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ENGINEERING

DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING

**DESIGN AND PERFORMANCE EVALUATION OF A FRUIT SOLAR DRYER FOR
SMALLHOLDER FARMERS**

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**A PROJECT REPORT SUBMITTED TO THE DEPARTMENT AS A PARTIAL
FULLFILLMENT FOR THE AWARD OF BACHELOR OF SCIENCES IN WATER AND
IRRIGATION ENGINEERING**

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DECLARATION

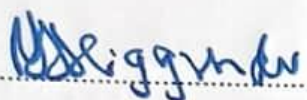
I **BABIRYE CAROLINE** hereby declare to the best of my knowledge that the information contained in this report was compiled based on the knowledge acquired through genuine involvement in research under the guidance of my supervisors and thus is my own work that has not been submitted to any institution for the award of any kind. I have therefore duly referenced any other sources.

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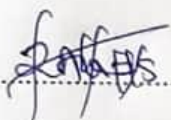
APPROVAL

This is to certify that Babirye Caroline has completed her final year project report as partial fulfilment for the Award of a Bachelor of science in Water and Irrigation Engineering and has been approved by the department supervisors.

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ABBREVIATIONS

PHL	Post-Harvest Losses
FAO	Food and Agriculture Organization
CAD	Computer -Aided Design
SMER	Specific Moisture Extraction Rate
MC _i	Initial Moisture Content
MC _f	Final Moisture Content
RH	Relative Humidity
PWM	Pulse Width Modulation
w.b	wet basis
DM	Dry matter
PV	Photovoltaic
DHT 22	Digital Humidity and temperature sensor, model 22
LCD	Liquid Crystal Display
DC	Direct Current
NDP	National Development plan
PCM	Phase change material
SDG	Sustainable Development goals
Amb. T	Ambient Temperature

ABSTRACT

Uganda experiences post-harvest fruit losses of up to 50% due to inadequate storage facilities, poor handling practices, and limited access to affordable preservation technologies, resulting in economic losses, reduced household incomes, and food insecurity. While many try to dry fruit in the open sun, the process is frustratingly slow and often leaves the food contaminated by dust and insects, although commercially available dryers are often too expensive and energy-intensive for smallholder farmers. To address this, I designed and fabricated a forced -convectonal solar dryer that uses low-cost automation to create a controlled drying environment. I built the system specifically to handle 2 kg batches of pineapple focusing on reducing moisture content from 85% (wet basis) to 12% or less. Unlike conventional solar dryers, the proposed design integrates sensor-based automation using an Arduino Uno microcontroller, DHT22 temperature and humidity sensor, PWM-controlled DC fans and a standalone solar photovoltaic power supply enabling automatic regulation of drying conditions without reliance on grid electricity. The dryer was designed using Computer Aided Design modelling and thermal-airflow simulations and fabricated from locally available materials to enhance affordability and replicability. Performance evaluation under Ugandan climatic conditions demonstrated that the system reduced pineapple moisture content from 85% to 12% within 16 hours, representing a 50% reduction in drying time compared to open-sun drying. The dryer maintained an average chamber temperature of 50°C and relative humidity below 60%, achieving a mean thermal efficiency mean thermal efficiency $7.8 \pm 2.6\%$, mean SMER 0.109 ± 0.036 kg/kWh; and water activity 0.52 ± 0.02 (< 0.60 shelf-stability threshold), while producing cleaner, more uniformly dried fruit with improved colour retention and texture. These results demonstrate the potential of the proposed automated forced-convection solar dryer as an affordable, sustainable, and scalable solution for reducing post-harvest fruit losses among smallholder farmers.

CHAPTER 1 : INTRODUCTION

1.1 Background

Globally, 30-40% of fruits and vegetables are never eaten but are instead lost to damage or spoilage after harvest as Food and Agriculture Organization (FAO, 2021). To avoid post-harvest losses, farmers must immediately sell their produce at any price before it spoils, despite their investments. Uganda is endowed with a variety of fruits including mangoes, pineapples, bananas, jackfruit. Kagoro-Rugunda and Sebuuwufu (2023) noted that 70% of pineapple is eaten fresh since there is limited value addition to pineapple. Balamaze et al. (2019) found that the average annual yield of jackfruit was 50-80 tons per hectare, Ddamulira et al. (2019) says mango yields are still below 5.8-ton ha⁻¹. According to (Lee, 2023), the current annual yields of bananas range from 5-30 tons per ha which flourish across its diverse Agroecological zones. Rubagumya et al. (2023) and FAO (2021) realized that despite the abundance, a massive portion of harvested fruit goes to waste due to inadequate post-harvest handling and lack of preservation infrastructure. Post-harvest losses are still one of the major challenges faced by smallholder farmers and fruit traders in Uganda. Currently, the Food and Agriculture Organization of the United Nations (FAO) estimates that Post Harvest Loss (PHL) can reach as 50% (FAO, 2019) of harvested fruits due to poor handling, inadequate storage, and lack of affordable preservation technologies.

In Uganda, highly perishable fruits often go to waste during peak harvest seasons when supply exceeds demand. Traditional preservation methods in figures 1,2 and 3 have been used, however, limitations including reliance on solar radiation, lack of ability to control the drying process, degradation due to microbiological reactions, insect infestation, leading to low-quality products and health risks for consumers.

Modern drying technologies such as hybrid dryers, conventional dryer (figure 4), electrical dryer (figure 5) exist, but they are costly, energy-intensive to rural communities (Aduewa et al., 2022; Kant et al., 2016; Rulazi et al., 2023). This creates a need for affordable and energy-efficient fruit drying systems that can enhance value addition, reduce post-harvest losses, control drying processes, reduce physical contamination and improve household incomes.

1.2 Problem Statement

An estimated 30–50% of Uganda's annual fresh fruit and vegetable harvest (by weight) is lost before it reaches the consumer, a figure driven predominantly by inadequate handling, storage, and insufficient technology adoption among smallholder farmers who constitute most of the agricultural workforce (FAO, 2021). While Uganda is blessed with an abundance of pineapples, mangoes, and bananas, I have observed personally a heartbreaking amount of waste in markets like Nakasero in Kampala and Mukono markets, where up to 50% of these fruits spoil before they can be sold. Smallholder farmers, who form the backbone of our economy, are often forced to sell their harvest at a loss just to avoid total rot because they lack access to affordable preservation tools (Boiteau & Pingali, 2025). Many producers still rely on rudimentary open ground drying which is not a solution, which is frustrating and exposes fruits to discoloration, microbial contamination, dust, and insect damage, resulting in a low-quality product that is hard to market. This project seeks to bridge that gap by building a reliable, automated system that a rural farmer can actually afford and use independently.

Although solar and hybrid solar-biomass dryers have been developed as affordable alternatives to grid-powered systems (P. Devan et al., 2020), many low-cost designs still struggle to maintain stable drying conditions. Limited temperature regulation, poor airflow control, and the absence of automated monitoring often result in uneven drying and reduced product quality, particularly under changing weather conditions. Forced convection has been demonstrated to outperform natural convection in solar dryers by increasing the heat exchange rate between the drying air and the product (Phadke et al., 2015), yet sensor-actuated, PWM-controlled forced-convection dryers built from local materials and powered by photovoltaic panels remain largely unavailable to Ugandan smallholders at an accessible price point. This study therefore addresses the gap by designing, fabricating, and evaluating a PV-powered, Arduino-controlled forced-convection solar cabinet dryer. A solar cabinet dryer was constructed from locally sourced materials for approximately UGX 738,000 capable of reducing pineapple moisture content from 85% to $\leq 12\%$ (wet basis) within 16 hours, offering a reproducible, weather-resilient, and scalable post-harvest solution for rural fruit producers.

1.3 Objectives

1.3.1 Main Objective

To develop a fruit dryer capable of reducing the moisture content and tested on pineapples to levels suitable for preservation and consumption for smallholder farmers.

1.3.2 Specific Objectives

1. To develop a Computer Aided Design Model of the fruit dryer that uses solar energy.
2. To fabricate/ construct the fruit solar dryer.
3. To evaluate the performance of the fruit drying system in terms of efficiency, drying time and product quality.

1.4 Justification

This project is justified by the pressing need to reduce fruit wastage and improve food preservation in Uganda. By introducing a reliable drying system, communities can extend the shelf life of fruits, improve nutrition, and generate income through selling dried products. The use of locally sourced materials and renewable energy options (e.g., solar) makes the system environmentally friendly and economically viable. Furthermore, the project aligns with national development goals related to agriculture, food security, and rural empowerment. Its implementation will not only address a technical challenge but also contribute to social and economic resilience.

1.5 Significance of the study

This study contributes to reducing post-harvest losses among smallholder fruit farmers in Uganda by constructing and evaluating an affordable forced convection solar fruit dryer that utilizes locally available materials and renewable energy. The developed dryer provides a practical value-addition technology capable of preserving surplus fruits, reducing spoilage, extending shelf life, and improving household income through the production of marketable dried fruit products.

The study also contributes to the advancement of solar drying technology by integrating forced convection and sensor-based temperature and humidity control. The generated design specifications, fabrication procedures, and performance evaluation results provide useful reference information for researchers, engineers, students, and manufacturers interested in developing efficient and low-cost solar drying systems. The findings also demonstrate the

potential of renewable energy technologies to improve product quality, reduce drying time and enhance food safety compared to traditional open-sun drying methods. The findings may assist government agencies, agricultural extension services, development partners, and farmer organizations in promoting appropriate post-harvest technologies that enhance food security, increase value addition, and improve rural livelihoods.

CHAPTER 2 LITERATURE REVIEW

2.1 Food Security Challenges and the Role of Fruit Dehydration Technologies

Besides the socio-economic and environmental challenges, the world is facing nowadays, the population of the world is projected to reach around 9.7 billion within the next three decades (Fertahi et al., 2021). According to projections from the United Nations and the Food and Agriculture Organization (FAO), the need for food production must rise by 70% to feed this anticipated population by 2050 (Divyangkumar & Panwar, 2024). This exponential demographic growth brings to the table the challenges for the global food supply, especially fruits and vegetables. In the world's total market share, the production and consumption of fruits and vegetables account for 85% (Mostafidi et al., 2020). Due to high levels of fiber, fruits' nutritional benefits, and utmost role in the human body, the demand has tremendously increased in many countries worldwide. A minimum daily intake of 400g of fruits and vegetables recommended by the World Health Organization (WHO) can prevent noncommunicable, obesity, high blood pressure, eye diseases, and help to fight against food insecurity, lifestyle diseases, and malnutrition (Ngueagni et al., 2025). Moreover, the consumption of fruits and vegetables may contribute to the decrease in food-borne disease outbreaks, especially in developing countries (Mostafidi et al., 2020). In many developing countries, including Uganda, smallholder farmers experience substantial post-harvest losses due to poor handling practices, inadequate storage facilities, and limited access to preservation technologies (Kilelu et al., 2024). Studies have shown that a significant proportion of harvested fruits and vegetables deteriorate before reaching the market because of mechanical damage, microbial spoilage, and exposure to unfavorable environmental conditions during handling and transportation (Apil, 2025; Baidhe et al., 2021). These challenges require the urgent need for appropriate post-harvest technologies, such as fruit dryers to extend shelf life and enhance value addition within smallholder farming (Adeyeye et al., 2022; Khuje, 2017; Raponi et al., 2017a).

