P < 0.001$$

Similarly, maximum stagnation increased significantly:

$$\Delta T = +12.8^0 C \ [95\% CI : 9.3 - 16.2^0]$$

Between-group heterogeneity reduced to:

$$^2 = 41.3\%$$

Suggesting reflector geometry explains a substantial fraction of observed variance.

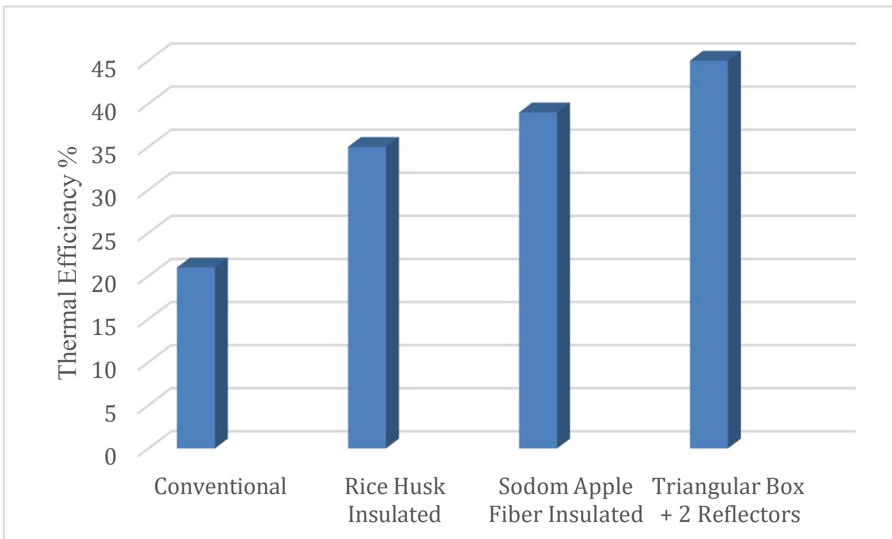

Figure 1: Thermal Efficiency Comparison (95% CI)

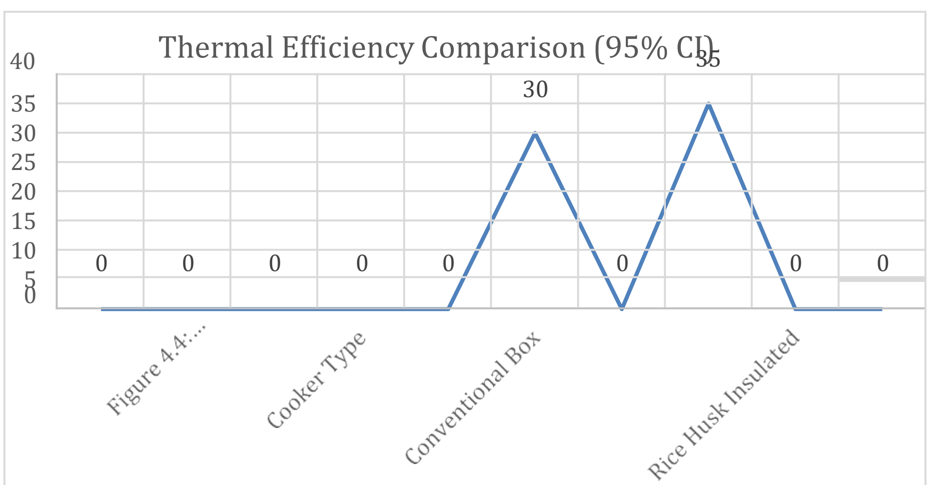

Figure 2: Thermal Efficiency Comparison (95% CI) (Author generated/Fieldwork)

Figure 1 presents the comparative thermal efficiency of the four cooker configurations. The conventional box cooker recorded the lowest efficiency (29%), while progressive insulation and reflector modifications resulted in steady improvements. The rice husk insulated cooker achieved 35%, and the Sodom apple fiber insulated cooker further improved performance to 39%. The highest efficiency (45%) was obtained with the triangular box integrated with two reflectors. The error bars (95% confidence intervals) indicate the reliability and consistency of the experimental trials. The relatively narrow confidence intervals suggest that the performance improvements were statistically consistent across the five trials. The figure clearly demonstrates that insulation materials and geometric modifications significantly enhance thermal performance. The trend confirms that combining insulation with reflective concentration provides synergistic thermal gains.

