



## Thermal performance and specific energy consumption of traditional tobacco curing barns in Tanzania

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### Keywords

Tobacco curing;  
Traditional flue-curing barn;  
Thermal efficiency;  
Specific energy consumption;  
Environmental sustainability

### Abstract

Traditional tobacco curing barns remain the dominant technology in Tanzania due to their low construction cost and accessibility, particularly in major producing regions such as Tabora. However, their thermal inefficiency results in excessive firewood use and environmental degradation. This study presents a field-based performance evaluation of a traditional flue-curing barn at the Tobacco Research Institute of Tanzania. Environmental parameters and fuel consumption were monitored at 15-minute intervals throughout the yellowing, leaf drying, and stem drying stages. The curing process handled 429 kg of fresh tobacco using 1,016 kg of firewood, equivalent to 16,256 MJ of energy input. The specific energy consumption was 165.3 MJ/kg of dried tobacco, thermal efficiency was 5.99%, and moisture removal efficiency was 0.42 kg of water per kilogram of firewood. More than 90% of the supplied energy was lost through conduction and uncontrolled airflow, highlighting the structural inefficiencies of traditional barns. These findings provide localized benchmarks under actual operating conditions and demonstrate the urgent need for retrofitting measures to reduce fuel demand and promote sustainable curing practices in rural Tanzania.

### Introduction

Tobacco (*Nicotiana tabacum* L.), a species of the genus *Nicotiana* in the Solanaceae family (Zhang et al. 2024), remains a key economic crop in Tanzania (Nyange et al. 2014; Lyimo and Losaru 2022; Makoye et al. 2022). It supports rural livelihoods and contributes significantly to national export earnings (Gilmore et al. 2015). Among various post-harvest processes, curing plays a crucial role in determining leaf quality and market value by driving biochemical changes, such as chlorophyll degradation and sugar transformation (Gilmore et al. 2015 Nyambara and Nyandoro 2019; He et al. 2020). Among the available curing methods, flue-curing is the most widely adopted in Tanzania, particularly for Virginia tobacco (Alfred 2023, Ndomba 2018). The Tabora region alone contributes over 50% of the country's flue-cured tobacco, largely relying on traditional wood-fired curing barns (Rweyemamu et al. 2024). These barns are affordable and accessible for smallholder farmers. Yet, they are highly energy-intensive and environmentally unsustainable due to their dependence on firewood sourced primarily from the surrounding miombo woodlands (Mataruse et al. 2018). Curing one hectare of flue-cured tobacco requires between 20 and 25 tons of firewood (Kalepa 2018 Raman Manoharlal 2023). With over 30,000 hectares cultivated annually in Tabora, this equates to approximately 600,000 to 750,000 tons of wood consumption each season (Liu et

al. 2023; Alfred 2023). This demand for firewood places mounting pressure on local forest ecosystems, particularly the miombo woodlands, which are already under threat from agricultural expansion and land use changes (Jimu et al. 2017 WHO 2017). Beyond environmental concerns, inefficient curing systems also burden farmers with increased fuel costs, labor intensity, and compromised tobacco quality due to uncontrolled drying conditions.

Traditional barns in Tanzania are typically constructed using uninsulated clay bricks and corrugated iron roofing (Munanga et al. 2017). They lack automated mechanisms for regulating temperature, humidity, and airflow, relying on farmers' manual adjustments guided by experience (Lan et al. 2016). Structural limitations such as unsealed joints, poor insulation, and flue gas leaks contribute to thermal losses exceeding 60% of the generated heat (Bortolini et al. 2019). These inefficiencies prolong curing durations and increase firewood consumption (Harmsworth 2020), thereby reducing curing uniformity and ultimately compromising final product quality. Despite these widespread issues, no comprehensive field-based studies have evaluated the energy performance of traditional barns under real operational conditions in Tanzania. This lack of practical data creates a significant knowledge gap, hindering the development and deployment of effective, evidence-based interventions to

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improve curing efficiency and reduce environmental impact (Mataruse et al. 2018).

While the energy inefficiencies of traditional barns are widely acknowledged, site-specific data on their thermal behaviour remain scarce. This study addresses that gap by conducting a full-cycle, field-based performance evaluation of a traditional flue-curing barn in Tabora, Tanzania. The novelty lies in stage-wise quantification of thermal performance, moisture removal efficiency, and fuel consumption, providing the first localized benchmarks to inform retrofitting strategies and policy interventions for sustainable curing.

Although international benchmarks estimate that flue-curing requires between 20 and 80 MJ per kilogram of cured tobacco (Bortolini et al. 2019; Cao et al. 2017), these figures are not directly transferable to Tanzania due to differences in barn construction, climatic conditions, and fuel types (Marwa 2017). The lack of localized performance data prevents researchers, policymakers, and extension officers from designing appropriate energy-saving interventions or recommending alternative technologies. Consequently, smallholder farmers remain dependent on inefficient systems with limited access to performance-based guidance (Taffese and Nigusie 2023; Becerra-Encinales et al. 2024).

The study pursues three objectives: (i) to quantify stage-wise firewood input, moisture removal, and environmental parameters across a complete curing cycle; (ii) to calculate specific energy consumption (SEC), thermal efficiency, and moisture removal efficiency (MRE); and (iii) to assess the contribution of structural heat loss and uncontrolled ventilation to overall energy demand. The central hypothesis is that poor insulation and structural leakages in traditional barns cause substantial thermal losses, leading to SEC values at least twice those reported for improved barn designs.

## **Materials and Methods**

### **Study site description**

The experimental study was conducted at TORITA, located in Tumbi, Tabora Region, western Tanzania. The site lies at approximately 5° S latitude and 33° E longitude, at an elevation of 1,190 meters above sea level. The region experiences a tropical savanna climate with distinct wet and dry seasons. The average annual temperature in Tabora ranges between 18-30 °C, with a mean of 18.6 °C. Relative humidity averages about 65%, and the region receives a mean annual rainfall of approximately 850 mm. The prevailing climatic