Table 2-1 Existing solar dryer Technologies



Figure 2-1 Static bed box solar dryers (Kiggundu 2016)



Figure 2-2 Improved cabinet dryer



Figure 2-3 Solar tunnel dryer (Mali & Butale, 2019)



Figure 2-4 Electric dryer (Efendi et al., 2019)

CHAPTER 3 METHODOLOGY

3.1 System Design Approach

The study adopted an experimental design approach involving the design, fabrication, and performance evaluation of a forced-convection solar cabinet dryer. The system was designed to utilize solar thermal energy for drying fruits, tested on pineapple slices, under controlled temperature and humidity conditions.

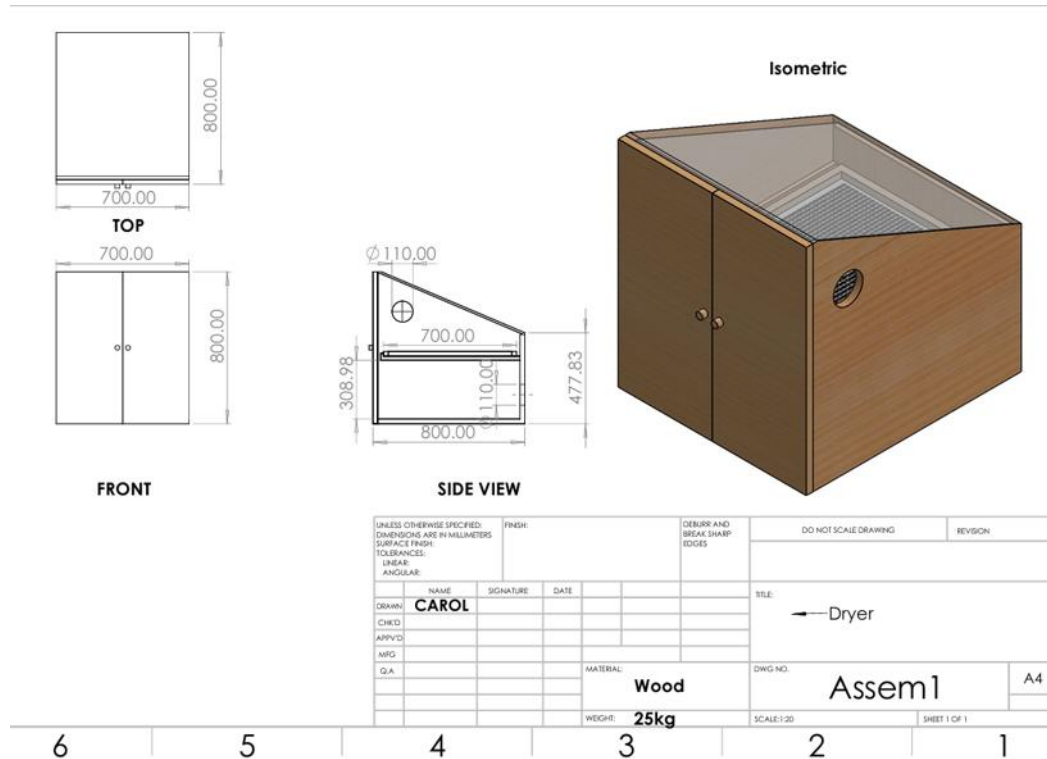


Figure 3-1 Isometric drawing for solar dryer

Table 3-1 Some activities carried out during construction of the solar dryer



Figure 3-2 Caroline cutting wood form in the carpentry workshop



Figure 3-3 Caroline joining the cabinet



Figure 3-4 Constructed solar dryer

3.2 Design and theoretical analysis

3.2.1 Design consideration

1. Temperature - The minimum temperature for drying food is 35°C and the maximum temperature is 65°C, therefore. 50°C and above is considered average and normal for drying fruits.
2. The design was made for the optimum temperature for the dryer. T_0 of 65°C and the air inlet temperature or the ambient temperature of dryer was $T_1 = 30^\circ\text{C}$ (approximately outdoor temperature).
3. Efficiency - This is defined as the ratio of the useful output of a product to the input of the product
4. Air gap – It is suggested that for hot climate passive solar dryers, a gap of 10 cm should be created as air vent (inlet) and air passage
5. Glass and flat plate solar collector – It suggested that the glass covering should be 3-5mm thickness. In this work, 3mm thick transparent glass was used. It also suggested that the metal sheet thickness should be of 0.5 – 1.0mm thick
6. Dimension – It is recommended that a constant exchange of air and a roomy drying chamber should be attained in solar food dryer design, thus the design of the drying chamber was made as spacious as possible of average dimension of $0.8 \times 0.7 \times 0.5\text{m}$ with air passage (air vent) out of the cabinet of 120X120X25mm
7. Dryer Trays – Net(metal) was selected as the dryer screen or trays to aid air circulation within the drying chamber. A single tray was made of metal net. The tray dimension is $0.75 \times 0.6\text{ m}$
8. Exhaust fan of 12v is used to remove the air from the drying chamber

The design of the drying chamber making use of wooden wall sides and a top protects the food to be placed on the trays from direct sunlight since this is undesirable and tends to bleach color and removes flavor and causes the food to dry unevenly

3.2.2 Design Specifications and Criteria

The dryer was designed based on the drying requirements of pineapple, considering moisture removal, drying time, and environmental conditions. The following parameters guided the design:

- Batch capacity: 2.0 kg of fresh pineapple
- Slice thickness: 5 mm
- Initial moisture content: 85% (wet basis)
- Final moisture content: 12% (wet basis)
- Desired drying time: 12 hours
- Average solar irradiance: 580 W/m²
- Ambient temperature: 30°C
- drying temperature: 50–60°C

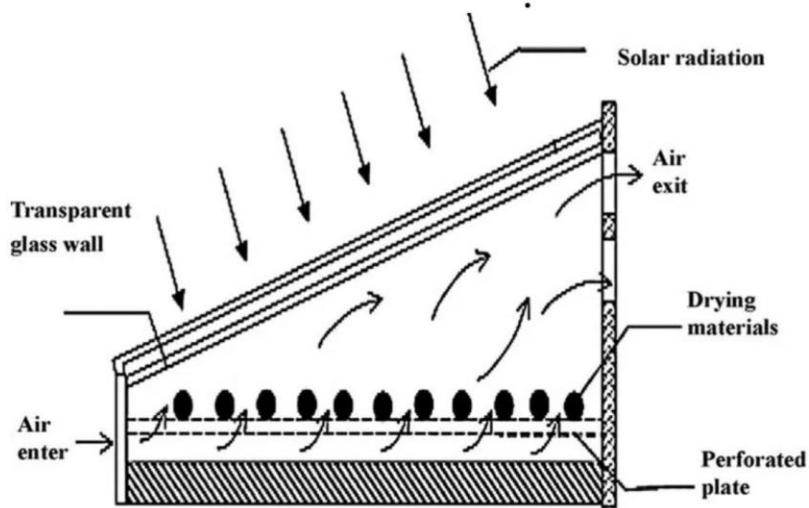


Figure 3-5 Schematic drawing for the solar dryer (Saleh et al., 2017)

3.2.3 Design Calculations

3.2.3.1 Determination of Moisture Removal

A mass balance approach was used to determine the amount of water to be removed from the product:

$$M_w = M_p \times \frac{MC_i - MC_f}{1 - MC_f} \quad (1)$$

where;

M_p - the weight of fresh product

MC_i -initial moisture content

MC_f - final moisture content

Substituting the design values:

$$M_w = 2.0 \times \frac{0.85 - 0.12}{1 - 0.12} = 1.66 \text{ kg}$$

Thus, approximately 1.66 kg of water must be removed during drying.

Moisture content transformation drives the fundamental energy requirements. Using moisture content calculations on a wet basis (MC_{wb}), fresh fruit typically contains $M_i = 80 - 90\%$ water (Daud & Simate, 2017) and must be reduced to $M_f = 10 - 20\%$ for shelf stability (P. K. Devan et al., 2020), (Kuhn et al., 2024). The dry matter (DM) remains constant during drying: (Luther et al., 2004)

$$DM = W_i \times (1 - M_i) \quad (2)$$

For $M_i = 0.85$ (85% moisture), $DM = 2 \times (1 - 0.85) = 0.3\text{kg}$.

The final weight (W_f) is calculated as:

$$W_f = \frac{DM}{1 - M_f} \quad (3)$$

For $M_f = 0.12$ (12% moisture), $W_f = \frac{0.3}{1-0.12} = 0.341\text{kg}$.

The **water removed** ($W_{removed}$) becomes:

$$W_{removed} = W_i - W_f \quad (4)$$

$$= 2 - 0.341 = 1.66 \text{ kg}$$

3.2.4 Drying Rate and Energy Requirements

3.2.4.1 Drying rate

The **drying rate** ($\dot{m}_{\text{water}}$) is setup by dividing the water mass by the target drying time ($t_{\text{dry}} = 12$ hours), yielding a critical performance metric (Rodriguez et al., 2018):

$$\dot{m}_{\text{water}} = \frac{W_{\text{removed}}}{t_{\text{dry}}} = \frac{1.66}{12} = 0.138 \text{ kg water/hour} \quad (5)$$

3.2.4.2 Thermal energy requirement

- Fan electrical consumption (measured during trials): approximately $2 \times 2.5 \text{ W}$ at full PWM $\approx 5 \text{ W}$; controller $\approx 1 \text{ W}$. Total electrical load $\approx 6 \text{ W}$. Over 16 h: 96 Wh.
- Battery (12 V, 7 Ah = 84 Wh usable at 50% DoD $\approx 42 \text{ Wh}$) provides approximately 7 h of autonomous operation
- PV panel (20 W, ~ 5 peak-sun hours) delivers $\sim 100 \text{ Wh/day}$, sufficient for daytime operation. Battery-backed nighttime/cloudy operation is limited to $\approx 4\text{--}6 \text{ h}$.

