Design and Performance Evaluation of a Low-Cost Dryer for Reducing Postharvest Banana Losses and Supporting Flour Processing in Smallholder Systems

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Abstract

Banana (Musa acuminata) is a vital staple food, but it suffers from high postharvest losses due to rapid ripening and poor processing. This study designed and evaluated a low-cost solar dryer for banana flour production to reduce postharvest losses. The dryer, constructed using local materials with surfaces of aluminium foil paper and aluminium tall-list (aluminium alloy 6061 (Magnesium and Silicon) drying, incorporated solar-powered fans for forced convection. It is backed with a tall black aluminium list to trap solar radiation. Experiments compared five treatments in quadruplicate: aluminium foil paper without a fan (T1), aluminium tall-list without a fan (T2), aluminium foil with a fan (T3), aluminium tall-list with a fan (T4), and open-air drying (control, T5). Economic analyses were performed to assess the economic viability of the drying systems. Results revealed that there was no significant difference between treatments T1, T2, T3 and T4, which performed better than the control. Aluminium surfaces enhanced heat retention, with internal temperatures reaching 53.1 °C in T1 compared to ambient (30 °C). Fan-assisted drying reduced drying time by 50% compared to natural convection, while aluminium surfaces alone (T2) also outperformed the control. Passive dryers (T2) are optimal for short-term return on investment (26-day Payback Period (PBP). Fan-assisted dryers (T4) maximise long-term profitability (4.760,000M CFA net profit). The study concludes that solar-assisted drying with aluminium surfaces and forced convection significantly improves efficiency, offering a cost-effective solution for small-scale processors in tropical regions. Future research should explore hybrid designs for further optimisation.

Keywords:
Aluminium surfaces, banana chips, forced convection, postharvest losses, solar dryer

Introduction

Bananas (*Musa acuminata*) are one of the most significant staple crops globally, placed just behind maize, rice, and wheat in terms of production size (Perrier et al. 2011). They serve as a crucial source of nutrition and income for millions of people, particularly in tropical and subtropical regions where they are a dietary cornerstone. In East Africa, for instance, per capita consumption exceeds 200 kg of fresh weight annually, highlighting their role in food security (Scott, 2021). India dominates global production, contributing over 30 million metric tons annually; yet, only a fraction (less than 5%) of the banana yield undergoes processing (Horticultural Statistics at a Glance, 2018). While bananas are a major export commodity, their high perishability and the lack of value addition processes, such as flour production, limit their economic potential, especially in developing countries where infrastructure to enhance value is lacking (Voora et al., 2020; Ravi et al., 2023). Addressing these losses through improved processing techniques could unlock substantial economic benefits, particularly in regions where bananas are a primary carbohydrate source.

The high perishability of bananas emanates from their climacteric nature, which accelerates ripening and decay after harvest. Factors such as improper handling, bulk

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transportation, inadequate storage facilities, and limited access to processing technologies exacerbate postharvest losses, exceeding 20% of total production in some regions (Shanthi & Poornakala, 2020; Voora et al., 2020). These losses are particularly severe in rural and semi-rural areas, where traditional sun drying, although widely practised, is inefficient and weather-dependent (Tiwari, 2016). Moreover, the lack of affordable and scalable drying technologies forces many small-scale farmers and processors to rely on open-air drying, which is slow, inconsistent, and susceptible to contamination. In humid tropical climates, where bananas are predominantly grown, ambient conditions further hinder effective drying, leading to spoilage and reduced product quality. Consequently, there is an urgent need for cost-effective, energy-efficient drying solutions that can mitigate these losses while preserving the nutritional and economic value of bananas.

Processing bananas into flour presents a sustainable strategy to reduce postharvest losses while enhancing their marketability and nutritional benefits. Banana flour is rich in total starch (above 70%) and resistant starch (RS) (about 20%), a type of dietary fibre that resists digestion in the small intestine and offers numerous health benefits, including improved glycemic control and gut health (Pragati et al., 2014; Lockyer & Nugent, 2017). Furthermore, bananas are a valuable source of essential micronutrients, including potassium and magnesium, as well as bioactive compounds such as phenolics, carotenoids, and flavonoids, which exhibit antioxidant properties (Singh et al., 2016).

The nutritional profile of banana flour makes it an attractive ingredient for functional foods, including high-fibre bread, cookies, and infant weaning products (Juarez-Garcia et al., 2006; Aparicio-Saguilan et al., 2014). Its low glycemic index (GI) is reported to enhance its use in diabetic and weight-management diets (Hermansen et al., 1992). Despite these advantages, the commercial production of banana flour remains limited, with most processing efforts focused on niche products, such as banana chips or purees (Shanthi & Poornakala, 2020). Expanding the use of banana flour will reduce postharvest losses and create new economic opportunities for small-scale processors in developing countries.

Several drying technologies have been explored to improve the preservation of bananas, ranging from traditional sun drying to advanced hybrid systems. Solar dryers, for instance, have been widely studied due to their sustainability and low operational costs. Maiti et al. (2011) demonstrated that reflective surfaces in passive solar dryers could enhance drying efficiency. They caused 1 kg of papad (a popular Indian wafer) to lose 12% moisture, with a moisture removal rate of 0.0412 g/s. Kumar et al. (2025) reported significant energy savings using a photovoltaic-integrated heat pump drying system. Recently, microwave-assisted hot air (Zhao et al., 2023) has also shown promise, reducing drying time by up to 81 % compared to conventional methods.

However, many of these technologies face practical limitations in low-resource settings, particularly in most developing countries. High-tech systems, such as heat pump dryers or refractance window drying (Timurtas & Gűrlek, 2024), are often prohibitively expensive for small-scale farmers. Passive solar dryers, though affordable, suffer from slow drying rates and inconsistent performance in humid climates (Simate et al., 2025). Moreover, many existing designs lack scalability or require grid electricity, which is unreliable or unavailable in rural areas. These challenges emphasise the need for an accessible, efficient, and low-cost drying solution tailored to the needs of smallholder farmers and low-income processors.