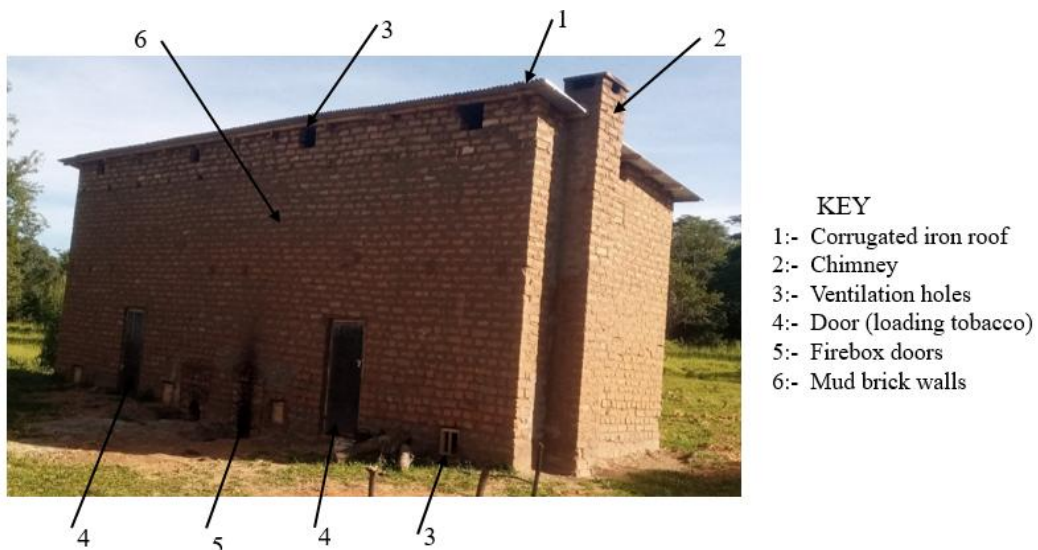
conditions, characterized by an extended dry season, create a favourable environment for flue-curing tobacco. Tabora, which produces more than half of Tanzania's flue-cured tobacco, is therefore highly representative of smallholder curing practices in the country. Within this context, the availability of traditional barns at TORITA offered an ideal setting for conducting an empirical assessment of thermal performance under real operating conditions.

### **Description of traditional tobacco curing barn**

The study utilized a traditional flue-curing barn located at the TORITA facility in Tabora, representative of the structures widely used by smallholder farmers. The barn was constructed from 75 mm-thick sun-dried clay bricks and roofed with galvanized iron sheets. The floor plan measured 6.0 m × 6.4 m, with a height ranging from 5.15 m at the front to 5.75 m at the rear, creating a slight slope to aid airflow and smoke evacuation.

Internally, the barn contained five wooden tiers for suspending tobacco sticks. A brick-lined combustion chamber ran along one side, connected to an external firebox. Hot flue gases generated from firewood combustion were directed through embedded ducts beneath the floor, allowing heated air to rise into the curing chamber. Ventilation relied on unsealed inlet vents positioned above the firebox and a vertical chimney for exhaust.

The structure lacked insulation and exhibited multiple leakage points at wall joints, doors, and the chimney base. These shortcomings, together with the absence of automated controls for temperature and humidity, made the barn heavily reliant on manual operation and farmer experience. Such limitations are known to cause significant thermal losses, extend curing times, and result in inconsistent leaf quality. Figure 1 shows the photograph of the traditional flue-curing barn used in the study (external view). The barn is constructed with mud bricks, a corrugated iron roof, and roof-level ventilation holes. Fireboxes are located at the base, with a vertical chimney for smoke exhaust. These structural features directly affect the barn's thermal performance by influencing heat retention, ventilation, and curing efficiency. Specifically, poor insulation and uncontrolled airflow lead to uneven temperature distribution and excessive fuel consumption, ultimately lowering energy efficiency and compromising the uniformity of tobacco curing.



**Figure 1:** Photograph of the traditional flue-curing barn at TORITA used for field-based thermal performance evaluation (external view)

### Tobacco sample and fuel characteristics

Freshly harvested Virginia tobacco leaves with uniform maturity were used for the curing experiment. A total of 429 kilograms of wet tobacco were prepared and suspended on 240 wooden curing sticks. Each stick was evenly loaded and arranged across five vertical tiers within the curing chamber to ensure consistent airflow and uniform drying. This setup followed the traditional stick-based flue-curing method commonly practiced by smallholder farmers in Tanzania.

Miombo hardwood, the predominant firewood species used in Tabora for tobacco curing, served as the sole energy source throughout the experiment. A total of 1,500 kilograms of air-dried miombo firewood was used across the three curing stages: yellowing, leaf drying, and stem drying. Firewood input at each stage was measured using a calibrated 100 kg-capacity digital platform scale. All firewood was pre-stored under covered and ventilated conditions for three days before use to ensure uniform drying and minimize moisture content variation.

For energy input calculations, a calorific value of 16 MJ/kg was adopted based on literature values for dry miombo wood. The firewood was manually fed into the combustion chamber at regular intervals as needed to maintain stage-specific curing temperatures.

### Measurement instruments and data acquisition

**Table 1:** Technical Specifications of Measuring Instruments

Instrument	Measurement Range	Accuracy	Resolution	Application
SSN-11E USB temperature data logger meter	-40 to 125 °C	±0.5 °C	0.1 °C	Air temperature measurement
SSN-22 USB temperature and humidity data logger	0-100 %RH; -35 to 80 °C	±0.3 %RH; ±0.3 °C	0.3%RH; 0.1 °C	Temperature and humidity measurement
TES 132 solar power meter	0-2000 W m <sup>-2</sup>	±10 W m <sup>-2</sup>	0.1 W m <sup>-2</sup>	Solar radiance measurement
Kestrel 3000 wind meter	0.6-40 m s <sup>-1</sup>	±0.1 m s <sup>-1</sup>	0.05 m s <sup>-1</sup>	Air velocity measurement

### Environmental monitoring and sensor placement

To evaluate the internal conditions of the curing

environment, temperature, relative humidity, solar radiation, and wind speed, were continuously monitored throughout the four-day tobacco curing process. Measurements were performed at multiple points to capture both internal and external conditions. Inside the barn, sensors were placed at three locations: the curing zone within the tobacco layers, the midpoint at the central barn height, and the exhaust outlet. External measurements were taken at two locations: the ambient environment and the inlet above the firebox.

Temperature and relative humidity were recorded at 15-minute intervals using SSN-11E and SSN-22 USB digital data loggers, each equipped with a thermocouple and a humidity sensor, which were installed inside the barn at representative curing positions to capture the internal microclimate. Solar irradiance was measured with a TES 132 solar power meter placed outside the barn to assess external weather conditions influencing the curing process. Wind speed was monitored using a Kestrel 3000 handheld anemometer operated outside the barn to evaluate ambient airflow patterns affecting ventilation. All instruments were factory-calibrated and verified prior to deployment. Table 1 summarizes the technical specifications of the measuring instruments, including their ranges, accuracies, resolutions, and uses.

environment, temperature and relative humidity were continuously monitored using calibrated SSN-11E and

SSN-22 USB digital data loggers. The sensors were strategically installed at five key locations within and around the curing barn to capture spatial and temporal variability throughout the four-day curing cycle. These locations included the ambient environment outside the barn, the inlet zone positioned just above the firebox, the interior curing zone at the level of the tobacco leaves, the vertical midpoint of the barn structure, and the exhaust outlet. Each sensor was securely mounted using non-conductive brackets at standardized heights to ensure accurate readings without disrupting airflow or tobacco placement.

