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Drying Characterization of Uganda's Popular High Value Food Products

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Abstract

Food preservation in Uganda is critical due to high post-harvest losses resulting from inadequate storage and preservation techniques. Solar drying offers a sustainable solution, yet its performance for diverse high-value products remains under-characterized. This study aims to address this gap by investigating the drying behavior of pineapple, mango, cassava, banana, and beef, focusing on drying kinetics and system efficiency under Uganda's wet and dry seasons. An indirect solar dryer equipped with a flat plate thermal collector was used to monitor key parameters, including ambient and dryer temperatures, ambient and dryer relative humidity, drying time and moisture content. Experiments conducted at Busitema University included two seasonal runs, with predictive models developed using Python. Results indicate that dryer temperatures peaked at 60˚C during the dry season, while humidity dropped significantly, enhancing drying efficiency. Mango exhibited the shortest drying time (7 h), followed by cassava (8 - 9 h), while pineapple required the longest (8 - 13 h), depending on the season. Peak drying rates were observed between 12:00 pm and 3:00 pm, coinciding with maximum solar irradiance. Predictive models for dryer conditions and moisture content showed strong conformity with experimental data ($R^2 > 0.7$ in most cases). These findings underline the solar dryer's capability to efficiently preserve high-value food products, although incorporation of thermal energy storage or auxiliary heat sources like biomass is necessary for consistent wet-season performance.

Keywords

Drying, Solar Dryer, Characterization, Food Products, Food Losses

1. Introduction

Food preservation is a critical concern in many developing countries, including Uganda, where agricultural production often exceeds local consumption during peak harvest seasons. A substantial portion of this surplus is lost due to inadequate preservation techniques and poor storage infrastructure [1] [2]. Solar drying has emerged as a sustainable and energy-efficient solution to address these challenges, particularly in tropical regions like Uganda, which receive high solar radiation throughout the year [3]. Traditional drying methods, such as open sun drying, are widely practiced but come with several drawbacks, including contamination, uneven drying, and loss of nutritional quality [4] [5]. Solar dryers, on the other hand, provide a controlled environment for drying, leading to improved product quality and reduced drying time [6] [7] as demonstrated in an experimental study of a modified Icaro solar dryer, which achieved enhanced heat transfer efficiency and reduced the moisture content of coffee cherries from 70% to 9.87% in 30.2 hours [8]. Similarly, investigating the performance of a single-basin, double-slope solar dryer utilizing natural convection for drying bottle gourds and tomatoes revealed superior moisture removal efficiency, achieving a 94.42% reduction in tomatoes and 83.87% in bottle gourds compared to open sun drying, further underscoring the advantages of solar drying technology in preserving product quality and enhancing drying efficiency [9]. Characterizing solar dryers for different food products is essential for optimizing their design and ensuring their efficiency in diverse applications. In Uganda, where agriculture plays a significant role in the economy and post-harvest losses remain a pressing challenge [10], research into this area is highly relevant. Different food products have unique drying requirements to maintain quality and safety. For example, cassava chips dried on raised platforms demonstrated higher drying rates and better microbial quality than those dried in direct passive solar dryers [11]. Similarly, solar drying of vegetables like solanum aethiopicum (Shum) has been shown to preserve nutrients more effectively than traditional sun drying methods [12]. Given that Uganda experiences post-harvest losses of up to 45% for certain crops, inadequate drying methods exacerbate food insecurity and reduce farmer's incomes [10]. By optimizing solar drying conditions for crops, significant reductions in losses can be achieved, enhancing product quality and market access for farmers. Pineapple, mango, cassava, banana and beef were selected for this study due to their economic and nutritional significance in Uganda, with pineapples and mangoes serving as prime examples of major horticultural exports that are highly perishable and prone to post-harvest losses due to their high moisture content [13]. Cassava, a staple food for millions demands proper drying to enable storage and its processing into products like flour [14], while beef, as a protein-rich food source, requires meticulous preservation to prevent microbial spoilage [15]. This research aligns with SDG 1 and SDG 2, supporting rural livelihoods and sustainable development by enhancing food security and reducing post-harvest loss through renewable and cost-effective alternatives to traditional drying methods. The performance of a solar dryer is influenced by factors, such as temperature, humidity, airflow, and the characteristics of the food being dried. Uganda experiences two main rainfall seasons, from March to May and September to November, with a generally dry period from June to August across most regions [16] [17]. This study was conducted between March and July 2024, encompassing both the rainy season (March to May) and the dry season (June to July). Its primary objective is to characterize the performance of a solar food dryer with selected food types, evaluating its efficiency and drying kinetics under varying seasonal conditions. Characterizing the drying process is essential for enabling automation, ensuring safe and reliable dryer operation, and enhancing overall efficiency [18]. Furthermore, the study aims to identify opportunities for optimizing the solar dryer to maintain consistent and effective performance, particularly during the challenges posed by the wet season.