Despite advancements in drying technology, a significant gap remains in the availability of affordable, efficient, and scalable drying solutions for small-scale banana processors. Most existing dryers are either too expensive, energy-intensive, or poorly suited to tropical conditions. This study addresses these limitations by developing a low-cost solar dryer that combines aluminium surfaces (for improved heat retention) with forced convection (via solar-powered fans) to optimise drying efficiency.

The proposed design leverages locally available materials and renewable energy, making it accessible to farmers in off-grid or resource-constrained settings. By comparing different configurations, including passive and fan-assisted drying, our study aimed to identify the most effective and economically viable approach for reducing postharvest losses in bananas. Furthermore, we conducted an economic analysis to assess the feasibility of scaling the technology for broader adoption, ensuring long-term sustainability and impact. Following the identification of research gaps, objectives were formulated. These objectives were to develop a low-cost solar dryer for banana chips, analyse drying kinetics, evaluate the cost-effectiveness, and determine the efficiency of various drying systems. Following our objectives, we hypothesised that: the integration of aluminum surfaces and forced convection will significantly enhance drying efficiency, reducing drying time by at least 50% compared to passive and open-air methods; fan-assisted drying will achieve superior moisture removal rates and lower final moisture content than natural convection or traditional sun drying; the proposed dryer will demonstrate economic feasibility, with a payback period of less than one year, making it viable for small-scale processors in tropical regions.

This study sought to bridge the gap between advanced drying technologies and the practical needs of smallholder farmers by introducing an affordable, solar-powered dryer for banana processing. The proposed design can enhance food security, increase farmer incomes, and promote sustainable agricultural practices by improving drying efficiency and reducing postharvest losses.

Materials and Methods

Materials

Unripe bananas were sourced from farmers in the Donga Mantung Division of the North West Region, Cameroon. Sourcing of bananas for this study ensured that raw materials were obtained from farms while ethically adhering to fair labour practices and sustainable agriculture, minimising environmental impact. Aluminium tall list, aluminium foil paper, black aluminium tall list, switches, solar inverter, solar converter, solar panels, panel cables, connecting cables, solar battery, nails, pins, foams, polyethene bags, and wood for the construction of the dryer were purchased from renowned dealers in Nkambe market, as detailed in Table 3. Aluminium tall-list is a high-grade aluminium alloy (6061, Containing Magnesium and Silicon) that offers an optimal strength-to-weight ratio, with an average density of 2.7 g/cm³ and a thickness of 0.5 mm. It features a natural oxidation surface that enhances its high resistance to corrosion. Alloy 6061 aluminium tall-list also has high thermal conductivity, allowing for effective heat dissipation from light sources. Labour was sourced from the Nkambe Centre Sub-division.

Methods

Design and construction of the dryer structural framework

The solar dryer was constructed as a rectangular wooden chamber with dimensions of 1.8 m (length) x 1.8 m (width). The structural framework consisted of:

Vertical supports: Eight wooden planks (1.8 m length) were used as the primary vertical members. Base and roof inclination: Two shorter planks (0.78 m front, 0.55 m rear) were attached to create a sloped roof (≃7° inclination). Internal reinforcement: Additional wooden battens were cross-braced to enhance structural rigidity (Fig. 1).

Thermal and drying surface optimisation

Aluminium cladding: Both interior and exterior surfaces were lined with 0.5 mm-thick black aluminium sheets to improve thermal conductivity and durability.

Drying surface: Aluminium sheets and aluminium foil papers (1.6 m x 0.8 m) were installed, leaving a space of 0.12 m (base to roof) to serve as drying platforms.

Solar absorption enhancement: Black-painted aluminium tall list sheets were affixed to the roof surface to maximise solar irradiance absorption, increasing convective heat transfer to the product (Fig. 2a, b, c, and d).

Ventilation and airflow management

Passive ventilation: A rectangular vent (40 mm x 20 mm) was integrated into the rear panel, fitted with a stainless steel mesh (1mm aperture) to prevent insect ingress while allowing moisture egress (Fig. 1 and Figure 2a & b).

Active convection system: Two 12V DC axial fans (80 mm diameter, 0.8 m³/min flow rate) were mounted at the air inlet, powered by a 240W photovoltaic system (two 120W panels in parallel). Fan operation was regulated via independent switches to enable forced convection studies (Fig. 2d).

Thermal insulation and sealing

Perimeter sealing: Closed-cell polyethene foam (10 mm thickness) was applied at roof joints to minimise heat loss.

Weatherproofing: All external wooden surfaces were treated with water-resistant varnish to enhance durability under tropical conditions.

Dryer design rationale

The inclined roof geometry (≃7° pitch) was optimised for rainwater drainage and solar exposure (Fig. 2a & 2b). The 0.12 m product-to-roof clearance was determined through preliminary simulations to ensure adequate air circulation while maintaining thermal efficiency. Material selection was prioritised to optimise banana chip drying kinetics and ensure system drying efficiency. High solar absorptivity for black aluminium tall-list surfaces (Fig. 2b). Low thermal emissivity ($\varepsilon \simeq 0.03$) for aluminium foil paper and aluminium tall-list lined treatments used as drying surfaces.

Corrosion resistance for tropical deployment

This modular design systematically evaluates passive (T1-T2) and active (T3-T4) drying configurations while maintaining consistent chamber geometry across all treatments. The integrated instrumentation allows real-time temperature monitoring (±0.5 °C) and relative humidity (±2%) at multiple nodal points.

Experimental site and climatic conditions

The experiments were conducted in April 2024 in Nkambe, North West Region, Republic of Cameroon. Nkambe is located at a latitude of 6.2333°N and longitude 10.9833°E, approximately 1800 m above sea level, with an average temperature of 18 °C to 28 °C (64 °F to 82 °F) in April. April marks the beginning of the rainy season, with sunshine days lasting 10-14 days/month, wind speed of 10-14 km/h, and light to moderate breezes (Weather Atlas, 2024).