Data were recorded at 15-minute intervals for the entire duration of the curing process, covering the yellowing, leaf drying, and stem drying stages. This high-resolution data acquisition allowed the capture of dynamic fluctuations in temperature and humidity, which were critical to understanding the barn's thermal performance. The temperature gradient between the inlet and interior curing zones was used to quantify thermal losses within the structure. At the same time, relative humidity readings from the exhaust outlet provided insights into the system's moisture evacuation efficiency.

The collected environmental data also served as the foundation for calculating key performance indicators such as thermal efficiency, specific energy consumption, and energy utilization ratio. Additionally, the variability in temperature and humidity conditions across the curing stages was assessed using statistical measures, including mean, standard deviation, and coefficient of variation. This comprehensive monitoring and analytical approach enabled a detailed diagnosis of the barn's thermal behaviour and highlighted critical inefficiencies in heat retention and moisture control under real operational conditions.

#### Tobacco weight and moisture content measurement

Moisture content removal during the curing process was determined by measuring the weight loss of tobacco leaves before and after drying. A total of 140 tobacco-laden sticks were selected as the representative sample for this analysis. Each stick was individually weighed before curing to record the combined mass of the green tobacco and the stick itself. The empty weight of each stick was also documented in advance to allow for accurate calculation of net leaf mass. Upon completion of the curing cycle, the same sticks were re-weighed to obtain the post-curing weight, including the dried tobacco.

The net weight of green and cured tobacco per stick was calculated by subtracting the stick's empty mass from the pre- and post-curing measurements, respectively. The difference between the net fresh and dried tobacco weights represented the quantity of moisture removed during curing. This data was used to quantify total moisture loss as well as to compute performance indicators such as moisture removal efficiency (MRE) and drying effectiveness. This weighing approach ensured consistency, traceability, and precision in assessing the system's ability to reduce moisture content under actual operating conditions.

#### Energy input calculations

The total thermal energy input to the curing system was determined from the mass of firewood consumed over the entire curing cycle. Miombo hardwood, used exclusively

as the fuel source, was weighed at each stage of the curing process using a calibrated 100 kg platform scale to quantify both total and stage-specific consumption. All firewood was pre-dried under ventilated conditions to minimize moisture content variability, ensuring consistent combustion efficiency and reliable energy estimates. The total energy supplied during curing ( $Q_{total}$ ) was calculated using the product of the total mass of firewood ( $m_{wood}$ ) and its calorific value ( $CV$ ), expressed in megajoules (MJ) as follows:

$$Q_{total} = m_{wood} \times CV \quad (1)$$

The calorific value of miombo wood was assumed to be 16 MJ/kg, consistent with literature values for air-dried hardwood species commonly used in sub-Saharan Africa. This value allowed for standardized energy calculations across all experimental replicates.

Stage-wise energy input was also determined to assess energy distribution across the curing phases: yellowing, leaf drying, and stem drying. For each stage, the energy supplied,  $Q_{stage}$ , was calculated using the mass of firewood consumed during that stage as follows:

$$Q_{stage} = m_{stage} \times 16 \text{ MJ/kg} \quad (2)$$

This stage-specific analysis enabled identification of phases with higher thermal demands, revealing how energy was allocated throughout the curing process. Quantifying energy inputs at each stage supported further performance metrics, including specific energy consumption, energy utilization ratio, and overall thermal efficiency of the curing system. All energy values were reported in mega joules (MJ) to maintain consistency and comparability across measurements. This systematic approach ensured that both total and phase-specific energy requirements were captured accurately, providing a clear basis for evaluating the efficiency and effectiveness of the curing process under controlled experimental conditions.

#### Curing efficiency and performance metrics

To evaluate the overall performance of the curing system, several energy efficiency metrics were calculated based on measured firewood consumption, tobacco mass, and moisture removal data. These metrics provided a comprehensive assessment of how effectively the traditional barn converted biomass energy into useful thermal energy for tobacco drying.

Specific Energy Consumption (SEC) was calculated to determine the total energy input required to produce one kilogram of cured tobacco. It was expressed in MJ/kg and calculated using the formula in equation (3):

$$SEC = \frac{Q_{total}}{m_{dried}} \quad (3)$$

where SEC represents the specific energy consumption in MJ/kg,  $Q_{total}$  is the total thermal energy supplied from firewood in MJ and  $m_{dried}$  is the mass of cured tobacco in kg.

Moisture Removal Efficiency (MRE) was used to quantify the mass of water removed per unit of firewood consumed. It was computed As Shown in Equation (4) below; where  $M_{water}$  is the total moisture lost during curing (kg) and  $M_{wood}$  is the total firewood mass used (kg). Higher MRE values indicate more effective thermal utilization for dehydration.

$$MRE = \frac{M_{water}}{M_{wood}} \quad (4)$$

The Energy Utilization Ratio (EUR) was calculated to evaluate the curing process's efficiency further. This metric represents the proportion of total energy input effectively used to evaporate moisture from the tobacco, providing insight into how much fuel energy was contributed directly to drying. The EUR was computed using Equation (5) below, where EUR is the energy utilization ratio (dimensionless or percentage),  $Q_{Evap}$  is the theoretical energy required to evaporate moisture in MJ/kg and  $E_{total}$  is the total energy supplied from firewood combustion in MJ/kg:

$$EUR = \frac{Q_{Evap}}{Q_{total}} \quad (5)$$

Thermal efficiency is a critical metric in evaluating the extent to which the energy supplied from firewood combustion is effectively utilized for moisture evaporation during curing. It reflects the proportion of useful thermal energy relative to the total energy input, offering insights into the functional performance of the curing system. The thermal efficiency was calculated using Equation (6), where  $\eta_{thermal}$  represents thermal efficiency (expressed as a percentage),  $Q_{evap}$  is the energy required to evaporate water from the tobacco leaves in MJ/kg, and  $Q_{total}$  is the total thermal energy supplied from firewood in MJ/kg:

$$\eta_{thermal} = \frac{Q_{evap}}{Q_{total}} \times 100 \quad (6)$$

Energy productivity is a performance indicator that reflects the amount of cured product obtained per unit of energy consumed. It provides a useful benchmark for comparing the effectiveness of different tobacco curing systems regarding energy utilization. Higher values indicate better system performance, as more output is generated for the same input energy. Energy productivity was calculated using Equation (7) below, where EP denotes energy productivity in MJ/kg,  $M_{dried}$  is the total mass of cured tobacco in kilograms, and  $Q_{total}$  is the total thermal energy supplied from firewood in MJ/kg:

$$EP = \frac{M_{dried}}{Q_{total}} \quad (7)$$

The recorded temperature, relative humidity (RH), and firewood consumption data during the curing stages were statistically analyzed to determine the mean, standard deviation, and coefficient of variation. These indicators characterize the central tendency and variability of the curing environment and energy consumption patterns, as illustrated in equations (8), (9), and (10), respectively. First, the mean ( $\mu$ ), represented by Equation (8), was calculated for each measured parameter during the yellowing, leaf drying, and stem drying stages. The mean is determined by summing all individual observations and dividing by the total number of recorded measurements. It provides a central reference value that represents the typical condition experienced in the barn, serving as a benchmark for temperature, humidity, and wood usage performance during each curing phase.