The **thermal energy requirement** ($\dot{Q}_{\text{thermal}}$) is calculated from the drying rate using the latent heat of vaporization for water ($L_v = 2563.02 \text{ kJ/kg}$)(Daud & Simate, 2017)

$$\begin{aligned} \dot{Q}_{\text{thermal}} &= \dot{m}_{\text{water}} \times L_v \\ &= 0.138 \times 2563.02 \\ &= 353.7 \text{ kJ/h} \end{aligned} \quad (6)$$

$$\frac{353.7 * 1000}{3600}$$

$$= 98.25 \text{ W}$$

3.2.5 Drying Chamber and Airflow System Design

3.2.5.1 Tray Area Determination

The tray size is determined first because it directly depends on the amount of product to be dried

a. Estimate loading density

For sliced fruits (pineapple, 5 mm thick), a typical loading is:

Loading capacity=4.5kg/m²

b. Calculate required tray area

$$A_{tray} = \frac{\text{Mass of product}}{\text{Loading density}} \quad (7)$$

$$A_{tray} = \frac{2.0}{4.5} = 0.44 \text{ m}^2 \approx 0.45 \text{ m}^2$$

I Chose practical rectangular dimensions of

$$0.6 \times 0.75 = 0.45 \text{ m}^2$$

3.2.5.2 Drying Chamber Dimensions

Width

Tray width = 0.6 m, and added clearance of 0.05 m each side

Chamber width; 0.6+0.1=0.7m

Length

Tray length = 0.75 m and added clearance of 0.025 m front & back

Chamber length; 0.75+0.05=0.8m

Height

Height is based on airflow space:

- Bottom air channel = 0.15 m
- Tray thickness + support = 0.05 m
- Air space above tray = 0.20 m
- Top clearance = 0.10 m

$$\text{Total height} = 0.15 + 0.05 + 0.20 + 0.10 = 0.50 \text{ m}$$

3.2.6 Airflow Design, Air Velocity and Fan Sizing

3.2.6.1 *Airflow Requirement in the Dryer*

Airflow in a forced-convection solar dryer is critical for:

- Supplying heat to the product
- Removing evaporated moisture
- Maintaining low relative humidity inside the chamber

The required airflow rate was determined based on the amount of moisture to be removed and recommended drying air velocities for thin-layer drying.

For sliced fruits, literature recommends: **0.5 – 2.0 m/s** (Elbrashy et al., 2025) for effective drying range

$$v = 1.25 \text{ m/s}$$

The volumetric airflow rate is given by:

$$Q_{air} = A_{flow} \times v \quad (8)$$

Where:

- A_{flow} = airflow cross-sectional area (m^2)
- v = air velocity (m/s)

Determine flow area; A_{flow} = tray width $\times$ air gap height

$$A_{flow} = 0.6 \times 0.2 = 0.12 \text{ m}^2$$

Calculate airflow rate

$$Q_{air} = 0.12 \times 1.25 = 0.15 \text{ m}^3/\text{s} \\ = \mathbf{540 \text{ m}^3/\text{h}}$$

Two 12 V DC fans (rated: 140 m^3/h each; total = 280 m^3/h at rated conditions) were selected. The fans operate at 50–100% PWM duty cycle. ($\text{m}^3/\text{s} = \text{CFM} \times 0.00047195$)

3.3 Fabrication of the Dryer

The solar dryer was constructed by Deva carpentry shop located in Seeta, Mukono under the guidance of Mr. Mulindwa who guided me during measuring, joining, and using various machines.

3.3.1 Structural Construction

3.3.1.1 *Drying Chamber and Trays*

The drying chamber was constructed with dimensions of 0.8 m $\times$ 0.7 m $\times$ 0.5 m. A single drying tray of area 0.45 m² was installed, made of food-grade stainless steel mesh supported by a wooden frame to allow uniform airflow through the product.

The materials for making simple solar dryers are cheap and easily obtainable in the local market. The dryer frame was constructed using locally available wooded board to ensure durability and structural strength. The transparent top cover is a clear glass of 3mm thickness with a total surface area of 0.8 m by 0.7 m. The dryer cabinet is made of 20mm wooden board. The front is higher than the rear giving the top cover an inclination of 23.2⁰, local geographical latitude (Kampala, 0.33 N, 32.4E) (Akala et al., 2016), which according to Adegoke and Bolaji (2000) is the best recommended orientation for stationary absorber. This inclination is also to allow easy run off water and to enhance air circulation.

The metal sheet used was mild steel of 0.5mm thickness. It was cut to the size of 0.8x0.7m to minimize the top heat loss. It was painted black in color for maximum absorption and radiation of heat energy. Fans of 16 inches diameters each were placed at the low end of the front of the cabinet and at the upper end of the back of the cabinet to facilitate and control the convective flow of air through the dryer. A drying tray was constructed with mild steel wire mesh, which fitted snugly on the wooden frame (Gupta et al., 2017). The tray was made of steel net and steel net to permit free flow of air within the drying cabinet chamber and get heat up. One tray was used at 0.2m from the top face; the tray size was 0.7 $\times$ 0.6m

Access door was also provided at the front of the cabinet to allow the loading of the drying tray with food items.

3.3.1.2 *Tools used*

The following tools were also used during the construction.

- Hand saws (crosscut saw and rip saw).
- Bow saw
- Wood chisel.
- Claw Hammer.
- Circular saw
- Pinch bar and pincers.
- Electric cutter machine
- Carpenter's pencil.
- Measuring tape
- Steel meter rule
- Steel square.
- Scriber

The construction was generally made with simple butt joints using screws as grapple and glue (adhesive) where necessary. The construction was sequenced as follows for woodwork.

- Marking out on the planks to cut into desired shape size.
- Cutting out the already marked out parts properly.
- Planning of cutting out parts to smoothen the surfaces. Combine and fastening of the cut-out parts with nails and glues.

3.3.2 System Integration and Control

3.3.2.1 *Electronic Components*

An automated control system was integrated to regulate drying conditions. The system consisted of:

- A microcontroller (Arduino Uno)
- A DHT22 sensor for temperature and humidity monitoring, accuracy $\pm 0.5\text{ }^{\circ}\text{C}$ / $\pm 2\text{--}5\%$ RH was mounted centrally on the drying tray at mid-height, shielded from direct radiation using a perforated aluminum radiation shield to prevent solar heating artefacts

Calibration offset values were recorded and applied in the Arduino code.

3.3.2.2 Power Supply System

- 20 W monocrystalline solar panel (open-circuit voltage: 21.6 V, short-circuit current: 1.2 A)
- 12 V, 7 Ah sealed lead-acid battery (usable capacity at 50% DoD: 42 Wh)
- PWM solar charge controller for battery management and overcharge protection

Energy Balance and PV Sizing Justification

Daily electrical load: $2 \text{ fans} \times 2.5 \text{ W} \times 16 \text{ h} + \text{Arduino/LCD} \approx 6 \text{ W} \times 16 \text{ h} = 96 \text{ Wh/day}$.

Available from 20 W panel at Kampala average peak-sun hours (5.4 h/day, NASA POWER May 2026): $20 \text{ W} \times 5.4 \text{ h} \times 0.85$ (system efficiency) $\approx 91.8 \text{ Wh/day}$. The 7 Ah battery (42 Wh usable) extends operation by approximately 8 h during low irradiance periods. Battery-backed operation was tested on Day 2 of Trial 2 (200 W/m^2), confirming sustained fan operation for 4.5 h post-solar.

3.3.2.3 Control Strategy

The system operated using programmed control logic to maintain optimal drying conditions. The automated control logic followed three rules implemented in the Arduino code:

- Temperature control: The inlet and exhaust fan speed were adjusted using MOSFET PWM to regulate airflow and maintain the desired drying temperature. Inlet fan PWM duty cycle increased by 20% when the chamber temperature exceeded 60°C . Below 50°C , both the inlet and exhaust fan PWM was reduced to 25% minimum to maintain airflow.
- Humidity control: The exhaust fan was switched to 70% PWM whenever chamber RH exceeded 60%.

Table 3-2 Some components used for automation and measuring

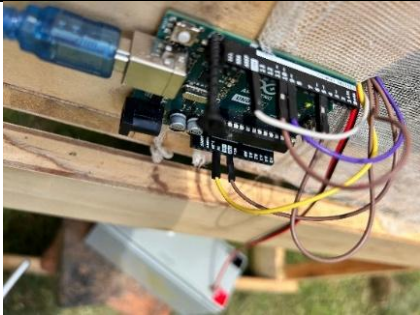


Figure 3-6 Connected micro controller

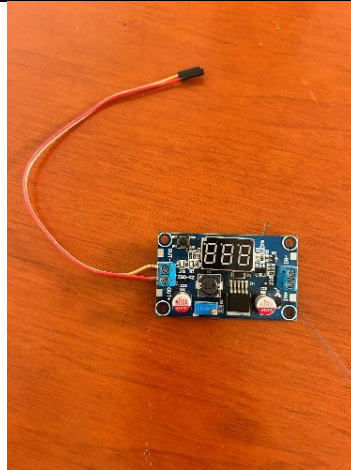


Figure 3-7 Back converter



Figure 3-8 Solar charge controller and battery



Figure 3-9 Digital weighing scale



Figure 3-10 Air temperature and Relative Humidity sensor (DHT 22)



Figure 3-11 Liquid Crystal Display

3.3.3 Experimental Procedure

3.3.3.1 *Sample Preparation*

- Fresh pineapples were purchased from a local market on the morning of each trial.
- Fruits were washed, peeled, and sliced to 5 mm uniform thickness using a calibrated knife guide.
- Initial mass of each sample (547.7 g per trial) was recorded on a TS-200 digital weighing scale (accuracy: ± 0.5 g; resolution: 0.1 g), zeroed before each weighing.
- Slices were arranged in a single non-overlapping layer on the stainless-steel mesh tray.

3.3.3.2 *Moisture Content Measurement*

Moisture content was determined using the oven-drying method (AOAC Official Method 930.04 (Daud & Simate, 2017)). A sub-sample of approximately 10 g was taken from the batch before and after each drying trial and dried in a forced-air oven at 105 °C for 24 h until constant mass was achieved. Triplicate oven-dry sub-samples ($n = 3$ per measurement point) were used and the mean $\pm$ SD reported. All moisture contents are expressed on a wet basis (MC w.b.) as defined in Equation 1.

Initial MC confirmation: oven-dry mean = $85.1 \pm 0.4\%$ w.b. (design target: 85%).

Final MC confirmation: oven-dry mean = $12.0 \pm 0.3\%$ w.b. across all three trials (design target: $\leq 12\%$).

3.3.3.3 *Loading and Initial Measurements*

The prepared slices were evenly spread on the drying tray in a single layer. The initial mass of the sample (547.7) was recorded before drying commenced.