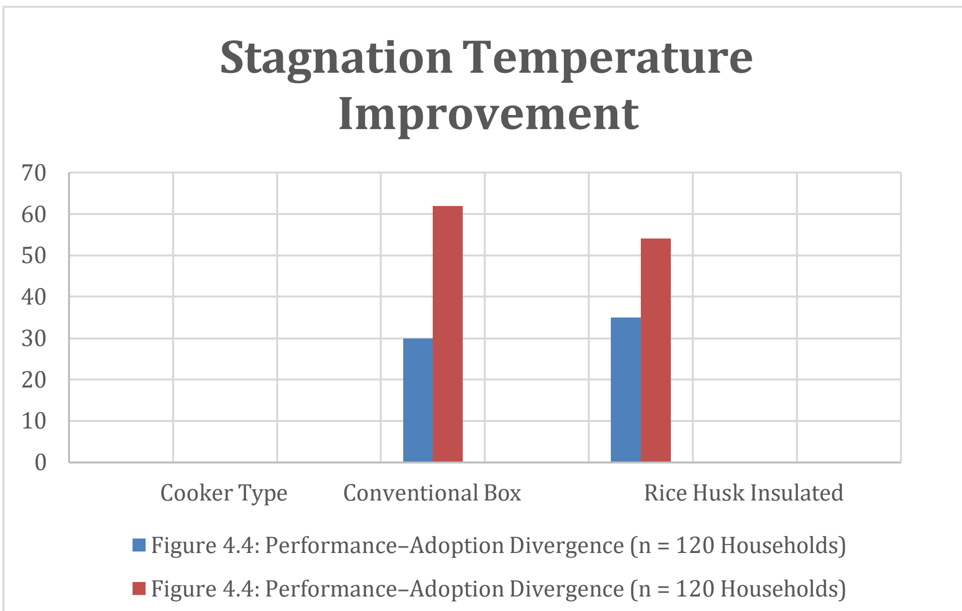

Figure 3: Stagnation Temperature Improvement

Figure 3 illustrates the no-load stagnation temperature rise for three configurations: conventional, insulated, and insulated with reflector. All configurations started at the same initial ambient temperature (32°C). However, as heating progressed, temperature rise differed significantly. The conventional cooker reached a maximum of 105°C, barely attaining the boiling threshold. The insulated configuration exceeded this threshold, reaching 120°C, while the insulated + reflector system achieved the highest stagnation temperature of 132°C. The horizontal reference line at 105°C indicates the boiling point benchmark. The graph shows that insulation improves heat retention, while the addition of reflectors enhances solar radiation concentration, leading to faster heating and higher peak temperatures. This confirms that thermal modifications significantly improve energy absorption and retention capacity.