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (8)$$

Second, the standard deviation ( $\sigma$ ) was computed using Equation (9) to quantify the degree of variability around the mean value. The standard deviation measures how widely individual recorded values deviate from the mean, offering insights into the consistency or instability of the curing environment. A lower standard deviation suggests

a stable curing process, while a higher standard deviation indicates greater fluctuations, which could adversely affect curing uniformity and energy efficiency.

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2} \quad (9)$$

Finally, the coefficient of variation (CV) was calculated as presented in Equation (10), defined as the ratio of the standard deviation to the mean and expressed as a percentage. The CV provides a normalized measure of variability relative to the average, allowing easy comparison across different parameters and stages. Higher CV values reflect greater instability, while lower CV values indicate more controlled conditions. In the context of tobacco curing, analyzing the CV was critical to identify which stages were most prone to environmental fluctuations, helping to pinpoint weaknesses in thermal retention and airflow management.

$$CV = \left( \frac{\sigma}{\bar{X}} \right) \times 100 \quad (10)$$

Where  $\bar{X}$  is the Mean (average) value of temperature ( $^{\circ}\text{C}$ ), relative humidity (%), or firewood consumption (kg) during each curing stage,  $X_i$  is the Individual recorded value of temperature ( $^{\circ}\text{C}$ ), relative humidity (%), or firewood consumption (kg), the Total number of recorded measurements or observations,  $\sigma$ ; The Standard deviation of temperature, relative humidity, or firewood consumption, and CV is the Coefficient of variation (%) for temperature, relative humidity, or firewood consumption.

## Results and Discussion

### Curing output and energy use

The curing process handled 429 kg of raw tobacco over four days, producing 98.31 kg of cured tobacco and achieving an 81.4% moisture loss. This falls within the typical target range for Virginia flue-cured tobacco, generally reported between 78 - 82% moisture reduction (Liu et al. 2023). However, achieving this result required 1,016 kg of miombo-sourced firewood, translating to approximately 16,256 MJ of energy input. Traditional barns typically consume more energy than modernized systems, but this level of fuel demand points to deep inefficiencies in both barn design and curing practice. In comparison, energy-efficient barns often complete the same process using 30 - 50% less firewood (Bortolini et al. 2019).

This inefficiency has practical consequences: it raises smallholder production costs, increases wood collection labour demands, and accelerates local deforestation. In regions where tobacco curing competes directly with food security and woodland conservation, these inefficiencies are neither economically nor environmentally sustainable.

### Stage - wise firewood consumption and environmental conditions

Table 2 summarizes firewood usage, curing duration, and average environmental conditions across the three curing stages. Energy demand increased progressively across stages, with stem drying requiring the highest input 536 kg of firewood, accounting for over 53% of total consumption. This stage also spanned the most extended curing period, reflecting the critical need for sustained high temperatures to dry dense stem tissues effectively.

A notable jump in firewood consumption was observed during the transition from yellowing to leaf drying, highlighting the barn's inability to retain residual thermal energy. Instead of leveraging heat from earlier stages, fresh energy had to be continuously supplied, pointing to major structural inefficiencies. The barn's construction of uninsulated clay bricks and poorly sealed ventilation points resulted in uncontrolled heat losses and ineffective thermal momentum between stages.

Although internal conditions showed gradual dehydration, relative humidity (RH) control remained

**Table 2:** Firewood Consumption and Environmental Conditions by Curing Stage

Curing Stage	Firewood Used (kg)	Duration (hrs)	Avg. Temp (°C)	Avg. RH (%)
Yellowing	120	24	34.2	88.6
Leaf Drying	360	30	49.7	58.3
Stem Drying	536	42	66.1	39.5
Total / Avg.	1,016	96	-	-

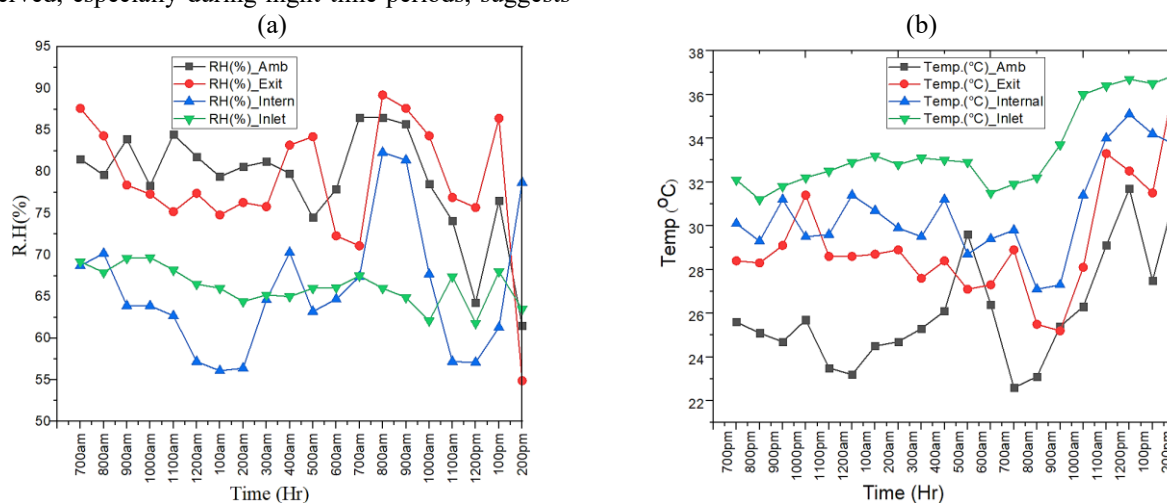
**Temperature and humidity distribution in the barn**  
*Yellowing stage*

During the yellowing stage, conducted from 7:00 PM on 27 March to 11:00 PM on 28 March 2024, the interior curing zone temperatures ranged between 28.5°C and 34.5°C, with an average of 31.2°C ± 2.1°C and a coefficient of variation (CV) of 6.7%. Relative humidity (RH) fluctuated between 58% and 71%, yielding an average of 64.5% ± 4.3% with a CV of 6.7%.