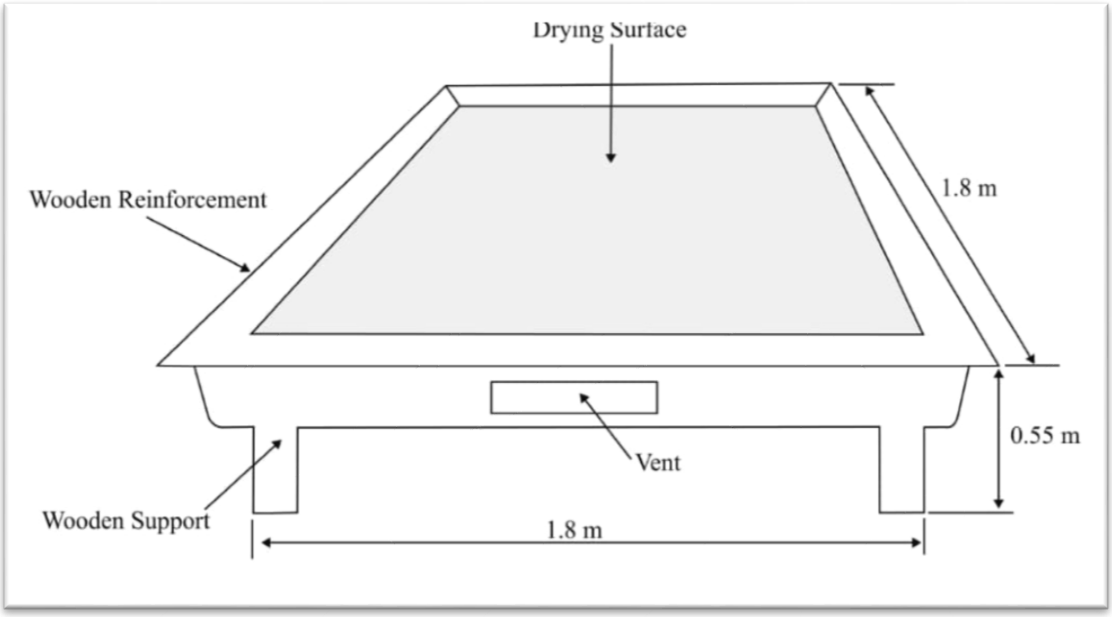

Figure 1: Structural Framework of Dryer Design

Figure 2a: Closed Dryer Design View

Figure 2c: Opened Dryer Design View

Figure 2b: Closed Dryer View

Figure 2d: Opened Dryer View Showing Position of Fan

Figure 2: Dryer Design and Construction

Treatments and experimental layout

Five distinct drying configurations were evaluated, which were arranged in a completely randomised design (CRD) in four replications: T1 (aluminum foil paper-lined drying surface, natural (passive) convection), T2 (aluminum tall-list drying surface, natural (passive) convection), T3 (aluminum foil paper-lined surface with (active) forced convection), T4 (aluminum tall-list surface with (active) forced convection) and T5 open-air ambient drying (control) on tarpaulin.

Measurement protocol

Banana chips preparation, drying, and milling

A modified protocol of Adeola et al. (2019) was used for the preparation of raw banana chips for drying. We purchased unripe bananas, separated the fingers, sorted, washed, and peeled them with a stainless steel knife. The peeled banana fingers were thinly sliced into 0.5 mm slices and were blanched for three minutes to destroy microbes and inactivate enzymes. Each chip was measured using a Vernier calliper to ensure uniform sizes. A given weight (5 Kg) was calculated for each treatment and loaded into the dryer for drying. The dried chips were milled into flour and stored under hermetic conditions. During drying, food safety protocols were maintained by sanitising all equipment and ensuring proper airflow to prevent moisture retention and mould formation. Sampling was conducted in accordance with strict hygiene standards, using sterilised tools and random, quadruplicate batches to ensure representative and uncontaminated results for quality assessment. Mass of water to be evaporated from fresh raw banana chips. The mass of water needed to be evaporated from fresh banana chips to ensure safe storage was calculated in accordance with Hussein et al. (2021), using the formula (equation 1):

$$mw = zp\frac{zi - zf}{100 - \mathrm{zf}} \qquad (1)$$

Where zp is the weight (initial) of the bananas (Kg), and zi and zf are the moisture content of bananas before and after drying (percentage wet bases), respectively. The initial moisture content of the banana chips was assumed to be 70% for mass loss calculations.

Dimension of Vent

The dimension of the vent was computed by dividing the air flow volume by the wind speed, as shown in Equation 2. (Etim et al., 2019)

$$Dimension\ of\ Vent\ (H) = \frac{\mathrm{VR}}{\mathrm{v}} \qquad (2)\ ,$$

Where H is the convection vent area, m^2, air velocity = v, m/s, and VR volume air flow rate, the length of the air vent (rectangular 2W; 2:1 ratio), was calculated using the formula, 2W x W=A.

Temperature and Humidity Measurement

The variation in ambient temperature, dryer internal temperature, and relative humidity was measured hourly with three Temperature/Clock/Humidity, HTC-1, sensors. Temperature and humidity sensors were calibrated prior to experiments using certified reference instruments in a controlled environment, with adjustments made to eliminate any deviations. A standard salt solution was used for humidity calibration at 75% RH, while boiling and ice-water points (100 °C and 0 °C) verified temperature accuracy, ensuring the reliability of the sensors during experimentation. The sensors were positioned at three different points in the drying medium to ensure accuracy.

Daily moisture loss

Daily moisture loss, ML was estimated using equation (3) in accordance with Umayal et al. (2013).

$$Daily\ Moisture\ Loss(ML) = \mathrm{zi} - \mathrm{zf} \qquad (3)$$

Where zi is the sample's weight (initial) and zf is the sample's weight (final). The weight (initial) of the banana chips was measured using a digital balance before and after drying. These chips were reweighed at four-hour intervals, from 8:00 AM to 4:00 PM daily. The results were then subtracted from the initial weight of the chips each day to obtain the daily moisture loss.