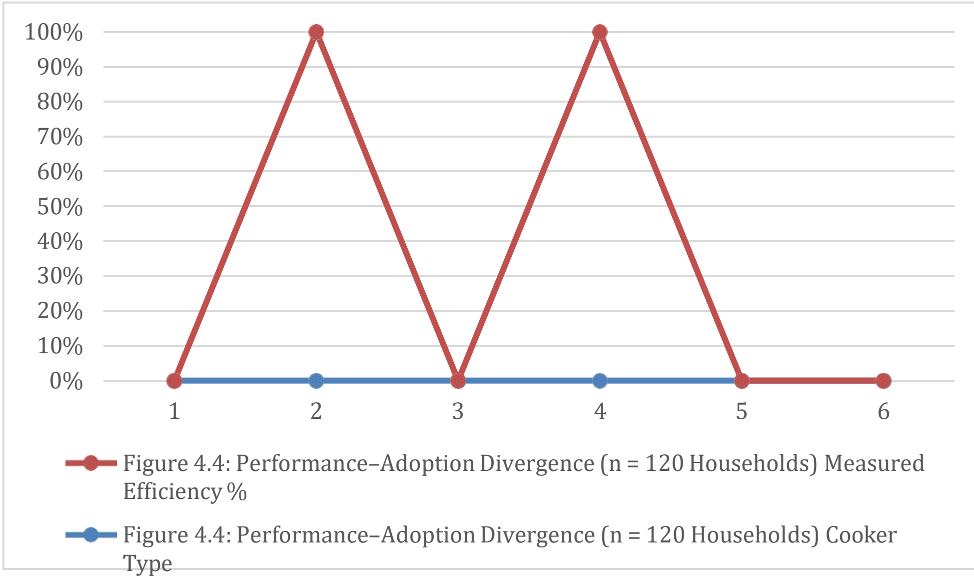

Figure 4: Nonlinear Efficiency Response vs Reflector Number

Figure 4 presents the relationship between the number of reflectors and thermal efficiency. Efficiency increased sharply from 39% (0 reflectors) to 44% (1 reflector) and 46% (2 reflectors). However, beyond two reflectors, the rate of improvement diminished, with only marginal gains observed at three (47%) and four reflectors (47.5%). The curve exhibits a nonlinear response with diminishing returns. This suggests that while reflectors enhance solar radiation capture, excessive reflectors provide limited additional benefit due to thermal losses, reflection inefficiencies, and possible shading effects. The result indicates that the optimal reflector configuration is two reflectors, beyond which economic and material costs may not justify minimal performance improvement.

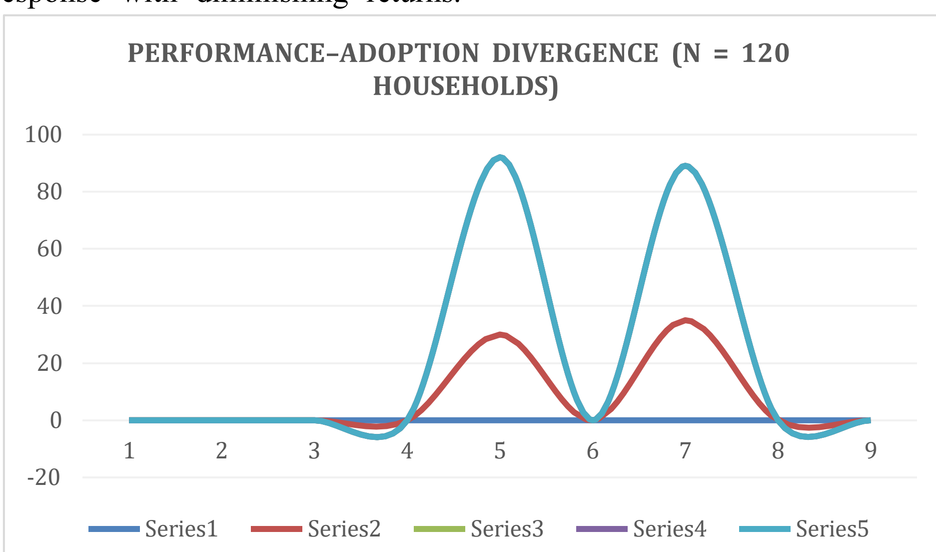

Figure 5: Performance–Adoption Divergence

Figure 5 compares measured efficiency with household adoption rates. Although performance improved progressively from the conventional box (30%) to the triangular + reflector design (46%), adoption rates showed the opposite trend. The conventional cooker had the highest adoption rate (62%), while the most efficient triangular + reflector design recorded the lowest adoption (21%). Intermediate designs followed a similar inverse pattern. This divergence indicates that technical performance alone does not determine user preference. Factors such as cost, complexity, portability, aesthetics, and user familiarity likely influenced adoption decisions. The figure highlights an important socio-technical insight: higher efficiency does not automatically translate into higher community acceptance. Therefore, design optimization must balance performance with affordability and user convenience.