Temperature profiles remained largely within the optimal 30-38°C range recommended for effective chlorophyll degradation, promoting good yellowing outcomes. However, the moderate RH instability observed, especially during night-time periods, suggests

inconsistent, particularly during night hours when combustion intensity naturally declined. These fluctuations further undermined curing efficiency and extended the drying cycle. In an efficient curing system, energy demand should decrease progressively as moisture content diminishes. However, in this case, the opposite trend occurred. Poor thermal capture and rapid heat losses forced excessive firewood use to sustain target temperatures at each stage, revealing systemic inefficiencies inherent in traditional barn designs.

that moisture retention was inconsistent, potentially prolonging the biochemical yellowing process. These fluctuations emphasize the importance of stabilizing RH during this critical phase to avoid delays and quality degradation. Figure 2. Temporal variation of temperature and relative humidity during the yellowing stage (27-28 March 2024), monitored at ambient, inlet, interior curing zone, and exhaust zones. Interior temperatures remained within the optimal 30-38°C range for chlorophyll breakdown, although relative humidity exhibited moderate fluctuations, potentially affecting uniform leaf colour transformation.



**Figure 2:** Temporal variation of temperature and relative humidity during the yellowing stage

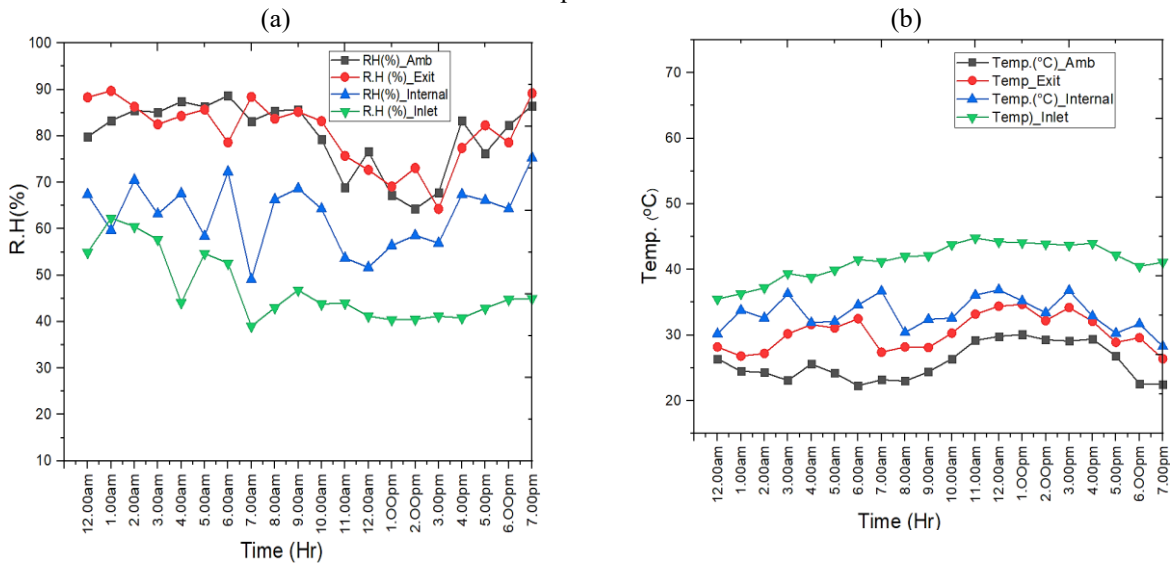
**Leaf Drying Stage**

The leaf drying stage, from midnight on 29 March to 11:00 PM on 31 March 2024, exhibited higher thermal variability than the preceding yellowing phase. Interior barn temperatures fluctuated between 30.2°C and 50.7°C, averaging 42.8°C ± 5.6°C (CV 13.1%), while relative humidity decreased from 72% to 58%, averaging 64.1% ± 6.2% (CV 9.7%). Effective leaf drying requires stable temperatures of 50-60°C to enable uniform moisture

removal from the lamina. The observed temperature dips, particularly during early mornings and nights, fell below this optimal range, slowing moisture evaporation and prolonging the drying period. Concurrent RH fluctuations further reduced drying efficiency by altering the vapor pressure gradient, which drives water movement from the leaves. These instabilities likely arose from variable combustion intensity, structural heat losses, and uneven air circulation within the barn.

Figure 3 shows the temporal variation of temperature and RH across ambient, inlet, interior curing, and exhaust zones. The data reveal that thermal management inconsistencies concentrated in the interior curing zone correlate with increased firewood consumption and

extended drying duration. Correcting these fluctuations through controlled heating/improved airflow is expected to reduce energy input and standardize drying rates, enhancing overall process efficiency.