2. Materials and Methods

In order to determine the drying characteristics of selected agricultural products, the solar dryer was loaded to its full capacity. Five (5) agricultural products were used namely, pineapple, mango, beef, banana and cassava. In this work, moisture content, ambient temperature, temperature inside the drying chamber (Dryer temperature), ambient relative humidity, relative humidity inside the drying chamber (Dryer relative humidity), drying time were measured and results presented.

2.1. Description of the Solar Drying System

The crop dryer in this study is an indirect type adopted from [19]. It is shown in **Figure 1**. It is composed of a flat plate solar thermal collector which traps and concentrates the solar energy, the cute and ducting which guide air into and out of the drying chamber, the drying chamber where food products are placed on trays for drying and a door for access to food products under drying. The dryer

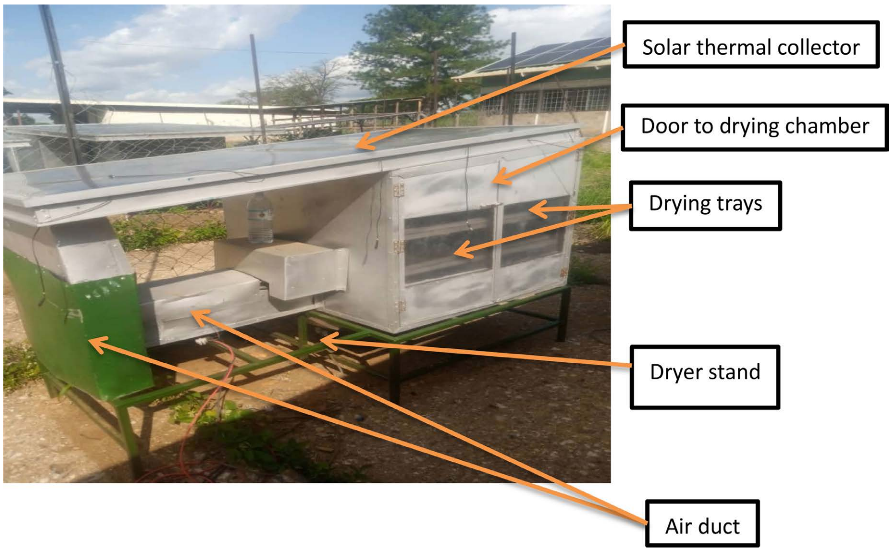


Figure 1. Solar crop dryer (Source: Primary data).

operates as an open-air circulation system with fans to assist the air circulation. Air is drawn from the atmosphere by use of a suction fan. It is then circulated through trays carrying food to be dried in the drying chamber and after passes it to the ducting. The ducting eventually releases that air out of the dryer since it is now humid given that it carries moisture evaporated from the food.

2.2. Sample Preparation

Experimental samples for cassava, pineapple, mango, beef and banana were prepared for drying in a solar dryer at Busitema University main campus, located in Busia district, Eastern Uganda at an altitude of 1130.8 m, geographic coordinates of 0˚32'40.9"N (latitude) and 34˚01'16.3"E (longitude). Samples for each of these agricultural products were washed and sliced into pieces of 4 mm thickness as shown in **Figure 2**.

Figure 2. Sample preparation (Source: Primary data).

2.3. Experimental Set Up

In this experiment, data was collected during the dry season (June to July) as well as wet season (March to May) of the year 2024. Samples were randomly distributed in 3 replicates for 2 experimental runs during each season. Drying characteristics of the sample materials monitored were initial moisture content, final moisture content, dryer temperature and dryer relative humidity as shown in **Figure 3**. Other drying conditions such as drying time, ambient temperature and ambient relative humidity were also measured and recorded. All parameter measurements were taken and recorded at hourly intervals. Moisture loss was also monitored hourly by weighing samples on a scale and using Equation (3). Initial moisture content and moisture content at two hourly intervals was determined using oven method. Models to predict dryer temperature, dryer relative humidity and moisture content, for all the agricultural products were generated using Python since they are fundamental for understanding drying characteristics of any commodity [4].