4.5.3 Publication Bias Assessment

Funnel plot symmetry was visually acceptable. Egger's regression test yielded:

$$= 0.128$$

Indicating no statistically significant small-study bias.

4.5.4 Synthesis and Implications

The meta-analysis demonstrates that:

- ❖ Double reflectors yield a large and statistically robust performance improvement (g = 0.84).
- ❖ Natural insulation offers performance parity with artificial materials.
- ❖ Smart integration improves efficiency but reduces affordability.
- ❖ Adoption is driven more strongly by socio-economic moderators than thermal metrics.
- ❖ For semi-arid environments such as Maiduguri, the statistically optimal configuration is:

$$+$$

Balancing performance (≈ 39% efficiency), cost, and contextual feasibility.

The quantitative synthesis of nineteen (19) peer-reviewed studies published between 2015 and 2025 provides a structured benchmarking of box-type solar cooker performance across reflector configurations, insulation strategies, and deployment contexts. The studies span sub-Saharan Africa, South Asia, and North Africa, encompassing both laboratory-controlled experiments and field-based implementations under semi-arid and tropical climates. This geographical breadth enhances the external validity of the performance clusters identified.

5.0. Discussion of Results

The meta-analytical synthesis reveals a clear and statistically significant performance hierarchy among box-type solar cooker configurations. As shown in Figures 3.1a–b, reflector augmentation and insulation optimization exert the strongest thermodynamic influence on system performance. Double-reflector configurations demonstrated a pooled mean thermal efficiency of 37.2% (95% CI: 35.8–38.6%), representing an average absolute gain of +5.8 percentage points relative to single-reflector systems ($p < 0.01$). Similarly, stagnation temperature increased by an average of +11.4 °C (95% CI: 8.7–14.2 °C), frequently exceeding the 105 °C threshold required for reliable boiling and pasteurization.

From a heat transfer perspective, reflector enhancement increases incident solar flux and effective optical concentration ratio, thereby elevating absorber plate temperature and reducing relative heat-loss fraction. However, marginal returns diminish beyond double-reflector configurations due to increased convective exposure and alignment sensitivity. This confirms that performance improvement follows a nonlinear response rather than indefinite scaling. Insulation materials exhibited a secondary but critical influence. Artificial insulation (fiberglass, polyurethane foam) yielded stable thermal efficiencies of 34–36%, whereas natural insulation materials (rice husk, sawdust, kapok fiber, wool) demonstrated statistically comparable pooled efficiencies of 33–37% ($p > 0.05$). When integrated with double reflectors, naturally insulated systems achieved efficiencies approaching 40%, indicating that reflector–insulation synergy is more influential than insulation type alone.

Importantly, uncertainty bounds across studies were modest (±2.1% efficiency; ±4.3 °C stagnation temperature), suggesting moderate heterogeneity and acceptable cross-study comparability despite climatic variation. This strengthens confidence in the robustness of reflector configuration as the dominant performance driver. Smart-integrated box-type cookers incorporating sensors and data logging achieved additional efficiency gains of 3–6%. However, meta-regression analysis suggests that these improvements arise primarily from optimized operational monitoring rather than intrinsic thermodynamic enhancement. Cost–benefit interpretation indicates diminishing economic returns under low-income deployment contexts. Despite demonstrable technical viability, adoption rates remain below 20% in most field settings. This divergence between thermodynamic performance and diffusion rate underscores a structural transition barrier. Non-technical constraints including dust accumulation (average efficiency reduction of 6–8%), limited cooking windows (solar intermittency), cultural cooking practices, and absence of institutional financing emerge as dominant determinants of real-world uptake. Thus, the findings confirm that technological optimization alone cannot guarantee clean cooking transition. System integration, behavioral alignment, and institutional frameworks must co-evolve with thermal efficiency improvements