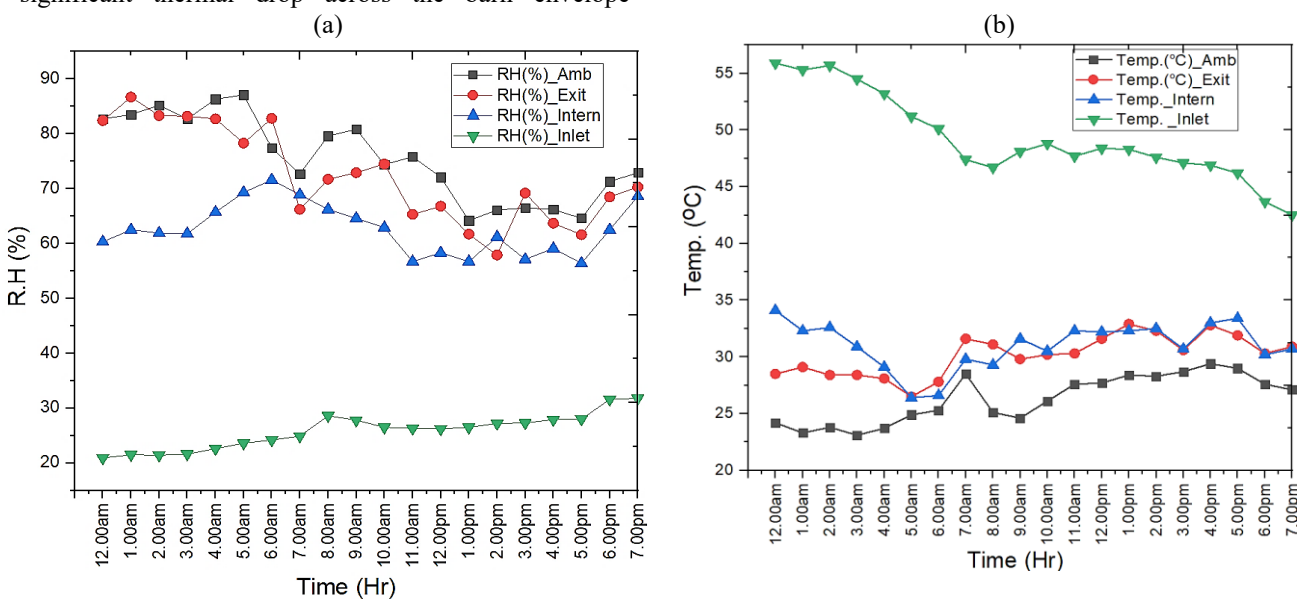


**Figure 3:** (a) Relative Humidity and (b) Temperature Profiles Across Barn Zones During the Leaf Drying Stage of Tobacco Curing

**Stem Drying Stage**

The stem drying stage, conducted from midnight on 1<sup>st</sup> April to 3:00 AM on 2<sup>nd</sup> April 2024, revealed the most pronounced performance gaps. Despite inlet air temperatures starting at 55°C and gradually decreasing to 48°C, interior temperatures remained much lower, fluctuating between 28.3°C and 34.7°C, with an average of 31.5°C ± 2.7°C and a CV of 8.6%. Relative humidity levels persisted between 60% and 72%, with an average of 66.4% ± 3.8% and a CV of 5.7%.

(approximately 20°C loss from inlet to interior) and consistently high RH reflected substantial heat losses and poor moisture evacuation capacity. Consequently, the barn required the highest firewood input during this stage, highlighting its thermal inefficiencies. Figure 4. Temporal variation of temperature and relative humidity during the stem drying stage (1-2 April 2024), measured at ambient, inlet, interior curing zone, and exhaust zones. Despite sufficient inlet temperatures, the interior environment exhibited significant heat losses and high RH levels, indicating poor thermal retention and moisture control during the most energy-intensive curing phase.



**Figure 4:** (a) Relative humidity and (b) Temperature Profiles Across Barn Zones During the Stem Drying Stage of Tobacco Curing

**Table 3:** Variability of Environmental Parameters Across Curing Stages

Curing Stage	Parameter	Mean ± SD	CV (%)
Yellowing Stage	Temperature (°C)	31.2 ± 2.1	6.7
	Relative Humidity (%)	64.5 ± 4.3	6.7
Leaf Drying Stage	Firewood Consumption (kg)	120	4.2
	Temperature (°C)	42.8 ± 5.6	13.1
	Relative Humidity (%)	64.1 ± 6.2	9.7
Stem Drying Stage	Firewood Consumption (kg)	360	5.5
	Temperature (°C)	31.5 ± 2.7	8.6
	Relative Humidity (%)	66.4 ± 3.8	5.7
	Firewood Consumption (kg)	536	6.2

Environmental variability across curing stages influenced both drying efficiency and energy consumption. The yellowing stage maintained low variability (CV 6.7% for both temperature and relative humidity), providing stable conditions that facilitated uniform leaf yellowing with minimal firewood usage. In contrast, the leaf drying stage experienced pronounced fluctuations, with interior temperatures ranging from 30.2°C to 50.7°C (CV 13.1%) and relative humidity declining from 72% to 58% (CV 9.7%). These deviations frequently brought temperatures below the optimal 50 - 60°C range, reducing moisture removal rates by an estimated 25-30% and extending drying duration by approximately 12-16 hours, which corresponded with an increase in firewood consumption to 120 kg.

During the stem drying stage, variability was moderate (CV 8.6% for temperature), but interior temperatures remained below optimal thresholds for effective moisture removal. Firewood consumption further increased to 536 kg, reflecting the additional energy required to maintain the drying process under sub-optimal thermal conditions. The patterns across stages indicate that both the magnitude and timing of temperature and relative humidity fluctuations are critical, as they directly affect drying kinetics and energy efficiency. Controlled combustion, improved barn insulation, and optimized airflow are potential solution solutions that could reduce these fluctuations, stabilizing moisture removal rates and lowering firewood demand.

**Energy Efficiency and Thermal Performance**

The total energy input for the curing process was 16,256 MJ, derived from the combustion of 1,016 kg of firewood with an assumed calorific value of 16 MJ/kg (Msuya et al., 2011). This energy supported the processing of 429 kg of raw tobacco into 98.31 kg of dried product. Analysis of the energy metrics highlights substantial inefficiencies within traditional curing barns. The Specific Energy Consumption (SEC) was 165.3 MJ/kg, considerably higher than the 20–80 MJ/kg range reported for improved, energy-efficient barns (Weiss and Buchinger, 2012), indicating that a significant portion of the supplied energy

did not contribute effectively to moisture removal. Similarly, the Moisture Removal Efficiency (MRE) was only 0.42 kg/kg of wood, well below the 0.7-1.0 kg/kg benchmark observed in thermally enhanced systems (Yuan et al., 2014). The barn’s thermal efficiency and Energy Utilization Ratio (EUR) were limited to 5.99%, in contrast to the 15-30% efficiency reported in insulated or hybrid curing structures (Bortolini et al. 2019). Energy productivity, measured at 0.00605 kg/MJ, also fell short of the 0.01-0.025 kg/MJ standard typical of modernized systems (Reichard and Pearce 2013), reinforcing the magnitude of energy losses.

These inefficiencies reflect both structural limitations and operational inconsistencies. Heat escapes through the barn structure, reducing the fraction of energy available for drying. Uneven combustion intensity further limits the energy effectively applied to moisture removal. Fluctuating environmental conditions within the barn amplify these losses, creating periods when drying is slower or uneven. As a consequence, the curing process is prolonged, and firewood consumption increases, elevating operational costs. These factors also contribute to environmental pressures, accelerating deforestation in the miombo woodlands where the firewood is sourced (Bortolini et al. 2019).

Correcting these inefficiencies requires interventions that target both structural and operational aspects of the curing process. Structural insulation minimizes heat losses and stabilizes internal temperatures, while precise combustion control ensures a consistent energy supply. Integration of solar-assisted preheating further supplements the thermal input, reducing dependency on firewood and stabilizing drying conditions. Together, these measures improve the fraction of energy directed to moisture removal, enhance the barn’s thermal efficiency, and increase the MRE. By reducing the total energy required and optimizing drying rates, these improvements lower operational costs and mitigate environmental impacts, promoting a more sustainable and economically viable tobacco-curing process (Yuan et al. 2014).