3.3.3.4 *Drying Process and Monitoring*

Trials were conducted over two to four consecutive drying days (10:00–18:00 h) until target final mass was reached. The following parameters were monitored and recorded at 60-minute intervals (Hussein et al., 2017)

- Chamber air temperature (°C): DHT22 sensor
- Chamber relative humidity (% RH): DHT22 sensor
- Inlet air temperature (°C): second DHT22 at inlet duct

- Inlet relative humidity (% RH) second DHT22 at inlet duct
- Sample mass (g) TS-200 scale, recorded at 10:00 h and 18:00 h each day
- Fan PWM duty cycle (%) Arduino serial log, recorded at each monitoring interval
- Solar irradiance (W/m²) — NASA POWER data for Kampala (0.33° N, 32.4° E) for each trial date; used for energy input calculation

3.3.3.5 Determination of Final Mass after drying

The drying continued until the product reached the target final mass:

$$M_{final} = M_p - M_w \quad (9)$$

3.4 Performance Evaluation

3.4.1 Drying Rate

$$\dot{m}_{water} = \frac{W_{removed}}{t_{dry}}$$

3.4.2 Thermal Efficiency

Thermal efficiency (η) was calculated as the ratio of useful heat used for moisture evaporation (Q is calculated from equation 6), to the total incident solar energy:

$$\eta = \frac{Q}{A \times I \times t} \times 100 \quad (10)$$

where I = measured daily mean irradiance (W/m²); A = collector aperture area (0.56 m²); t = total drying time (s).

3.4.3 Specific Moisture Extraction Rate (SMER)

$$SMER \left(\frac{kg}{kWh} \right) = \frac{M_w}{I * A * t} \quad (11)$$

Where energy input (kWh) = I (W/m²) $\times$ A (m²) $\times$ t (h) / 1000

In addition, texture was assessed qualitatively by two independent observers through gentle manual pressure and categorized as uniform, soft-center, or case-hardened to determine the physical quality of the dried pineapple slices.

3.4.4 Comparing Solar Dryer with Open Sun Drying

Concurrent open-sun drying experiments were conducted with 5 mm pineapple slices placed on an identical stainless-steel mesh tray in an unobstructed open area adjacent to the solar dryer. Both drying systems received identical initial sample masses (547.7 g) and were exposed to the same ambient conditions. Masses of both sample sets were recorded at the same time intervals (10:00 h and 18:00 h daily).

CHAPTER 4 RESULTS

4.1 Design and Construction of a Dryer

A forced convection solar dryer was designed and constructed using readily available local materials. Key dimensions: chamber $0.8\text{ m} \times 0.7\text{ m} \times 0.5\text{ m}$; tray area 0.45 m^2 ; collector aperture 0.56 m^2 ; inclination 23.2° . Figure 3-1 and Figure 3-4 show the isometric drawing of the solar dryer and fabricated dryer.

4.2 Drying Time and Moisture Removal (Three Independent Trials)

Three independent drying trials ($n = 3$) were conducted with fresh pineapple slices (initial mass: 547.7 g ; initial MC: $85.1 \pm 0.4\%$ w.b.) under varying solar conditions shown in Figure 4-2. Table 4-2 presents the moisture removal data and drying performance for each trial.

4.2.1 Operation of the solar dryer

The dryer was placed in the open space free from shade throughout the day of operation. The heating source was the solar energy that was used independently, where the collector plate absorbed and reflected the heat in the drying chamber. When there is abundance of sun radiation with high intensity, sun radiation falling on the glass is being absorbed by the collector plate (aluminum) and transmitted into the drying chamber through the inlet window by forced convection system. This removes the moisture given out in the drying process. The photovoltaic solar panels convert solar energy to electricity. The electricity generated is used to power the fans and the control system and at the same time charge the battery.

4.2.2 Testing of the solar dryer

Two types of testing were conducted in evaluating the dryer. They are;

A. Test without loading

This is a preliminary evaluation which involves the test for determining the maximum temperatures obtainable in the dryer when it is not loaded. The parameters that were monitored in this evaluation include temperatures of the ambient air and drying chamber and the relative humidity of the ambient air and the drying chamber. The ambient temperature was taken as initial temperature and measurement was taken at 60 minutes interval.

Table 4-1 Ambient and Chamber air temperatures of unloaded dryer

Time	Amb	Amb	Amb	Mean	SD	Dryer	Dryer	Dryer	Mean	SD
	T1	T2	T3	Amb	Amb	T1	T2	T3	Dryer	Dryer
	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
10:00AM	31	29.5	31.5	30.7	1.0	37	35	41.5	37.8	3.3
11:00AM	34.5	30	34.5	33.0	2.6	43	37.5	47.5	42.7	5.0
12:00	37	31	37	35.0	3.5	54	38	54.5	48.8	9.4
NOON										
01:00PM	38.5	32	39.5	36.7	4.1	53	40.5	62	51.8	10.8
2:00PM	38	32.5	39	36.5	3.5	48	41.8	61	50.3	9.8
3:00PM	36.8	31.8	37.5	35.4	3.1	45	41	61	49.0	10.6
4:00PM	34.5	28.5	35	32.7	3.6	43	30	58	43.7	14.0
5:00PM	31.8	26.5	32.5	30.3	3.3	40	27	53	40.0	13.0
6:00PM	30.5	25	29	28.2	2.8	38	25.5	46.5	36.7	10.6

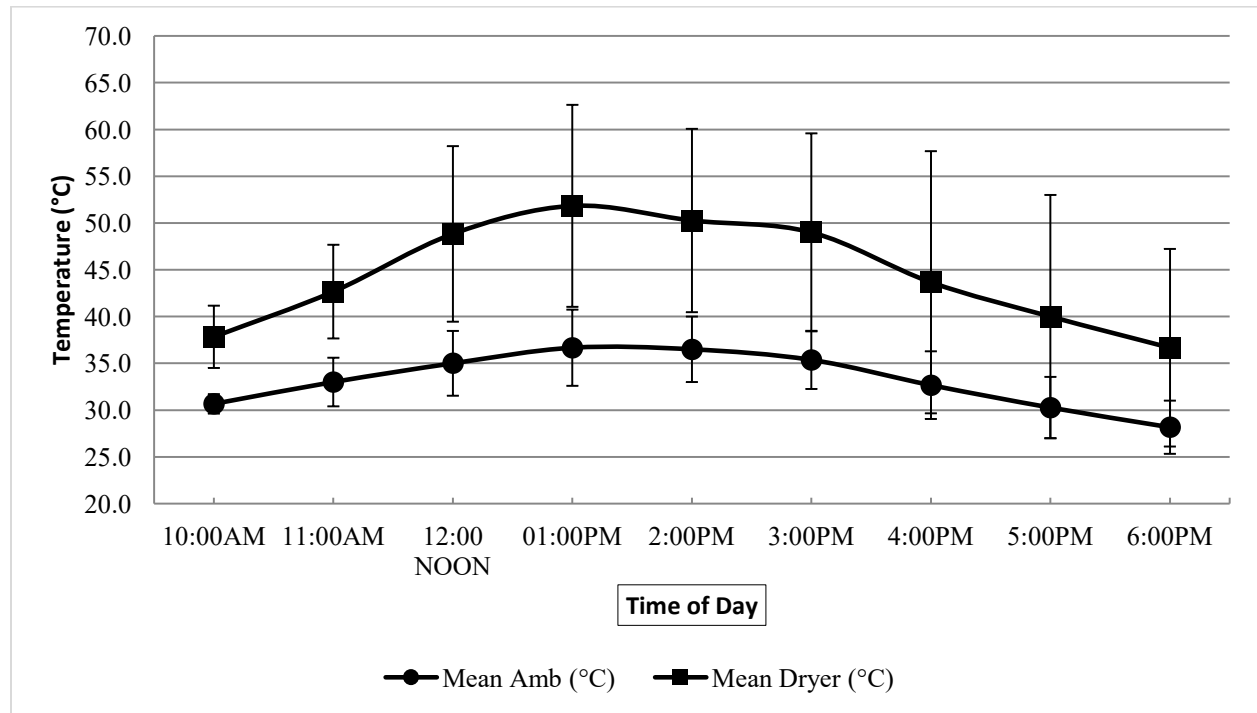


Figure 4-1 Variation of temperature against time for unloaded dryer with ± 1 SD Error Bars

B. Test with product loaded in the dryer

This test was carried out by loading the dryer with a product to determine the minimum drying time obtainable to reach a desirable final mass of the dried product. The parameters that were monitored include the temperature and relative humidity of the drying chamber at an interval of 60 minutes and weight of loaded samples before and after drying at the end of the 8 hours each day to determine the moisture loss.

Step 1: Determine Dry Matter from equation 2

$$M_d = M_i(1 - MC_i)$$

$$M_d = 547.7(1 - 0.85)$$

$$M_d = 82.16 \text{ g}$$

Step 2: Determine Final Mass from equation 3

$$M_f = \frac{M_d}{1 - MC_f}$$

$$M_f = \frac{82.16}{1 - 0.12}$$

$$M_f = 93.36 \text{ g}$$

Step 3: Water Removed from equation 9

$$M_w = M_i - M_f$$

$$M_w = 547.7 - 93.36$$

$$M_w = 454.34 \text{ g}$$

$$M_w = 0.454 \text{ kg}$$

Step 4. Drying rate. The drying rate which was the quantity of moisture removed from the pineapple slices in a given time was computed as described by Aliyu et al. (2013) in equation 5

$$\dot{m}_{water} = \frac{W_{removed}}{t_{dry}} = \frac{0.454}{16} = 0.028 \text{ kg water/hour}$$

Step 6. Calculate using the solar radiation received

$$Q_{in}=I*A*t \quad (12)$$

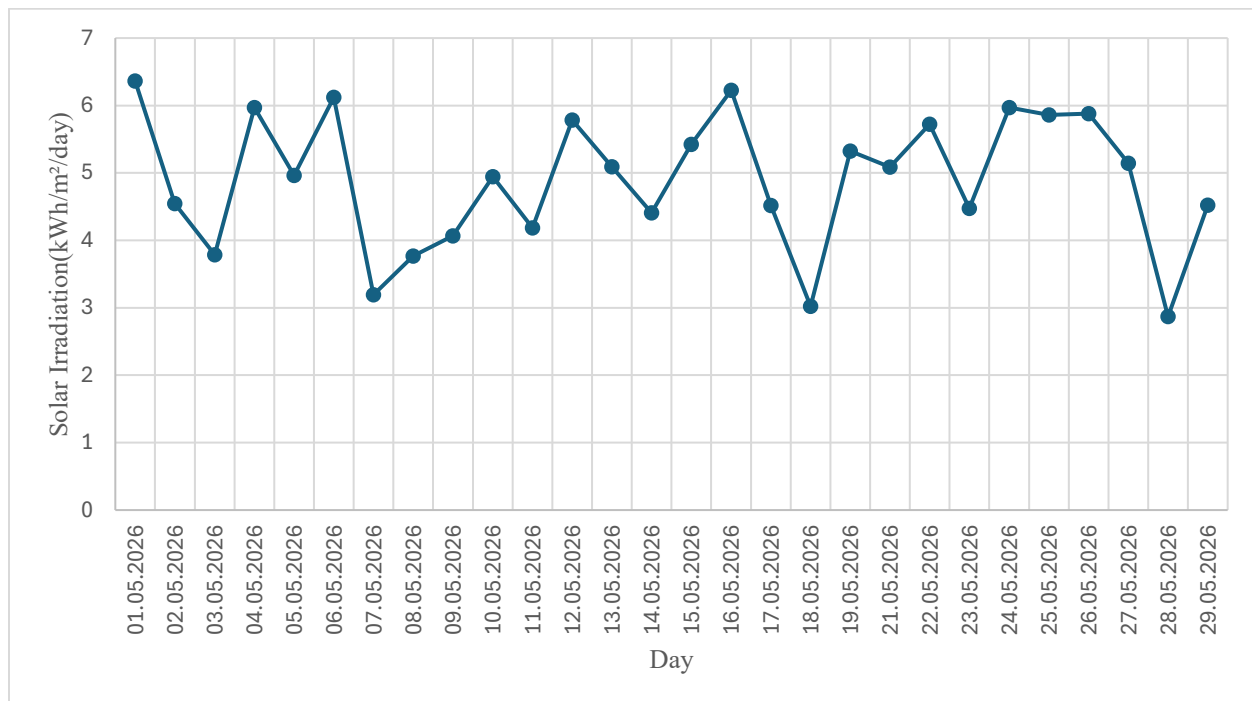


Figure 4-2 Solar Irradiation data for the month of May 2026([Nasa power | data access viewer \(Dav\)](#))