Drying Time (t)

Drying time was calculated according to the protocol used by Akoy & Hȍresten (2015) and modified. This was achieved by calculating the time (in hours) required for a given quantity of chips to reach a constant weight, measured every 4 hours.

Drying rate

Drying rate, DR, was evaluated by taking the moisture loss by heat waves within the dryer over time taken for the moisture loss and was estimated using (Akoy & Hȍresten 2015) and modified, shown in equation 4;

$$Drying\ Rate\ (DR) = \frac{\mathrm{zi} - \mathrm{zf}}{\mathrm{t}} \qquad (4)$$

zi is the weight of chips before drying, zf is the mass of chips after dehydration, and t is the drying period.

This was done for each batch of chips dried from April 6th to 24th, 2024.

Economic analysis of dryer designs

Mbakouop et al. (2025) protocol was employed to conduct an economic analysis of the dryers. The lifetime cost (LTC) and long-term gains (LTG) of the dryers under study were calculated to assess the economic viability of the systems. Furthermore, the economic payback period (PBP) of the various dryer designs was calculated to determine the economic feasibility of each drying system. Rana et al. (2024) protocol on LTC was used as in equation 5.

$$LTC = \mathrm{IC} + (\mathrm{MC\ x\ n}) + (\mathrm{OC\ x\ n}) \quad (5)$$

Where, IC = Initial Cost, MC = Maintenance Cost, Maintenance Cost = 10 % of Initial Cost, OP = Operational Cost, = 0 (Since solar dryers have no fuel/electricity cost), n = Life Span = 6 Years.

Long-term gains (LTG) computed in accordance with the protocol by Singh et al. (2017), denoted as in equation 6:

$$LTG = \text{Annual profit x n (Life Span)} \quad (6)$$

Where Annual profit is designated as (eqn. 7):

Annual profit=Revenue per batch–Input cost per batch x batches per year (7)

The payback period (PBP) was calculated using the formula (8).

$$\text{Payback Period} := \frac{\text{Initial Cost}}{Annual\ Profit} \quad (8)$$

Data analysis and calculations

The data obtained (four replications) were analysed using ANOVA in SPSS Version 20 and Excel 2016 software. Significantly different means were subjected to Least Significant Difference (LSD) for separation at a 95 % confidence level. Treatments with similar scores following LSD were subjected to Tukey Honestly Significant Difference (HSD). Results were presented on charts and tables. Calculations were carried out using standard formulae and methods. Calculations for the quantity of moisture that must be removed during drying and Vent Dimension are attached as a supplementary file.

Results and Discussions

Drying temperature and humidity

The temperature, humidity, and weight of drying chips were taken for treatments T1 to T5. T1 was an aluminium foil paper drying surface without fanning, T2 used an aluminium tall list drying surface, T3 used an aluminium foil drying surface with fanning, and T4 used an aluminium tall list drying surface with fanning. The control was a normal drying surface composed of tarpaulin (Fig. 3). Drying performance parameters for banana chips were measured from April 6th to 24th, 2024, to assess their impact on dryer design.

Temperature changes

The impact of dryer design configuration on ambient and drying medium temperature changes was determined. The drying medium reached a maximum temperature of 53.1 ± 0.058 °C, as illustrated in Figure 4 (drying medium lined with aluminium foil paper, T1). Küpper (2024), Akomolafe et al. (2021), and Simate et al. (2025) recorded temperatures within this range in various dryer designs. The high temperature achieved by the aluminium foil paper drying surface is consistent with findings by Maiti et al. (2011) on reflective surfaces, who suggested that reflective surfaces enhance solar absorption. T1 to T4 had higher drying temperatures compared to the control, with a range of 26.3±0.173 °C to 53.1±0.058 °C, with peaks at 48±0.816-53.1±0.058 °C, while the control was 26.2±0.115 °C to 30±0.816 °C (Fig.4 - Fig.8). The temperature range observed was also comparable to that of Zhao et al. (2022). The higher internal temperature of 53.1±0.058 °C in aluminium-based treatments (T1-T4) aligns with 54 °C reported by Admass et al. (2024) in aluminium can-based dryers. Aluminium surfaces improve thermal efficiency by reducing heat loss. The differences recorded in most cases between ambient and drying temperatures of more than 10 °C**,** with a maximum difference of 21.1 °C, were commensurate with observations by Kondrareddy et al. (2021), who reported temperature differences between drying medium and ambient conditions ranging from a minimum of 15% to a maximum of 18%. This temperature increase significantly impacted the study's banana chip drying process**.**

Humidity

The humidity ranged from a minimum of 19% ± 1.08% to a maximum of 52% ± 3.916%, as shown in Figures 4-8. Humidity fluctuations (19±1.08 % to 52±3.916%) are typical in natural convection dryers (Guo et al., 2024), which affect drying kinetics. Lower humidity coincided with peak drying temperature, and high humidity with low drying temperature. The lower humidity (19±1.08%) during peak drying hours correlates with faster moisture removal, as reported by Simate et al. (2025) and Zhao et al. (2023) for various dryer designs.

Figure 3: Pictorial view of treatments and initial banana chips drying stock, Trmt = Treatment

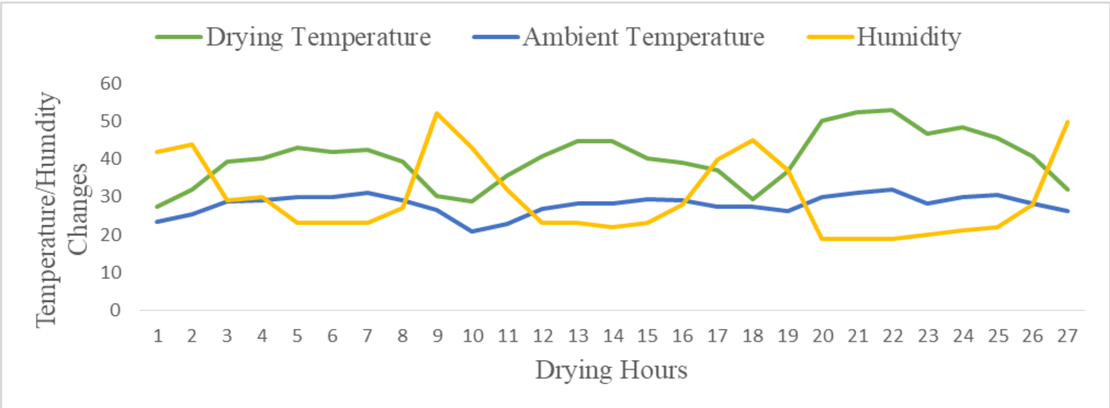

Figure 4: Temperature/Humidity changes during drying period of T1. Values are represented as mean ± standard error in quadruplets.