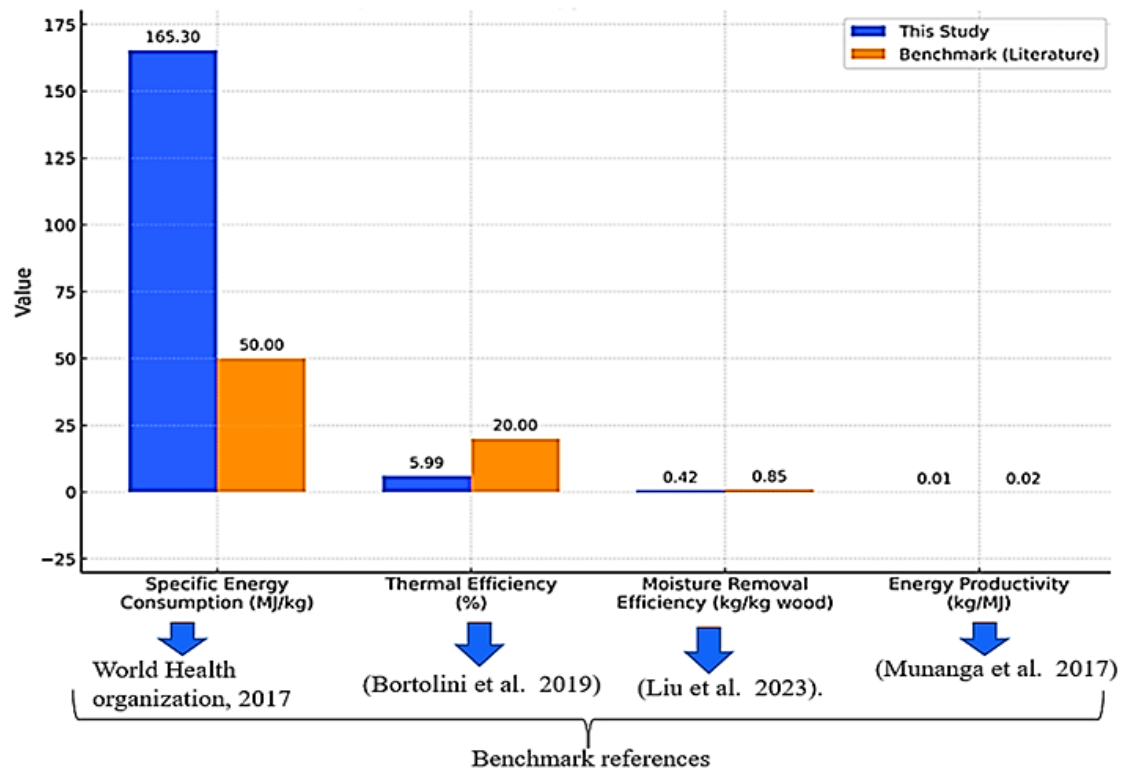


Figure 5: Comparison of key energy performance indicators with literature benchmarks

**Comparative Benchmarking with Literature**

The specific energy consumption (SEC) observed in this study was 165.3 MJ/kg, markedly higher than the 20-80 MJ/kg range reported for improved barns (Cao et al. 2017). This indicates that traditional curing systems operate with 2-8 times lower energy efficiency, as summarized in Table 4. Heat losses through uninsulated structures, coupled with uneven combustion, limit the fraction of energy effectively applied to leaf drying, prolonging the curing process and increasing firewood consumption. Thermal efficiency, measured at 5.99%, also remains far below the 20-30% range typical of rocket barns and hybrid curing systems (Bortolini et al. 2019), further demonstrating substantial energy wastage. These low values reflect both structural and operational limitations that prevent optimal conversion of supplied energy into effective moisture removal.

Moisture Removal Efficiency (MRE) was 0.4236 kg water per kg of wood, below the 0.6-0.7 kg/kg reported for semi-insulated or controlled airflow barns (WHO 2017). This gap underscores how environmental fluctuations, inconsistent airflow, and heat losses reduce

the effectiveness of moisture extraction during the curing process. Energy productivity, at 0.00605 kg/MJ, remains significantly lower than the 0.015-0.025 kg/MJ observed in solar-assisted or improved combustion systems (Munanga et al. 2017), reflecting the cumulative effect of high SEC, low thermal efficiency, and suboptimal moisture removal. Table 4 presents a comparative summary of these key performance metrics against benchmark values from the literature, highlighting the efficiency gaps between traditional barns and improved curing technologies. The combined analysis demonstrates that traditional systems not only consume excessive energy but also underperform in converting this input into productive drying output. Structural improvements, including insulation and controlled airflow, alongside precise combustion management, stabilize internal temperatures and enhance energy application. These measures improve MRE and energy productivity while reducing firewood consumption, emphasizing the importance of integrated thermal and operational management in closing the performance gap between traditional and modernized curing systems.

Table 4: Comparative Benchmarking of Energy Performance Indicators

Parameter	This Study	Benchmark (Literature)	Reference
Specific Energy Consumption (MJ/kg)	165.3	20-80	(WHO, 2017)
Thermal efficiency (%)	5.99	20-30	(Bortolini et al., 2019)
Moisture Removal Efficiency (kg/kg)	0.4236	0.6-0.7	(Cao et al., 2017)
Energy Productivity (kg/MJ)	0.00605	0.015-0.025	(Munanga et al., 2017)

**Structural Limitations and Heat Loss**

Thermal analysis and visual inspections revealed

significant structural deficiencies in the traditional tobacco curing barn, leading to significant energy losses.

The barn, constructed from uninsulated burnt bricks and characterized by unsealed gaps around the roof, door frames, combustion zones, and chimney outlets, demonstrated poor thermal retention capacity.

For example, in the stem drying stage, Temperature measurements during this stage showed that while inlet air temperatures peaked at 55 °C, interior chamber temperatures remained between 28°C and 35°C, resulting in a thermal loss ratio of approximately 36.4%. This indicates that more than one-third of the thermal energy supplied to the system was lost through the building envelope due to conduction, convection, and air leakage. Consistently high exhaust relative humidity levels (85-90%) during the leaf and stem drying stages further suggested poor moisture evacuation, primarily due to the

lack of directed airflow systems and inadequate sealing of ventilation points (Liu et al. 2023).

As summarized in Table 5, the barn's thermal performance metrics a thermal efficiency of 5.99% and a specific energy consumption (SEC) of 165.3 MJ/kg fall significantly below the benchmark ranges reported for improved barns, which typically achieve 15-30% efficiency and SEC values between 20-80 MJ/kg (Bortolini et al. 2019). These findings align with observations by Sibanda and Tsuyuki (2024), who demonstrated that thermal losses in traditional barns can be reduced by over 50% through design improvements such as wall insulation, sealable air inlets, and optimized chimney configurations.