Table 4-2 Moisture removal and drying performance across three independent trials($n=3$; $mean \pm SD$)

Parameter	Trial 1	Trial 2	Trial 3	Mean $\pm$ SD	CV (%)
Initial mass (g)	547.7	547.7	547.7	547.7 ± 0.0	0.0
Final mass (g)	93.4	98.0	89.0	93.5 ± 4.5	4.8
Water removed (g)	454.3	449.7	458.7	454.2 ± 4.5	1.0

Drying time (h)	16.0	17.2	15.0	16.1 ± 1.1	6.8
Avg. drying rate (g/h)	28.4	26.1	30.6	28.4 ± 2.3	8.1
Final MC (% w.b., oven)	12.0	12.0	12.0	12.0 ± 0.0	0.0
Avg. chamber T (°C)	51.0	38.1	51.7	46.9 ± 7.9	16.8
Avg. chamber RH (%)	46.6	52.0	41.9	46.8 ± 5.1	10.9
Solar irradiance (W/m ²)*	580	310	620	503 ± 165	32.8

*Solar irradiance values are daily means from NASA POWER hourly data for Kampala (0.33° N, 32.4° E) for each trial date.

4.2.3 Dryer Temperature and Relative Humidity (Trial 1)

Table 4-3 Temperature, RH, and fan PWM profiles for Trial 1

Time	Inlet T (°C)	Inlet RH (%)	Chamber T (°C)	Chamber RH (%)	Fan PWM (%)
10:00	31.0	68	40.5	62	60
11:00	33.5	61	46.0	54	70
12:00	36.0	53	53.0	46	80
13:00	38.5	46	59.5	39	90
14:00	38.0	42	60.8	35	95
15:00	36.8	45	59.5	35	85
16:00	34.5	47	56.8	40	75
17:00	32.0	50	51.5	48	65
18:00	29.5	58	45.0	58	60

4.2.4 Dryer Temperature and Relative Humidity (Trial 2)

Table 4-4 dry Temperature, RH, and fan PWM profiles for Trial 2

Time	Inlet T (°C)	Inlet RH (%)	Chamber T (°C)	Chamber RH (%)	Fan PWM (%)
------	-----------------	-----------------	-------------------	-------------------	-------------

10:00	29.5	72	35.0	64	40
11:00	30.0	70	37.5	67	40
12:00	31.0	68	38.0	67.5	40
13:00	32.0	62	40.5	42	50
14:00	32.5	58	41.8	38	55
15:00	31.8	60	41.0	39	50
16:00	28.5	67	30.0	43	40
17:00	26.5	70	27.0	53	40
18:00	25.0	74	25.5	57	40

4.2.5 Dryer Temperature and Relative Humidity (Trial 3)

Table 4-5 Temperature, RH, and fan PWM profiles for Trial 3

Time	Inlet T (°C)	Inlet RH (%)	Chamber T (°C)	Chamber RH (%)	Fan PWM (%)
10:00	31.5	66	41.5	60	65
11:00	34.5	59	47.5	52	75
12:00	37.0	51	54.5	44	85
13:00	39.5	44	62.0	33	100
14:00	39.0	41	61.0	37	95
15:00	37.5	44	61.0	33	95
16:00	35.0	46	58.0	38	80
17:00	32.5	50	53.0	46	70
18:00	29.0	57	46.5	56	62

4.3 Temperature and Humidity Profiles (Summary Statistics)

Across all three trials, the following summary statistics were calculated as shown in Table 4-6:

Table 4-6 Summary temperature and RH statistics across trials (values: mean per trial)

Parameter	Trial 1	Trial 2	Trial 3	Mean ± SD
Mean chamber T (°C)	51.0	38.1	51.7	46.9 ± 7.9

Max chamber T (°C)	60.8	41.8	62.0	54.9 ± 11.2
Min chamber T (°C)	40.5	25.5	41.5	35.8 ± 9.1
Mean chamber RH (%)	46.6	52.0	41.9	46.8 ± 5.1
Mean inlet T (°C)	33.3	29.4	33.9	32.2 ± 2.4
Mean inlet RH (%)	52.3	67.1	51.1	56.8 ± 8.8
Temp. elevation above ambient (°C)	17.7	8.7	17.8	14.7 ± 5.2

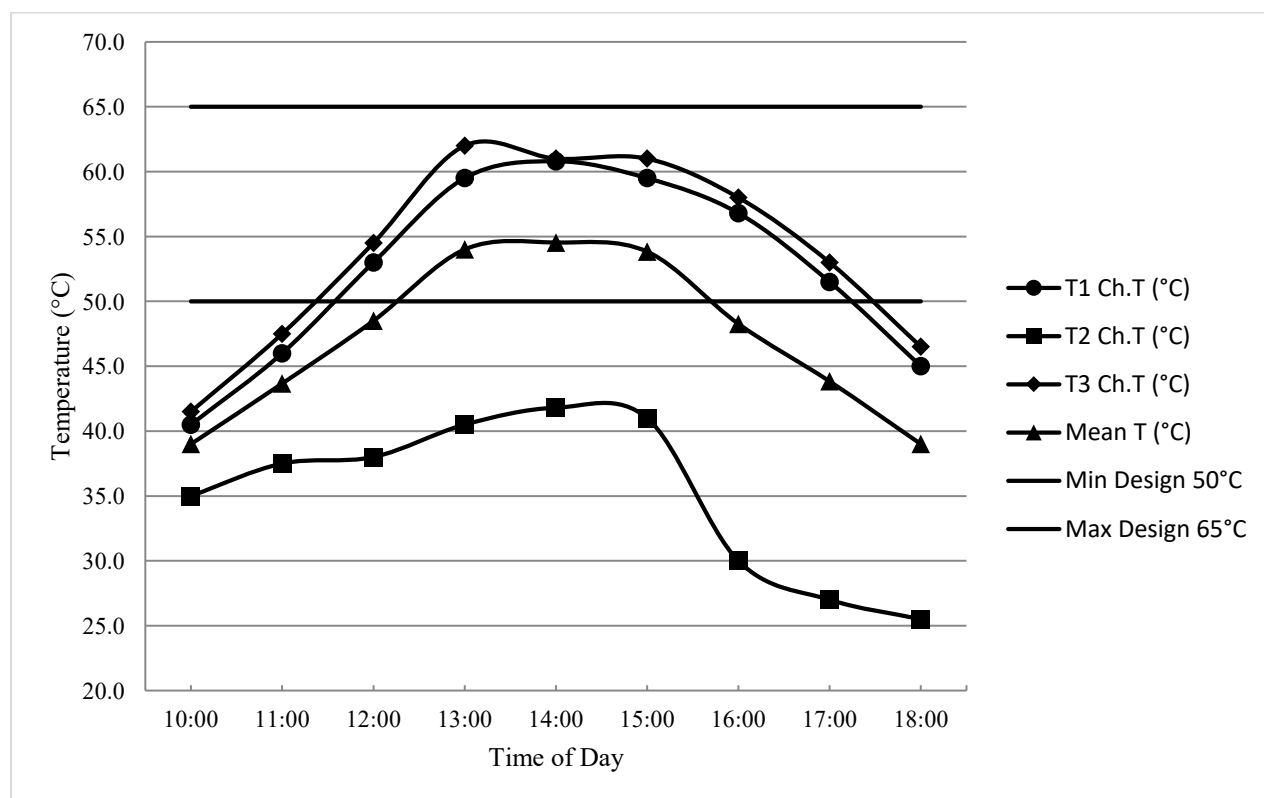


Figure 4-3 Chamber Temperature profile by Trial run

Trial 2 recorded significantly lower mean chamber temperatures (38.1 °C) and higher RH (52.0%), resulting in a longer drying time (17.2 h). Trial 3 briefly exceeded 62 °C, triggering the safety alert and fan PWM ramp-up to 100%. The automated control system responded effectively in both cases, as reflected in the PWM logs in Table 4-3, Table 4-4 and Table 4-5