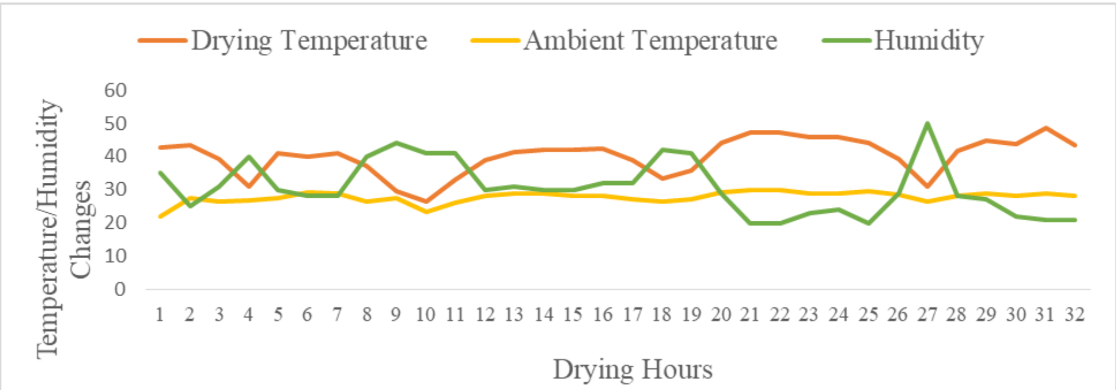

Figure 5: Temperature/Humidity changes during drying period of T2. Values are represented as mean ± standard error in quadruplets.

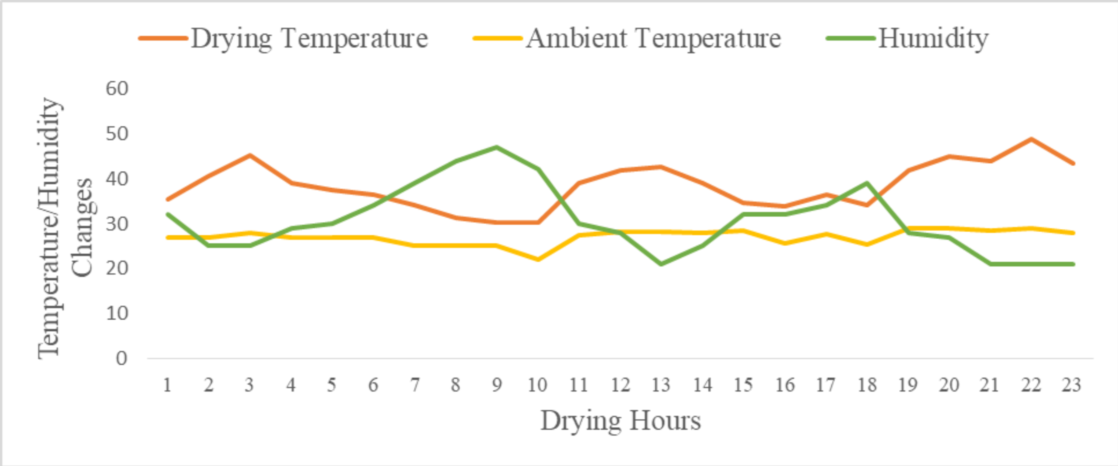

Figure 6: Temperature/Humidity changes during drying period of T3. Values are represented as mean ± standard error in quadruplets.

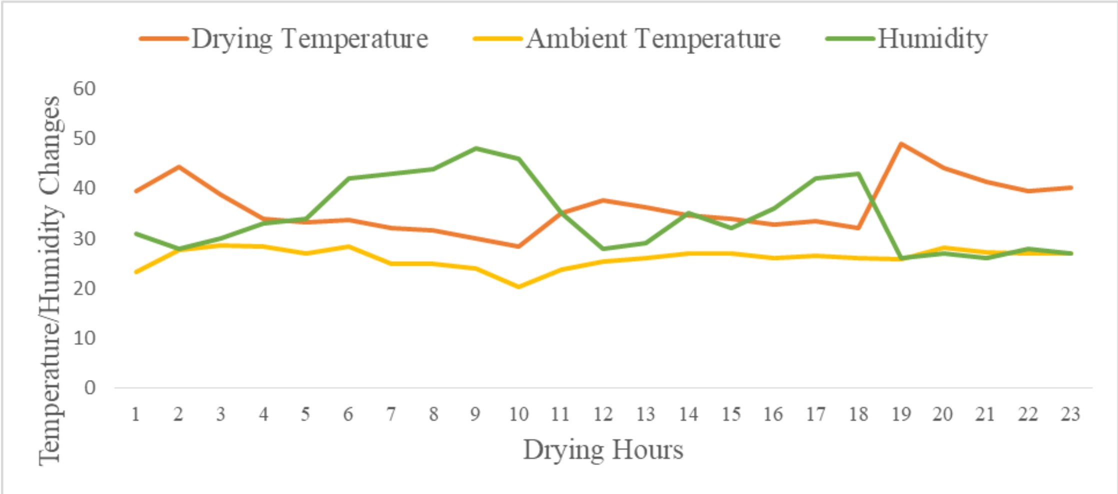

Figure 7: Temperature/Humidity changes during drying Period of T4. Values are represented as mean ± standard error in quadruplets.