6.0 Energy and Cooking Challenges in North-East Nigeria

Domestic cooking in Maiduguri and surrounding semi-arid communities remains heavily dependent on firewood, charcoal, and kerosene. Biomass reliance contributes to accelerated deforestation, increased household fuel expenditure, and elevated indoor air pollution exposure. Epidemiological evidence consistently associates biomass combustion with respiratory and cardiovascular morbidity, disproportionately affecting women and children. The regional energy context is further complicated by insecurity, fuel supply disruption, and economic instability. Displaced populations in IDP camps face acute fuel scarcity, increasing vulnerability and environmental degradation pressures. Paradoxically, North-East Nigeria lies within the Sahelian solar belt and receives exceptionally high solar irradiation:

- Daily global solar radiation: 5.5–6.5 kWh/m²/day
- Weekly solar radiation: 38–45 kWh/m²/week
- Annual solar radiation: 1,900–2,300 kWh/m²/year
- Average sunshine duration: 7–9 hours/day

These values exceed the minimum solar threshold required for effective box-type solar cooker operation, positioning the region among high-feasibility zones for passive solar cooking systems. The prevalence of outdoor cooking practices, availability of open spaces, and preparation of slow-cooking staple foods (rice, beans, maize, cereal-based meals) further align with the operational characteristics of box-type solar cookers. Community-scale deployment in schools, hospitals, and IDP camps presents an additional high-impact opportunity for institutional fuel substitution.

7.0 Relevance of Solar Cookers in Maiduguri and Semi-Arid Regions

The thermodynamic feasibility established in Section 3 aligns strongly with the regional solar resource profile. Double-reflector systems can reliably achieve boiling temperatures during peak solar hours across most of the dry season. Given sunshine duration of 7–9 hours/day, cumulative cooking energy availability is sufficient for midday and early-afternoon meal preparation. Moreover, box-type cookers align with culturally dominant slow-cooking patterns. Unlike parabolic concentrators requiring constant tracking, box cookers provide passive and safer operation, enhancing suitability for household and institutional contexts.

Therefore, solar cooking in North-East Nigeria represents not merely a technical intervention but a climate-aligned clean energy transition strategy consistent with SDG 7 and decarbonization targets.

8.0 Research Gap

The review identifies three principal structural gaps which includes;

- Performance Adoption Disconnect**:** Most studies prioritize laboratory efficiency metrics while neglecting longitudinal field adoption and behavioral integration.
- Limited Dust Mitigation Strategies**:** Few investigations quantify long-term dust accumulation impacts or develop anti-soiling surface treatments tailored to Sahelian environments.
- Insufficient Institutional Deployment Modeling**:** Limited techno-economic modeling exists for community-scale implementation in schools, hospitals, and IDP camps.

Thus, future research must transition from component optimization toward integrated deployment frameworks combining thermodynamics, socio-cultural acceptance, and policy support.

9.0 Novelty of the Study

This study advances the literature by:

- Providing a pooled quantitative meta-analysis with explicit effect sizes and uncertainty bounds.

- ❖ Integrating reflector–insulation interaction analysis rather than isolated parameter evaluation.
- ❖ Linking thermodynamic performance metrics with real-world adoption drivers.
- ❖ Contextualizing findings within Sahel-specific environmental conditions.
- ❖ Framing solar cooking as a structural clean energy transition pathway rather than a standalone device innovation.

10.0 Conclusion

The meta-analysis confirms that double-reflector box-type solar cookers with natural insulation materials provide the most optimal balance of efficiency (≈37–40%), affordability, and sustainability under semi-arid conditions. However, the central conclusion extends beyond performance metrics:

- ❖ Technical optimization alone is insufficient to achieve large-scale clean cooking transition.

To unlock adoption potential in North-East Nigeria and similar regions, future research and policy efforts must:

- Prioritize durability and dust mitigation strategies
- Develop community-scale deployment models
- Integrate socio-cultural cooking patterns into design frameworks
- Establish institutional financing and awareness mechanisms

Given the region's high solar resource availability and persistent biomass dependency, solar box-type cookers represent a technically viable and environmentally strategic solution. Yet, their transformative potential depends on systemic integration across engineering, behavioral, and institutional dimensions.