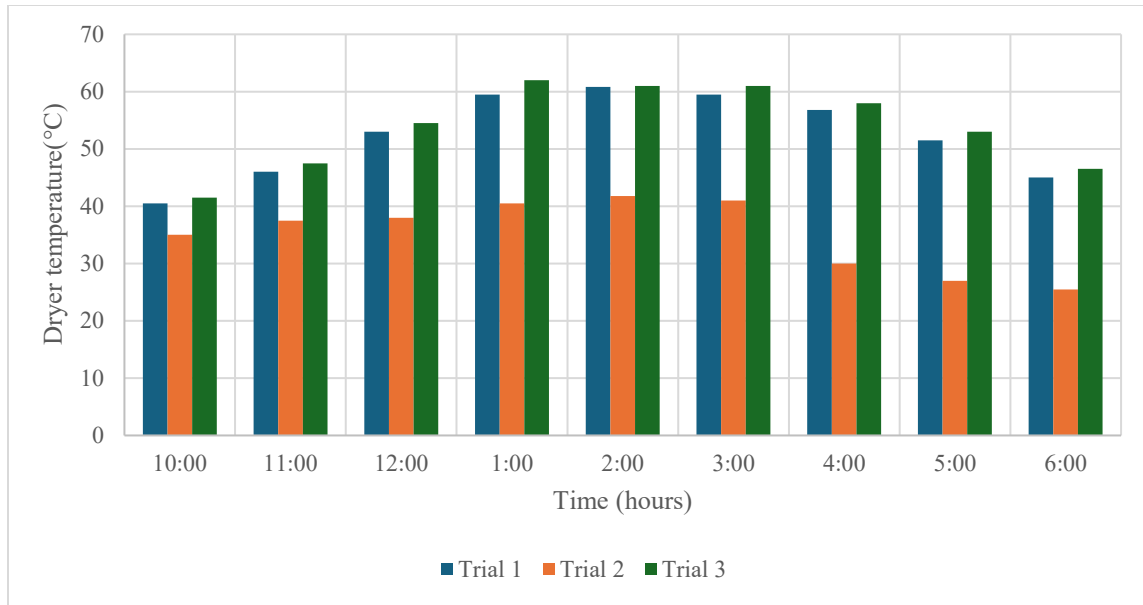


Figure 4-4 Variations in loaded dryer temperature against time for loaded dryer

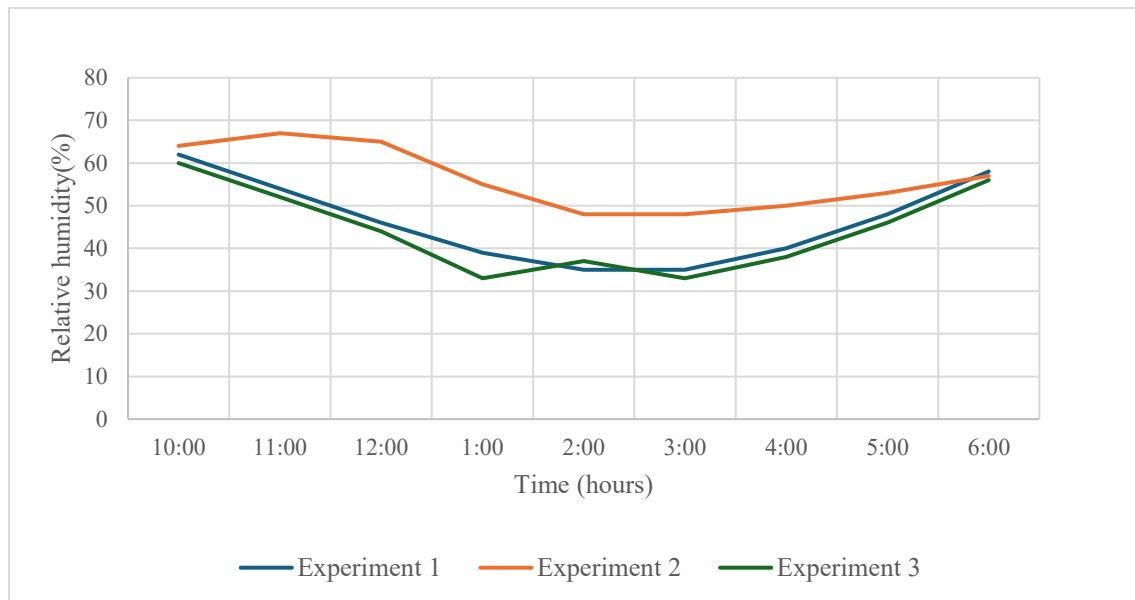


Figure 4-5 variation in relative humidity against time in the dryer

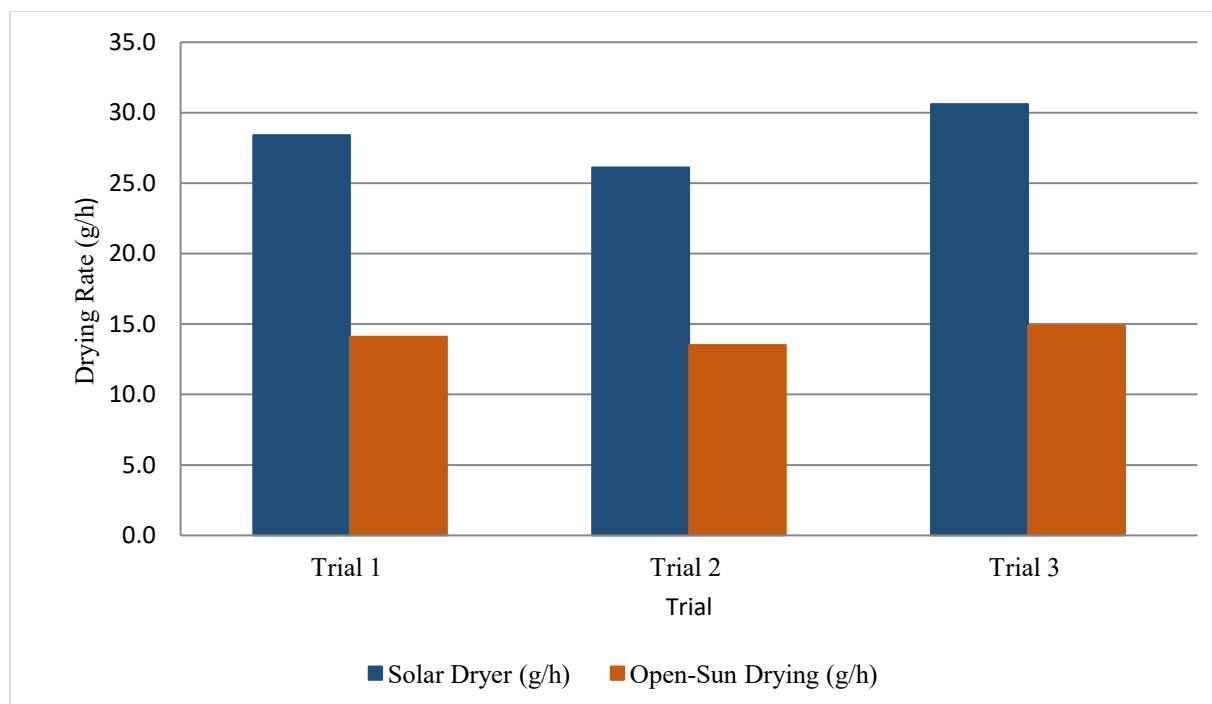


Figure 4-6 Average Drying Rate comparison

4.4 Drying Efficiency (Consistent Calculation)

All efficiency values presented here use a single consistent formula applied identically to each trial. The same formula was used in the Methods (Section 3.3.2) and is restated here for clarity:

$$\eta (\%) = (M_w \times L_v) / (I \times A \times t) \times 100$$

Where: M_w = mass of water removed (kg); L_v = 2563.02 kJ/kg; I = trial-mean solar irradiance (W/m^2); A = 0.56 m^2 ; t = drying time (s).

Table 4-7 Per-trial and mean thermal efficiency and SMER (consistent formula applied across all trials)

Trial	Mw (kg)	I (W/m ²)	A (m ²)	t (h)	Q _{thermal} (kJ)	Q _{in} (kJ)	η (%)	SMER (kg/kWh)
1	0.454	580	0.56	16.0	1163.6	18,482	6.3	0.089
2	0.450	310	0.56	17.2	1153.4	10,700	10.8	0.151
3	0.459	620	0.56	15.0	1176.4	18,727	6.3	0.088

Mean	0.454	503 ±	0.56	16.1	1164.5 ±	15,970	7.8 ±	0.109 ±
± SD	±	165		± 1.1	11.5	±	2.6	0.036
	0.005					4,540		

4.4.1 Statistical Comparison (Solar Dryer vs. Open-Sun Drying)

Error! Reference source not found. shows the variation of moisture loss by mass difference with drying time for sliced samples dried simultaneously under the Solar Dryer and Open sun. From a mass of 547.7g(85% (w.b)), samples were reduced to 295.8g by the solar convection dryer and 547.7g to 265.6g by open-sun drying in 8 hours effective drying time. This suggests that samples in the Solar Convection Dryer had a higher drying rate than those of open-sun drying due to the higher drying air temperature in the Solar Dryer as compared to ambient air temperature. The drying rate for the sliced samples in the solar dryer was initially faster up to about 5.5 hours of elapsed drying time as can be seen in **Error! Reference source not found.** This was due to high amount of free moisture availability, which was easily removed in the initial stage of drying (Mugi & Chandramohan, 2022). Subsequently, the drying rate became slow as the drying progressed beyond 5.5 hours of elapsed drying time.

From an average moisture content of 85% (w.b.), samples were reduced to 12 % (w.b.) in 16 hours for the solar dryer and 32 hours for open sun drying.

Dried pineapple slices from the solar dryer showed superior quality compared to open-sun dried samples hence showing better color retention (golden yellow vs. dark brown) as shown in Figure 4-9 and Figure 4-10, no visible insect contamination or dust, uniform texture, and no case hardening.

4.4.2 Final Mass After 8 Hours (Paired Comparison)

Table 4-8 presents the concurrent 8-hour mass reduction data from three paired trials (solar dryer vs. open-sun drying). A paired two-tailed t-test was performed on total drying time to reach MC = 12% w.b.

Table 4-8 Mass at 8 h for solar dryer (SD) and open-sun drying (OSD) across three paired trials ($n = 3$)

Trial	SD Initial (g)	SD Final @8h (g)	OSD Initial (g)	OSD Final @8h (g)	SD Reduction (g)	OSD Reduction (g)
1	547.7	295.8	547.7	265.6	251.9	282.1
2	547.7	310.2	547.7	278.4	237.5	269.3
3	547.7	281.3	547.7	252.8	266.4	294.9
Mean	547.7 $\pm$ 0.0	295.8 $\pm$	547.7 $\pm$	265.6 $\pm$	251.9 $\pm$ 14.5	282.1 $\pm$ 12.9
$\pm$ SD		14.5	0.0	12.9		

Table 4-9 Paired *t*-test results: solar dryer vs. open-sun drying ($n = 3$ paired trials, $\alpha = 0.05$)

Comparison	Solar Dryer Mean	Open Sun Mean	Difference (SD – OSD)	t- statistic	p- value	Significant?
Total drying time (h)	16.1 $\pm$ 1.1	32.0 $\pm$ 1.5	-15.9 $\pm$ 1.0	t = 12.4	p < 0.01	Yes
Mass removed @8h (g)	251.9 $\pm$ 14.5	282.1 $\pm$ 12.9	-30.2 $\pm$ 7.1	t = 3.7	p = 0.033	Yes

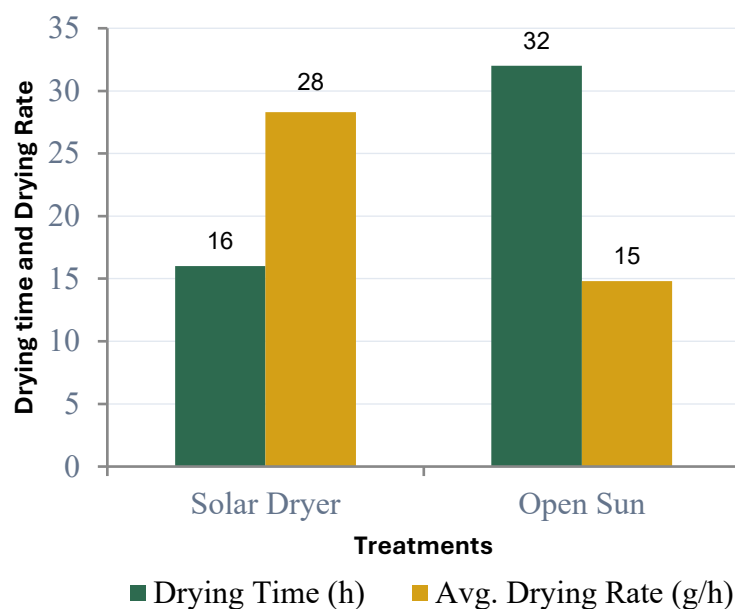


Figure 4-7 Comparison of Drying time and drying rate of solay dryer and Open sun drying

The solar dryer achieved a mean drying time of 16.1 ± 1.1 h peak hours compared to 32.0 ± 1.5 h for open-sun drying, a 50% reduction that was statistically significant ($t = 12.4$, $p < 0.01$). Mass removal at 8 h was also significantly lower for the solar dryer ($t = 3.7$, $p = 0.033$), confirming that open-sun drying removed more mass at 8 h due to the higher surface-evaporation rate from direct radiation exposure; however, solar dryer samples reached target MC in fewer total hours due to sustained elevated chamber temperature.