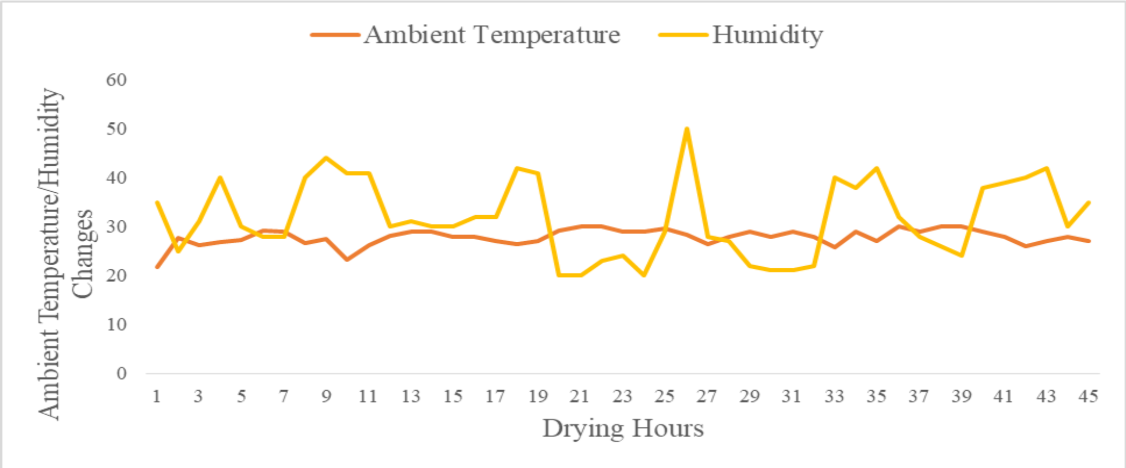

Figure 8: Ambient Temperature/Humidity changes during the drying period of T5 (Control). Values are represented as the mean ± standard error in quadruplets.

Daily moisture loss

The daily moisture loss was affected by the type of dryer design used ($p < 0.05$) and the difference was extreme ($F_{(4,15)} = 13.14$, $p = 0.0005$) across days (Table 1). T3 (Aluminium foil surface without a fan) showed higher moisture loss on the first day of drying compared to the other treatments. There was, however, a sharp drop in moisture loss on the second and third day for T3 (Table 1). The sharp drop in moisture loss on Day 1 for T3 (61±4.708 **g)** suggests rapid initial dehydration. Tyona & Ojiya (2020) reported the same trend. Forced airflow (from fans) disrupts boundary layers, thereby accelerating moisture transfer. The control (T5) revealed the slowest moisture loss for the five days of drying and recorded the lowest mean moisture loss (Table 1). This was likely due to low drying temperature and high humidity. All the treatments lose more water across days than the control (Table 1). The final moisture content (1.677–1.886 Kg) aligns with that reported by Tyona & Ojiya (2020), who linked rapid drying to better texture and nutrient retention.

Drying time and rate

Drying time

Values are represented as mean ± standard error in quadruplets. Values in the same column with different letters show significant differences (p<0.05). T1 (aluminium foil paper-lined drying surface, natural (passive) convection), T2 (aluminium tall-list drying surface, natural (passive) convection), T3 (aluminium foil paper-lined surface with (active) forced convection), T4 (aluminium tall-list surface with (active) forced convection) and T5 open-air ambient drying (control) on tarpaulin.

Dryer designs significantly impacted the drying time of banana chips ($F(4,15) = 32.5$, $p < 0.001$). Overall, all treatments (T1-T4) performed better than the control (T5). T4 and T3 with 20±2.16 hours drying time each, and T1 with drying time of 24±2.16 hours registered a reduction in drying time by 50 % and 40 % respectively compared to the control (Fig. 9). The observations for T3 and T4 align with Küpper (2024), who reported the same results using 12 volts' fan in active dryer designs and Guo et al. (2024) for pulsed fluidised bed dryers. These results were comparable to those of Zhao et al. (2023), who reported a reduction in drying time in the 51% to 81% range for microwave-assisted drying. The fan-assisted drying systems' air removes moisture from the drying medium. Moisture was noticed on the drying surface of natural passive dryer designs without an aluminium foil paper reflective surface (Fig. 9).

Table 1: Variation in Moisture Loss Among Treatments By Days (R1-R5), R=Day, ML = Moisture Loss.

Treatment	R 1	R 2	R 3	R 4	R 5	ML Mean
T1	48±2.63[b]	19±1.08[a]	7±0.629[b]	-	-	24.67±1.546[a]
T2	45±3.189[b]	18±1.633[a]	11±1.25[a]	3±0.854[b]	-	19.25±0.871[bc]
T3	61±4.708[a]	13±1.08[b]	2±0.707[c]	-	-	25.3±0.672[a]
T4	45±7.948[b]	21±1.08[a]	1±0.408[c]	-	-	22.33±1.037[ab]
T5	35±2.483[c]	15±1.225[b]	12±0.817[a]	10±0.817[a]	7±0.629[a]	15.8±1.372[c]
GM	46.8	17.2	6.6	6.5	7	21.47
SEM	1.23	0.87	0.65	0.71	0.82	1.092
LSD	4.12	3.45	2.89	3.01	3.22	3.44
PαF	<0.001	<0.001	0.002	0.015	>0.05	0.0005
F-value (4,15)	12.25	12.34	6.36	3.8	4.56	13.14
SD	**	**	**	*	NS	**

Figure 9: Moisture on Aluminium Tall List Surface with No Fan and No Foil Paper

Although the drying time for T1 (24±2.16 hours) was comparable to that of T3 (20±2.16 hours) and T4 (20±2.16 hours), it was not significantly different from the drying time of T2 (28±1.414 hours), which was lower than the control's 40±2.16 hours. T2 represents a 30 % decrease in drying time compared to the control. Yan et al. (2023) reported that aluminium-based drying surfaces improved heat retention, resulting in a reduction in drying time compared to mesh trays. Conversely, Salhi et al. (2022) reported that **porous** aluminium trays dried food faster than unperforated aluminium trays. This could be due to differences in solar intensity, dryer insulation, climatic conditions, or possibly because the porous surfaces prevent water accumulation on trays.