**Table 5:** Structural Performance Indicators Versus Literature Benchmarks

Parameter	Observed	Benchmark	Interpretation
Inlet Temp. (Stem stage)	~55 °C	-	Thermal input provided
Internal Temp. (Stem stage)	28-35 °C	60-70 °C	Significant thermal loss through walls
Temp. Loss Ratio	36.4%	<15% (ideally)	Indicates inefficient energy transfer
Exit RH (%)	85-90%	≤60%	Inadequate moisture venting and airflow
Thermal efficiency (%)	5.99%	15-30%	Substantial heat is lost before useful application
SEC (MJ/kg dried tobacco)	165.3	20-80	Excessive firewood use due to heat loss

**Environmental and Sustainability Implications**

This study highlights the significant environmental burden associated with traditional tobacco curing. A total of 1,016 kg of firewood was consumed to dry 98.31 kilograms of tobacco, resulting in an estimated energy input of 16,256 MJ as illustrated in Table 6. This translates to a high firewood-to-product ratio of over 10 kg of wood per kg of dried tobacco, signalling inefficiency and over-reliance on forest biomass. Using standard emissions factors (1.83 kg CO<sub>2</sub>/kg firewood), the curing process released approximately 1.86 tons of CO<sub>2</sub>. These emissions contribute to deforestation and climate change and pose health risks through exposure to particulate matter and carbon monoxide, especially in poorly ventilated barns. The observed specific energy consumption (SEC) of 165.3 MJ/kg and thermal efficiency of just 5.99% indicate substantial energy waste compared to improved barns, which achieve SEC values as low as 40 MJ/kg and efficiencies above 20% (Cao et al. 2017).

These findings call for urgent technological improvements, including insulated structures, solar-assisted preheating, and clean combustion systems, to reduce wood use, emissions, and health risks. Promoting sustainable curing technologies is essential for safeguarding forest resources and achieving low-emission agricultural processing in regions like Tabora.

**CO<sub>2</sub> Emissions Estimation**

The combustion of firewood during the tobacco-curing process contributes directly to greenhouse gas emissions. Based on the FAO/IPCC emission factor (Flammini et al. 2023; Sintayehu Eshetu 2025), burning 1 kg of air-dried

wood produces approximately 1.83 kg of CO<sub>2</sub>. With 1,016 kg of firewood consumed per curing cycle at TORITA, total CO<sub>2</sub> emissions were estimated at 1,858.88 kg. This high emission level reflects both the substantial energy input required and the low thermal efficiency of the traditional curing system.

Table 6 summarizes the key environmental and energy performance indicators for the barn. SEC remained at 165.3 MJ/kg, reflecting the significant energy demand per unit of dried tobacco, while thermal efficiency was limited to 5.99%, indicating that only a small fraction of the input energy contributed effectively to drying. Dried tobacco output per cycle was 98.31 kg, measured by stick weight before and after curing, emphasizing the low energy productivity relative to the environmental impact. The CO<sub>2</sub> emissions, derived from the mass of wood burned and the IPCC/FAO factor Ren et al. (2023), (Shati et al., Zhang et al., 2022), highlight the substantial carbon footprint associated with traditional curing practices.

The relationship between low thermal efficiency, high SEC, and elevated CO<sub>2</sub> emissions highlights systemic inefficiencies. Structural heat losses, uneven combustion, and inconsistent airflow limit the conversion of energy into effective moisture removal, prolonging curing time and increasing firewood demand. The resulting emissions not only increase operational costs but also contribute to deforestation and environmental degradation. Integrating improved combustion management, structural insulation, and potential solar-assisted preheating would stabilize thermal conditions, reduce energy demand, and lower associated CO<sub>2</sub> emissions, providing a more environmentally sustainable curing process.

**Table 6:** Summary of Energy and Environmental Performance of the Traditional Barn.

Parameter	Value	Justification
Firewood used per curing cycle	1,016 kg	Measured during curing at TORITA
Dried tobacco output	98.31 kg	Derived from the stick weighing before and after curing
Specific Energy Consumption (SEC)	165.3 MJ/kg	Calculated using Equation 3 based on total energy input and dried mass
Estimated CO <sub>2</sub> emissions	1,860 kg CO <sub>2</sub>	1,016 kg × 1.83 kg CO <sub>2</sub> /kg wood (IPCC/FAO factor)
Thermal Efficiency	5.99 %	Calculated using Equation (6) based on energy absorbed by tobacco vs. total input

### Conclusion and Recommendations

This study conducted a field-based evaluation of the thermal performance and energy consumption characteristics of a traditional tobacco curing barn in Tabora, Tanzania. The findings revealed critical thermal inefficiencies, with specific energy consumption (SEC) measured at 165.3 MJ/kg and thermal efficiency at 5.99%, substantially lower than benchmarks reported for improved barns. Moisture removal efficiency (MRE) and energy productivity were also considerably below optimal values, highlighting severe operational shortcomings associated with poor structural insulation, unregulated airflow, and uncontrolled curing environments.

Temperature and relative humidity monitoring across the yellowing, leaf drying, and stem drying stages demonstrated significant thermal losses between the heat source and curing chamber, accompanied by persistent moisture retention. These inefficiencies resulted in prolonged curing durations and excessive firewood consumption, reinforcing the unsustainable nature of current practices. This study provides the first empirical energy performance benchmarks for traditional tobacco barns in Tanzania, offering a critical baseline for future interventions targeting sustainable curing improvements.

Based on these findings, traditional barns are strongly recommended to undergo structural retrofitting, including wall insulation, sealing of ventilation points, and installation of controlled airflow systems. Integrating hybrid solar-thermal preheating and photovoltaic (PV) backup units could significantly reduce firewood dependence, enhance curing uniformity, and promote environmental sustainability. Future research should focus on designing cost-effective retrofit packages and validating their performance under diverse climatic conditions to accelerate the transition toward sustainable tobacco curing practices in rural, off-grid communities.

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### Author Contributions

Seuri Saiguran Kilakoi, Baraka Kichonge, Thomas Kivevele, Mtaki Thomas Maagi, and Jacob Bulenga Lisuma contributed to the conceptualization, methodology, validation, and formal analysis. Seuri Saiguran Kilakoi wrote the article and original draft and created the visualization. Baraka Kichonge, Thomas Kivevele, Mtaki Thomas Maagi, and Jacob Bulenga Lisuma revised the article for intellectual content and supervised, reviewed, and edited it. All authors approved the submitted version.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Availability of data

Data available on request from the authors

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