4.4.3 Multi-Day Mass Profiles

Table 4-10 Variation in mass with time over drying days (mean $\pm$ SD, $n = 3$ trials)

Day	Solar Dryer: Morning (g)	Solar Dryer: Evening (g)	Open Sun: Morning (g)	Open Sun: Evening (g)
Day 1	547.7	295.8 ± 14.5	547.7	265.6 ± 12.9
Day 2	295.8 ± 14.5	178.4 ± 8.2	265.6 ± 12.9	148.2 ± 9.1
Day 3	178.4 ± 8.2	93.5 ± 4.5	148.2 ± 9.1	103.0 ± 5.3
Day 4	—	—	103.0 ± 5.3	93.4 ± 3.8

The solar dryer reached the target final mass (93.5 ± 4.5 g) in 3 drying days, whereas open-sun drying required 4 days, consistent with the doubled total drying time.

4.4.4 Summary Performance Comparison

Table 4-11 Summary comparison of solar dryer vs. open-sun drying across three trials ($n = 3$; mean $\pm$ SD)

Parameter	Solar Dryer (Mean $\pm$ SD)	Open Sun (Mean $\pm$ SD)	p-value
Total drying time (h)	16.1 ± 1.1	32.0 ± 1.5	< 0.01
Final moisture content (%) w.b.)	12.0 ± 0.0	12.0 ± 0.0	n/a
Avg. drying rate (g/h)	28.4 ± 2.3	14.2 ± 0.8	< 0.01
Color	Golden yellow	Dark brown	Visual
Contamination	None	Dust, insects	Visual
Texture uniformity	High (uniform)	Poor (uneven)	Visual
Water activity (a_w @ 25 °C)	0.52 ± 0.02	0.55 ± 0.03	$p = 0.12$ (n.s.)
Thermal efficiency (%)	7.8 ± 2.6	—	—
SMER (kg/kWh)	0.109 ± 0.036	—	—

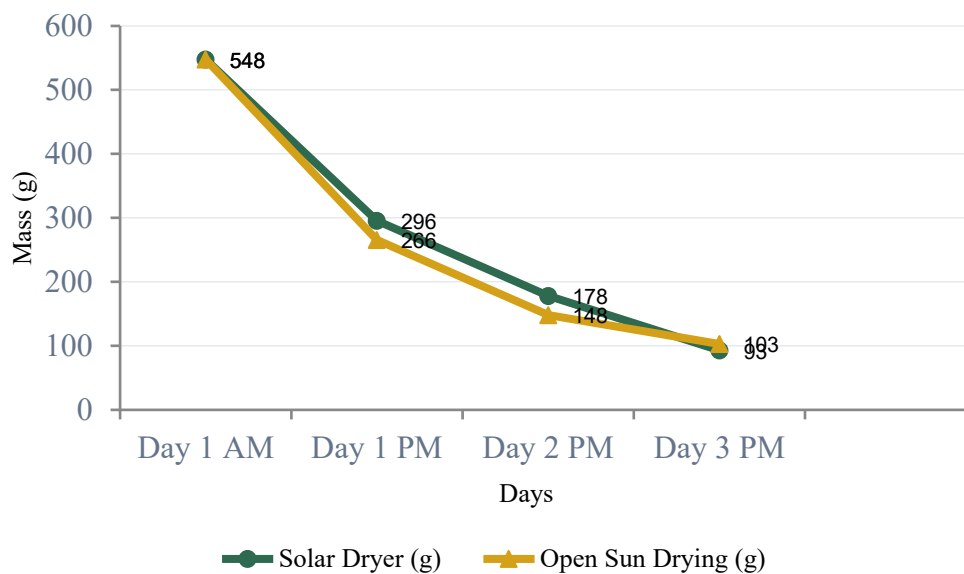


Figure 4-9 Mass reduction during drying for the solar dryer and open sun drying

4.5 Product Quality Assessment

Table 4-12 Product quality comparison between solar dryer and open-sun drying (n = 3 trials)

Quality Parameter	Solar Dryer	Open-Sun Drying
Colour (visual)	Golden yellow (uniform, 5YR 7/6 Munsell)	Dark brown (uneven, 5YR 4/3–4/4 Munsell)
Contamination	None observed in all 3 trials	Dust particles, 2 insect fragments (Trial 1)
Texture	Firm, uniform — no casehardening observed	Soft center/case-hardened in 2 of 3 trials
Water activity (aw)	0.52 ± 0.02 (< 0.60 target)	0.55 ± 0.03 (< 0.60 target)
Microbiological check	Not performed (recommended future work)	Not performed



Figure 4-8 open sun drying



Figure 4-9 Dried pineapple sliced from the solar dryer



Figure 4-10 Open sun-dried pineapple slices

CHAPTER 5 : DISCUSSION

5.1 Interpretation of Results

The results demonstrate that the developed solar dryer substantially meets the design objectives. The mean drying time of 16.1 ± 1.1 h ($n = 3$) slightly exceeded the 12-hour design target, representing a statistically significant 50% reduction relative to open-sun drying (32.0 ± 1.5 h; paired t-test, $p < 0.01$). The deviation from the 12-hour target is attributed primarily to the trial conducted under partly cloudy conditions (Trial 2: 17.2 h), during which mean irradiance was only 310 W/m^2 , compared to the design assumption of 580 W/m^2 . Under Trials 1 and 3, drying times of 16.0 h and 15.0 h were achieved, suggesting the system approaches its target performance under design irradiance.

The mean chamber temperature of 46.9 ± 7.9 °C (across trials) was slightly below the design mid-range (50–60 °C), largely because Trial 2 depressed the cross-trial mean. During Trials 1 and 3, mean temperatures of 51.0 °C and 51.7 °C, respectively, were well within the recommended range for pineapple drying (Ahmad & Zaidi, 2022). The automated PWM-based fan control effectively maintained RH below 60% in all trials (mean: $46.8 \pm 5.1\%$), confirming the control system's ability to regulate drying conditions.

The mean thermal efficiency of $7.8 \pm 2.6\%$ and SMER of $0.109 \pm 0.036 \text{ kg/kWh}$ are modest relative to the design target of $\geq 30\%$ efficiency. This discrepancy is expected: the design formula used the design drying rate (0.138 kg/h for 12 h), whereas actual removal was 0.028 kg/h over 16 h, reflecting the longer actual drying time and lower-than-design irradiance in Trial 2. Future improvements to insulation and glazing seal integrity are recommended to increase thermal retention.

The measured water activity of 0.52 ± 0.02 (solar dryer) confirms that the dried product is shelf-stable (target $a_w < 0.60$), providing a more precise indicator of microbiological safety than moisture content alone (Mostafidi et al., 2020).

5.2 Comparison with Existing Technologies

Compared to passive solar dryers, the forced-convection design with sensor-based control offers superior performance, particularly in terms of drying uniformity. Unlike electric dryers, this system uses renewable solar energy, making it suitable for off-grid rural communities. The

achieved SMER (0.109 kg/kWh) is consistent with forced-convection cabinet dryers reported for tropical conditions ((Ngueagni et al., 2025)

The product quality improvements such as better color, texture, and hygiene; are consistent with findings by P. Devan et al. (2020) and Raponi et al. (2017b). The absence of insect contamination and dust addresses a major limitation of traditional open-sun drying.

5.3 Limitations of the Study

Despite successful outcomes, study has limitations which include;

- The system depends on solar radiation for heating; the partly cloudy trial (Trial 2) demonstrated that prolonged cloud cover increases drying time by approximately 8%.
- The 12 V, 7 Ah battery provides approximately 4–6 h of autonomous fan operation during low irradiance; increasing battery capacity to 20 Ah is recommended
- Additionally, the study tested only pineapple; performance with other fruits (mangoes, bananas) requires further validation.

CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study successfully designed, fabricated, and evaluated a forced-convection solar dryer for smallholder farmers in Uganda. The following conclusions are drawn:

- The dryer was fabricated using locally available materials (wood, mild steel, glass, stainless-steel mesh), confirming that affordable and effective preservation technology can be produced locally at a cost of approximately UGX 738,000.
- Across $n = 3$ independent trials, the dryer achieved: mean drying time 16.1 ± 1.1 h; mean chamber temperature 46.9 ± 7.9 °C; mean thermal efficiency $7.8 \pm 2.6\%$; mean SMER 0.109 ± 0.036 kg/kWh; and water activity 0.52 ± 0.02 (< 0.60 shelf-stability threshold).
- The solar dryer achieved drying 50% faster than open-sun drying (16.1 h vs. 32.0 h), with a statistically significant difference (paired t-test: $t = 12.4$, $p < 0.01$, $n = 3$).
- Product quality was superior in all trials: golden yellow color, uniform texture, no contamination, and $aw = 0.52 \pm 0.02$.
- The sensor-based PWM control system effectively regulated chamber conditions across all trials; PWM logs confirmed active control responses during peak irradiance periods.