Drying rate

Drying rate was measured among the treatments to determine the fastest drying design. Dryer designs significantly affected the drying rates of the treatments

($F(4,15) = 12.45$, $p < 0.0001$). Mujumdar & Law (2010) reported that dryer design has a significant impact on moisture removal efficiency. Treatments T3 and T4 had the highest drying rate (Table 2). The high drying rate of T1-T4 compared to the control was due to the high temperatures within the drying medium, resulting from heat trapped by the black aluminium roof surface on the dryer, combined with the aluminium reflective drying surfaces. Control (T5) had the slowest drying rate ($0.08005 \pm 1.22 \times 10^{-5}$Kg/h).

Table 2: Calculations of Drying Rate Over Time/Hours Between T1–T5

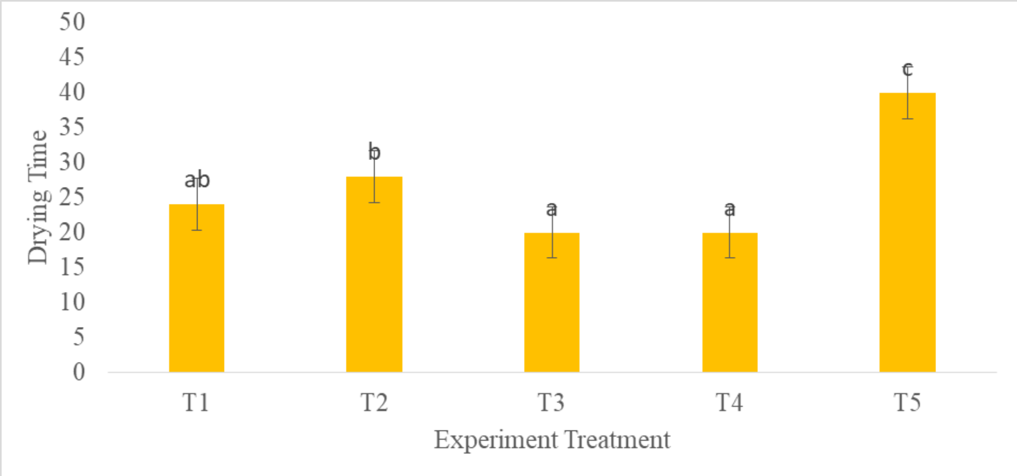

Figure 10: Drying Time for Treatments and Control Drying Parameters.
Values are represented as mean ± standard error in quadruplets. Values in the same column with different letters show significant differences (p<0.05). T1 (aluminium foil paper-lined drying surface, natural (passive) convection), T2 (aluminium tall-list drying surface, natural (passive) convection), T3 (aluminium foil paper-lined surface with (active) forced convection), T4 (aluminium tall-list surface with (active) forced convection) and T5 open-air ambient drying (control) on tarpaulin.

Treatment	zi/Kg	zf/Kg	$zi - zf$	$\frac{zi - zf}{td}$
T1	5	1.886	3.114	$0.1297 \pm 4.08 \times 10^{-5b}$
T2	5	1.677	3.323	$0.11868 \pm 4.08 \times 10^{-5c}$
T3	5	1.776	3.224	$0.1612 \pm 6.45 \times 10^{-5a}$
T4	5	1.876	3.124	$0.1562 \pm 8.16 \times 10^{-5a}$
T5	5	1.798	3.202	$0.08005 \pm 1.22 \times 10^{-5d}$
Grand Mean	-	-	-	0.1309
LSD	-	-	-	0.00018
SEM	-	-	-	0.0000577
PαF	-	-	-	<0.0001
F-value (4,15)				12.45
SD				**

Values are represented as mean ± standard error in quadruplets. Values in the same column with different letters show significant differences (p<0.05). T1 (aluminum foil paper-lined drying surface, natural (passive) convection), T2 (aluminium tall-list drying surface, natural (passive) convection), T3 (aluminium foil paper-lined surface with (active) forced convection), T4 (aluminium tall-list surface with (active) forced convection) and T5 open-air ambient drying (control) on tarpaulin.

Fan-Assisted Drying (T3 and T4) achieved the highest drying rates ($0.1612 \pm 6.45 \times 10^{-5}$ and $0.1562 \pm 8.16 \times 10^{-5}$Kg/h, respectively), which aligns with the results of Zhang et al. (2023) on hybrid drying but were higher than values reported by Admass et al. (2024).
In contrast to our results, Küpper (2024) observed that open-air drying with fans had the highest drying rates, followed by open-air without a fan, then NDM, while ODM showed the least drying rate. Akomolafe et al. (2021) also occasionally observed similar drying rates between open-air drying and two dryer designs for fermented cassava and cassava chips. This could be attributed to the seasonal nature of experimentation.

Economic evaluation

Our study also evaluated the economic viability of four solar dryer designs (T1–T4) using lifetime cost (LTC), long-term gains (LTG), and payback period

(PBP) analysis (Tables 3-7). Our findings revealed a highly significant difference in economic analytical characteristics (F(3,12) = 13.45, p < *0.001)* between dryer systems (Table 7). The dryer system T2 (Aluminium tall list, no fan), as shown in Table 6, offered the fastest payback time (26 days), while T4 (Aluminium tall list with fan) yielded the highest net profit (4,767,200 CFA). Gohain & Dutta (2025) reported that the least PBP was six months compared to 26 days in our study, for passive solar dryers in East Africa. This places our passive design among the cheapest solar designs for smallholder farmers and small-scale banana processors. Furthermore, in our study (T3 and T4), the fan-assisted drying with 110 days PBP was also lower than that of passive dryer designs in Eastern Africa. Rana et al. (2024) found that fan-assisted dryers had PBPs of 90-120 days, closely matching our results (110 days). The slide difference can be explained by the fact that solar radiation intensity and drying time vary by region. On the contrary, other researchers reported higher PBPs. Srivastava et al. (2022) and Mbakouop et al. (2025) reported PBPs of 18 months each, while Simate et al. (2025) reported 43 months for a maize dryer.