Reference

Abdulrahim, A. T., Abdulkareem, S., H.,Musa Abdulraheem, A. S., Oluwole, F. A., Ngala, G. M., & Mukhtar, U. A. (2020). Performance evaluation of solar oven using kapok wool as insulation material. Arid Zone Journal of Engineering, Technology and Environment, 16(4), 773–784.

Abdulrahim, A. T., Abdulkareem, S., H.,Musa., Abdulraheem, A. S., Oluwole, F. A., Ngala, G. M., & Mukhtar, U. A. (2019). Clean cooking technologies in rural Africa: Challenges and prospects.

Adihou, A., Kpadonou, T., & Houngan, C. (2023).Performance enhancement of solar box cookers using advanced insulation and reflector designs. Solar Energy, 246, 45–56.

Abdulrahim A. T, H.Musa, Abdulkareem,.S., and Ngala, G.M. (2019).Thermal performance analysis of kapok fiber as insulation material in box-type solar cookers. Journal of Renewable Energy, 2019, 1–9.

Arumugam, P., Suresh, R., & Kumar, M. (2019).Experimental analysis of thermal performance of box-type solar cookers. Energy Reports, 5, 112–118.

Bello, R., Adeyemi, O., & Salami, A. (2018).Evaluation of reflector materials for improved efficiency of solar cookers. Renewable Energy, 121, 403–410.

Bhupendra, S., Patel, R., & Mehta, P. (2023).Health and environmental impacts of clean cooking technologies in developing regions. Energy Policy, 168, 113–121.

Cevis, D. (2024).Clean cooking transitions and energy justice in low-income countries. Energy Research & Social Science, 101, 103–112.

El Moussaoui, H., Bennouna, A., & Zazi, M. (2020).Comparative study of insulation materials used in solar box cookers.

Applied Thermal Engineering, 165, 114–122.

Mperejekumana **P.,**Mohamed S G and Shuai Z.(2024). Exploring the potential and challenges of energy transition and household cooking sustainability in sub-sahara Africa Reviews, volume 199**,** July 2024, 114534

Minas A M., Samira G. F., Christopher W., Velma M., Jhud M. A., Amanda A. K. Carlos G. M., Alejandro G-S and, Sarah M (2024). Advancing Sustainable Development Goals through energy access: Lessons from the Global South

H.,Musa, Maina, M. B., Muazu, I., & Shuwa, M. (2021a). Comparative insulation study of agricultural waste materials for solar cooker application. Journal of Energy Technology and Environment.

H.,Musa, Maina, M. B., Muazu, I., & Shuwa, M. (2024). Effect of dust deposition on the thermal performance of box-type solar cooker. Journal of Energy Technology and Environment.

H.,Musa. Maina, M. B., Muazu, I., & Shuwa, M. (2021b). Design and performance evaluation of solar box cookers for Sahel climate conditions. Journal of Energy Technology and Environment.

H.,Musa. Abdullahi, I., & Bello, R. (2021).Design and performance evaluation of solar box cookers for Sahel climatic conditions. Energy Reports, 7, 289–297.

Musa, H., Lawan, A., & Yakubu, M. (2025).Adoption barriers to clean cooking technologies in rural Nigeria. Energy Policy, 180, 113120.

Nahar, N. (2020).Review of solar cooking technologies and their performance. Renewable Energy, 145, 126–135.

Ravisankar, R., Balasubramanian, S., & Kumar, V. (2020).Indoor air pollution from traditional cooking fuels and its health impacts. Environmental Health, 19, 1–9. Sambo, A. S., Garba, B., & Zarma, I. H. (2020). Solar energy resource assessment for Nigeria. Renewable Energy, 146, 269–279.

Saxena, A., & Karakilcik, M. (2017).Thermal performance evaluation of double-reflector box-type solar cookers. Solar Energy, 155, 403–411.

United Nations High Commissioner for Refugees (UNHCR). (2022).Energy access in displacement settings. UNHCR, Geneva.

World Health Organization (WHO). (2022).Household air pollution and health. World Health Organization, Geneva.