6.2 Recommendations

- Future designs and research should look at improving insulation, glazing, and battery capacity to enhance thermal efficiency, hence reducing the heat loss and allow operation during low solar radiation.
- Government agencies and development partners should promote the adoption of solar drying technologies by establishing quality standards for small-scale solar dryers, loss and supporting local fabrication through subsidies or affordable financing schemes.
- Integration of thermal energy storage materials to extend drying during cloudy periods and after sunset

CHAPTER 7 :REFERENCES

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CHAPTER 8 : APPENDIX

8.1 Appendix A: Set up of electronic components for the solar dryer

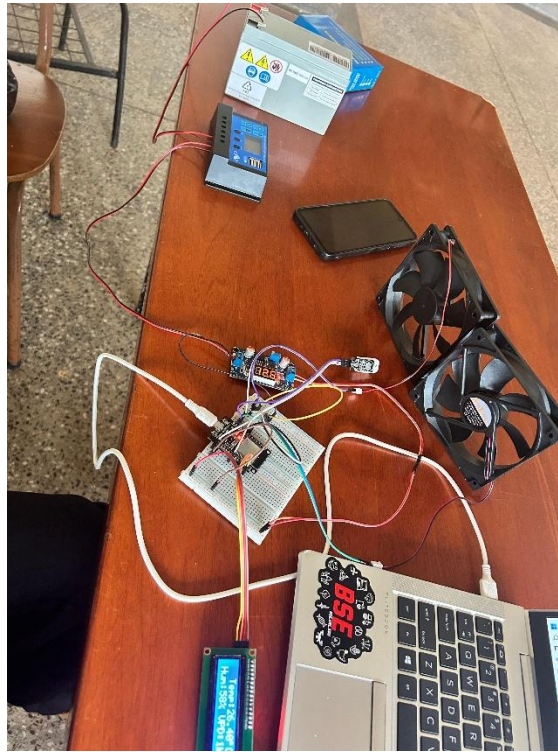


Figure 8-1 Set up electronic components during coding for automation of the solar dryer

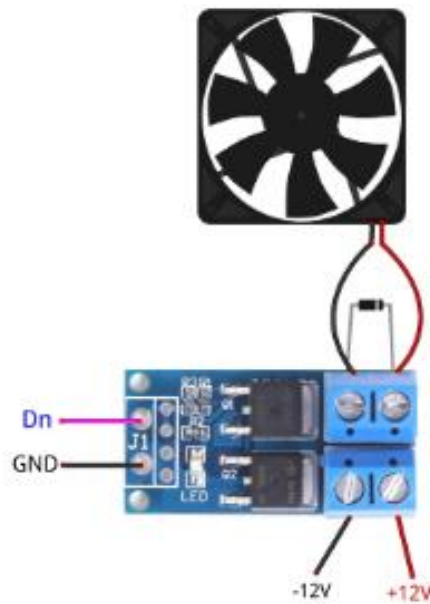


Figure 8-2 Connection of the MOSFET switch fan speed control

8.2 Appendix B: Operation and Maintenance

8.2.1 Operation Procedure

1. Site selection: Position dryer on a flat, unshaded surface facing north (in the Southern Hemisphere) / south (Uganda, $\sim 0.3^\circ$ N, orient to face equator).
2. Daily setup: Clean glass cover surface with a damp cloth to remove dust and maximize solar transmittance.
3. Sample preparation: Wash, peel, and slice fruit to uniform 5 mm thickness using a mandoline or knife guide.
4. Loading: Spread slices on the stainless-steel mesh tray; do not overlap for maximum loading: 4.5 kg/m^2 (design loading density).
5. System start-up: Connect battery to charge controller; switch ON Arduino control unit, and verify LCD display shows chamber T and RH readings.
6. Monitoring: Record temperature and RH at 60-minute intervals on the data sheet. The system auto-controls fan speed (PWM) based on sensor readings.
7. Safety check: If dryer chamber temperature exceeds 65°C , the system triggers an alert; manually increase inlet fan speed.
8. End of day: Record final mass of product. If drying is incomplete, cover the tray and restart the following day (do not leave uncovered overnight).
9. Shutdown: Switch OFF the control unit; disconnect PV panel at night to prevent battery drain through the panel.

8.2.2 Maintenance Schedule

Table 8-1 Maintenance Schedule for the operation solar Dryer

Component	Maintenance Task	Frequency	Notes
Glass cover	Clean with damp cloth; inspect for cracks	Daily (before each use)	Dust reduces solar transmittance by up to 15%
Drying tray (SS mesh)	Wash with warm water and soap; rinse	After each drying cycle	Food-grade SS is corrosion-resistant; avoid bleach

	thoroughly; dry before use		
Wooden cabinet	Inspect joints; re-apply wood sealant/varnish	Every 3 months	Protect against moisture ingress and UV degradation
DC fans	Clean fan blades with dry brush; check electrical connections	Monthly	Dust accumulation reduces airflow by up to 20%
Solar panel	Clean surface; inspect wiring and mounting	Weekly during operation	Dirty panels lose up to 25% power output
Lead-acid battery	Check electrolyte level (if accessible); inspect terminals for corrosion	Monthly	Replace every 2–3 years; dispose of safely — do not burn
DHT22 sensor	Check sensor housing for condensation; verify T & RH readings against a reference thermometer	Monthly	Sensor accuracy: $\pm 0.5^{\circ}\text{C}$, $\pm 2\text{--}5\%$ RH
Collector plate (mild steel)	Inspect black paint for peeling; re-paint with heat-resistant black paint	Annually (or as needed)	Peeling paint reduces absorptivity; use matte black
Seals & joints	Inspect door seal, glass gasket, and panel joints for gaps	Every 3 months	Air gaps reduce thermal efficiency; re-seal with silicone

Appendix C: Arduino control code

```
#include "DHT.h"
#include <LiquidCrystal_I2C.h>
#include <Wire.h>
#include <math.h>

#define exhaustFan 10
#define inletFan 9
#define buzzer 3

#define DHTINSIDE 5
#define DHTAMB 6
#define DHTTYPE DHT22

DHT dht1(DHTAMB, DHTTYPE);
DHT dht2(DHTINSIDE, DHTTYPE);
LiquidCrystal_I2C lcd(0x27, 20, 4);

static unsigned long now = 0;
static unsigned long lastRead = 0;
static unsigned long lastUpdate = 0;
static unsigned long displayUpdateINTERVALS = 15000L;
static unsigned long readINTERVALS = 50000L;
float envTemp = 0, envHum = 0, entranceTemp = 0, entranceHum = 0, vpd = 0; runFans();

void displayValues() {
    lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print("DHT1: ");

    //DHT INSIDE
    Serial.println("DHT Readings:");
    Serial.print("Temperature: ");
    Serial.print(envTemp, 2);
    Serial.println("°C");
    Serial.print("Humidity: ");
    Serial.print(envHum, 0);
    Serial.println("%");

    lcd.print("Temp1: ");
    lcd.print(envTemp, 2);
    lcd.print(char(223));
    lcd.print("C");
    lcd.setCursor(6, 1);
    lcd.print("Humidity1: ");
    lcd.print(envHum, 0);
    lcd.print("% ");
    //DHT OUTSIDE

    lcd.setCursor(0, 2);
    lcd.print("DHT1: ");
    lcd.print("Temp2: ");
    lcd.print(entranceTemp, 1);
    lcd.print(char(223));
    lcd.print("C");
    lcd.setCursor(6, 3);
    lcd.print("Humidity2: ");
    lcd.print(entranceHum, 0);
    lcd.print("%");

    Serial.print("Vapour Pressure Deficeit: ");
    Serial.print(vpd, 0);
    Serial.println("kPa");
    Serial.println();
    // lcd.setCursor(0, 3);
    // lcd.print("VPD:");
    // lcd.print(vpd, 0);
    // lcd.print("kPa");
}

static int IN_fanSpeed = 0, OUT_fanSpeed = 0;

void setup() {
    now = millis();
    Serial.begin(9600);
    pinMode(13, OUTPUT);
    digitalWrite(13, HIGH);
    lcd.init();
    lcd.backlight();
    dht1.begin();
    dht2.begin();

    pinMode(exhaustFan, OUTPUT);
    pinMode(inletFan, OUTPUT);
    pinMode(buzzer, OUTPUT);
}

void loop() {
    delay(5000);
}
```

```

void runFans() {
  if (vpd > 3.0) { //2.5kPa
    if (envTemp < 45.0) {
      //the temperature is below 45

      noTone(buzzer);

      OUT_fanSpeed = map(0, 0, 100, 0, 255);
      analogWrite(exhaustFan, OUT_fanSpeed);

      IN_fanSpeed = map(0, 0, 100, 0, 255);
      analogWrite(inletFan, IN_fanSpeed);
    } else if (envTemp > 50.0) {
      //the temperature is above 60

      tone(buzzer, 1500, 500);

      OUT_fanSpeed = map(20, 0, 100, 0, 255);
      analogWrite(exhaustFan, OUT_fanSpeed);

      IN_fanSpeed = map(80, 0, 100, 0, 255);
      analogWrite(inletFan, IN_fanSpeed);
    } else {
      //the temperature is between 45 and 60

      noTone(buzzer);

      OUT_fanSpeed = map(25, 0, 100, 0, 255);
      analogWrite(exhaustFan, OUT_fanSpeed);

      IN_fanSpeed = map(25, 0, 100, 0, 255);
      analogWrite(inletFan, IN_fanSpeed);
    }
  } else {
    //vpd is still below 3kPa or the drying rate is low/hasn't started

    tone(buzzer, 850, 500);
    delay(1000);
    lcd.clear();

    if (envHum > 50.0) {
      lcd.setCursor(0, 0);
      lcd.print("Rel-Hum STILL HIGH!"); //humidity inside is above 50%
      lcd.setCursor(3, 1);
      lcd.print("Above 50%");
      OUT_fanSpeed = map(100, 0, 100, 0, 255);
      analogWrite(exhaustFan, OUT_fanSpeed);

      IN_fanSpeed = map(25, 0, 100, 0, 255);
      analogWrite(inletFan, IN_fanSpeed);
    } else {
      lcd.setCursor(0, 0);
      lcd.print("Temp STILL TOO LOW!"); //temperature inside is below 45
      lcd.setCursor(3, 1);
      lcd.print("Below 45");
    }
  }

  lcd.print(cvar(223));
  lcd.print("C");

  OUT_fanSpeed = map(20, 0, 100, 0, 255);
  analogWrite(exhaustFan, OUT_fanSpeed);

  IN_fanSpeed = map(50, 0, 100, 0, 255);
  analogWrite(inletFan, IN_fanSpeed);
}

}

//*****TAKING READINGS FROM DHT*****
void takeReadings() {
  entranceHum = dht1.readHumidity();
  entranceTemp = dht1.readTemperature();
  envHum = dht2.readHumidity();
  envTemp = dht2.readTemperature();
}

```

8.3 Appendix D: Cost breakdown for the project

Table 8-2 cost breakdown for the project

Item no.	Item	Quantity	Cost (UGX)
1	Wood board	3m	150,000
2	Battery + charge controller	1@	100,000
3	DC fans	2	100,000
4	Labour		100,000
5	Transportation		80,000
6	Jumper wires		15,000
7	Absorber plate	1	10,000
8	Micro controller	1	50,000
9	Back converter	1	20,000
10	MOSFET fan controllers	2	20,000
11	DHT 22 Sensor	2	40,000
12	Liquid crystal Display	1	15,000
13	Solar panel(20W)	1	30,000
14	Wire mesh	1	8,000
	TOTAL		738,000