Table 3: Cost Description of Items Used in Dryer Construction

Item Used	CT1(CFA/USD)	CT2(CFA/USD)	CT3(CFA/USD)	CT4(CFA/USD)
Solar Battery (12V, 100AH)	-	-	90,000/162	90,000/162
Converter (DC 5V)	-	-	25,000/45	25,000/45
2 Solar Panel (120W)	-	-	60,000/108	60,000/108
Inverter (DC 12V, 500A)	-	-	20,000/36	20,000/36
2 DC Fans (0.5 A)	-	-	10,000/18	10,000/18
Black Tall List (6m)	9,000/16.2	9,000/16.2	9,000/16.2	9,000/16.2
Panel Cables (10m)	10,000/18	10,000/18	10,000/18	10,000/18
2 Switches	-	-	1,000/1.8	1,000/1.8
Wood (10 planks)	15,000/27	15,000/27	15,000/27	15,000/27
Nails	5,000/9	5,000/9	5,000/9	5,000/9
Aluminum Tall list (2m)	3,000/5.4	3,000/5.4	3,000/5.4	3,000/5.4
Aluminum Foil	2,500/4.5	-	2,500/4.5	-
Banana Chips	1,000/1.8	1,000/1.8	1,000/1.8	1,000/1.8
Zinc Gum	5,00/0.9	5,00/0.9	5,00/0.9	5,00/0.9
Labour Cost	8,000/14.4	7,000/12.6	10,000/18	9,000/16.2
Total	54,000/97.2	50,500/90.9	262,000/471.6	260,500/468.9

Available Information/Assumptions for Calculations
Initial Load: 5000 g (Cost = 1000 CFA)
The weight of chips gives the same weight of flour
Final Flour Weight**:**1700 g
Selling Price: 500 g of flour (sold in the market) at 1000 CFA
1700 g of flour will cost 3400 CFA
Profit per Batch**:** 3400−1000=2400 CFA
Lifespan (**n)**: 6 years
Operational Days/Year**:** 300 (assuming solar availability)
Maintenance Cost (MC)**:** 10 % of IC per year

Table 4: Calculations on Number of Batches/Year

Dryer	Drying Time/Hours	Batches/Day	Batches/Year(x300)	Annual Profit/CFA
T1	24	$\frac{24}{24} = 1$	300	2400x300=720,000
T2	28	$\frac{24}{28} = 0.857$	257	2400x257=616,800
T3	20	$\frac{24}{20} = 1.2$	360	2400x360=864,000
T4	20	$\frac{24}{20} = 1.2$	360	2400x360=864,000

Table 5: Calculations on Life Time Cost (LTC) and Long Term Gains (LTG)

Dryer	IC/CFA	MC(10 % of IC x 6)	LTC/CFA	LTG/CFA
T1	54,000	32,400	86,400	616,800x6 =3,700,800
T2	50,500	30,300	80,800	720,000x6 = 4,320,000
T3	262,000	157,200	419,200	864,000x6 = 5,184,000
T4	260,500	156,300	416,800	864,000x6 = 5,184,000

Table 6: Calculations on Payback Time

Dryer	IC/CFA	Annual Profit (CFA)	PBT (Years)	PBT (Days)
T1	54,000	616,800	0.088	≃32 Days
T2	50,500	720,000	0.07	≃ 26 Days
T3	262,000	864,000	0.3	≃ 110 Days
T4	260,500	864,000	0.3	≃ 110 Days

Table 7: Economic Analysis Characteristics Used to Determine Economic Viability of Dryers

Dryer	LTC/CFA	LTG(CFA)	Net Profit (LTG-LTC)	PBT (Days)
T1	86,400	3,700,800	3,614,400	≃32 Days
T2	80,800	4,320,000	4,239,200	≃ 26 Days
T3	419,200	5,184,000	4,764,800	≃ 110 Days
T4	416,800	5,184,000	4,767,200	≃ 110 Days
Grand Mean	250,800	4,572,200	4,346,400	≃ 69.5 Days
PαF	<0.001	<0.001	<0.001	<0.001
F-values(3,12)	28.6	35.2	30.8	32.1
SD	**	**	**	**

Our LTC for T3 (419,200 CFA) is lower compared to the observations of Srivastava et al. (2022), reported for mixed solar dryers. This difference may stem from local material cost variations due to the use of imported solar panels, whereas our study sourced local materials, thereby lowering costs. The economic analysis values suggest that our design is low-cost and can be a paramount factor in reducing postharvest losses in bananas, making it a promising option for smallholder farmers and low-income processors.

Conclusion

The study demonstrates that solar-assisted drying significantly reduces banana chip drying time by 50% (20 hours versus 40 hours) compared to open-air drying. In contrast, fans improve drying rates; aluminium foil paper surface (even without a fan) recorded maximum temperature (53.1 °C) and can achieve comparable efficiency, likely due to better heat absorption. Researchers should consider local climate, material conductivity, and airflow design when optimising dryers for banana chips for flour. Processors can adopt T1, T2, T3 or T4 designs for faster and more efficient drying, thereby reducing postharvest losses. Passive dryer (T2) is optimal for short-term return on investment (26-day PBP) compared to 110 days for T3 and T4. Fan-assisted dryer (T4) maximises long-term profitability (4.760,000M CFA net profit).

Further studies could explore hybrid designs, comparing the unperforated aluminium drying surfaces in our study to perforated aluminium trays with fans to balance energy use and drying speed. Sensitivity analysis of maintenance costs, for example, involves performing an economic analysis with 5% compared to 10% in our study. This work contributes to optimising low-cost solar dryers for banana chips to produce flour, particularly in regions with fluctuating humidity.

The study was limited because the aluminium reflective surfaces were not perforated, which might have affected the drying process. The climatic conditions under which the research was conducted are unique, posing a problem with generalising the results. Additionally, a fixed maintenance cost of 10% was applied in the economic analysis, which may impact real-time results.

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