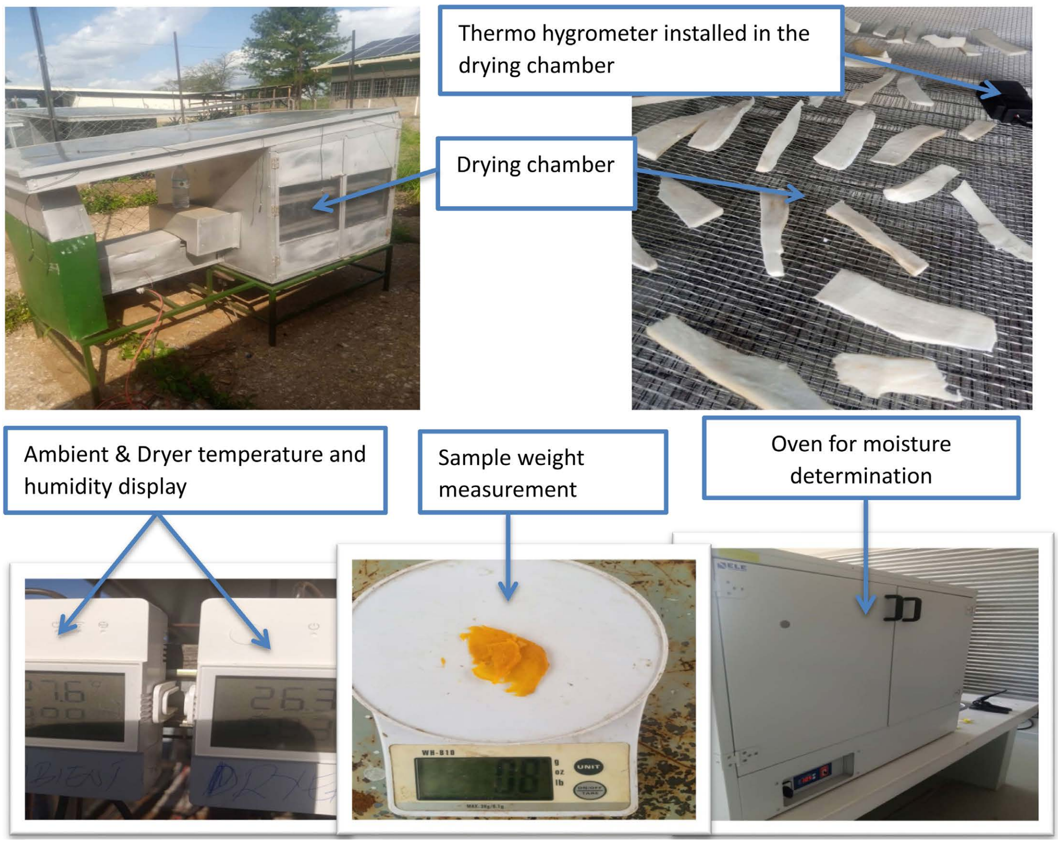


Figure 3. Experimental set up.

2.4. Analysis of Moisture Content

Samples were selected and measurements done at hourly intervals to monitor moisture content reduction during the drying process. Taking of samples from the drying chamber was done fast enough to prevent dryer temperatures from dropping drastically due to prolonged exposure to ambient conditions, and handled appropriately to minimize moisture re-absorption. Two methods of moisture determination were used; weight loss method for hourly moisture measurement and air oven method for initial and final product moisture measurement. The air oven method was done according to the procedure described by [20] at 105˚C for 24 h. The moisture content on wet basis was computed and reported as a percentage according to [21] using Equation (1).

$$\%\text{MCwb} = \frac{(\text{Dwt} + \text{Fwt}) - (\text{Dwt} + \text{Dried sample weight})}{\text{Fwt}} \times 100 \quad (1)$$

where MCwb—moisture content in wet basis; Dwt—dish weight; Fwt—Fresh sample weight.

Moisture determination by weight loss method was done using WBH-10 electronic scale and Equation (2) [22].

$$\text{MCt} = 100 - \left\{\text{IW}/\text{FW}\left(100 - \text{MCi}\right)\right\} \tag{2}$$

Where MCt—Moisture content at time t; MCi—Initial moisture content; IW—initial weight; FW—final weight.

Drying rate for each product during drying was calculated using Equation (3) [22].

$$\text{DR} = \left(M_t - M_{t-\Delta t}\right)/\Delta t \tag{3}$$

Where: DR = Drying rate (kg water/kg dry matter·h); M_t = Moisture content at time t (kg water/kg dry matter or % wet basis); $M_{t-\Delta t}$ = Moisture content at time $t + \Delta t$; Δt = Time interval (h or min).

3. Results and Discussion

3.1. Initial Measurements

Samples of fresh cassava, pineapple, beef, mango and Banana were tested for initial moisture content using oven method. Values obtained were similar to those reported in previous studies as shown in **Table 1**. The discrepancies could be attributed to difference in variety, difference in locality, age at harvest and seasonality of harvesting period [23].

Table 1. A comparison of initial moisture content results with findings of previous studies.

Food/Crop	Current study moisture content (% w.b)	Previous study moisture content (% w.b)	Reference
Cassava	63.8	61.4, 63	[11] [24]
Pineapple	88.5	85	[25]
Beef	70.4	72.98	[26]
Mango	79.4	73.21 - 87.2	[27]
Banana	71.2	66.23 - 75.25	[28]

3.2. Drying Kinetics

The graphs in **Figure 4** illustrate temperature profiles for ambient and dryer conditions during the wet and dry season. In the wet season (**Figure 4(a)**), ambient temperature remains relatively stable around 30˚C, while dryer temperature fluctuates between 31˚C and 47˚C. The stability of ambient temperature at around 30˚C is likely due to high humidity levels and frequent cloud cover which reduce temperature fluctuations [29] [30]. The dryer temperature fluctuation can be attributed to the system's struggle to overcome high ambient humidity which hampers efficient heat transfer and moisture removal [31] [32]. This emphasizes the need for better temperature regulation during the wet season to maintain consistent

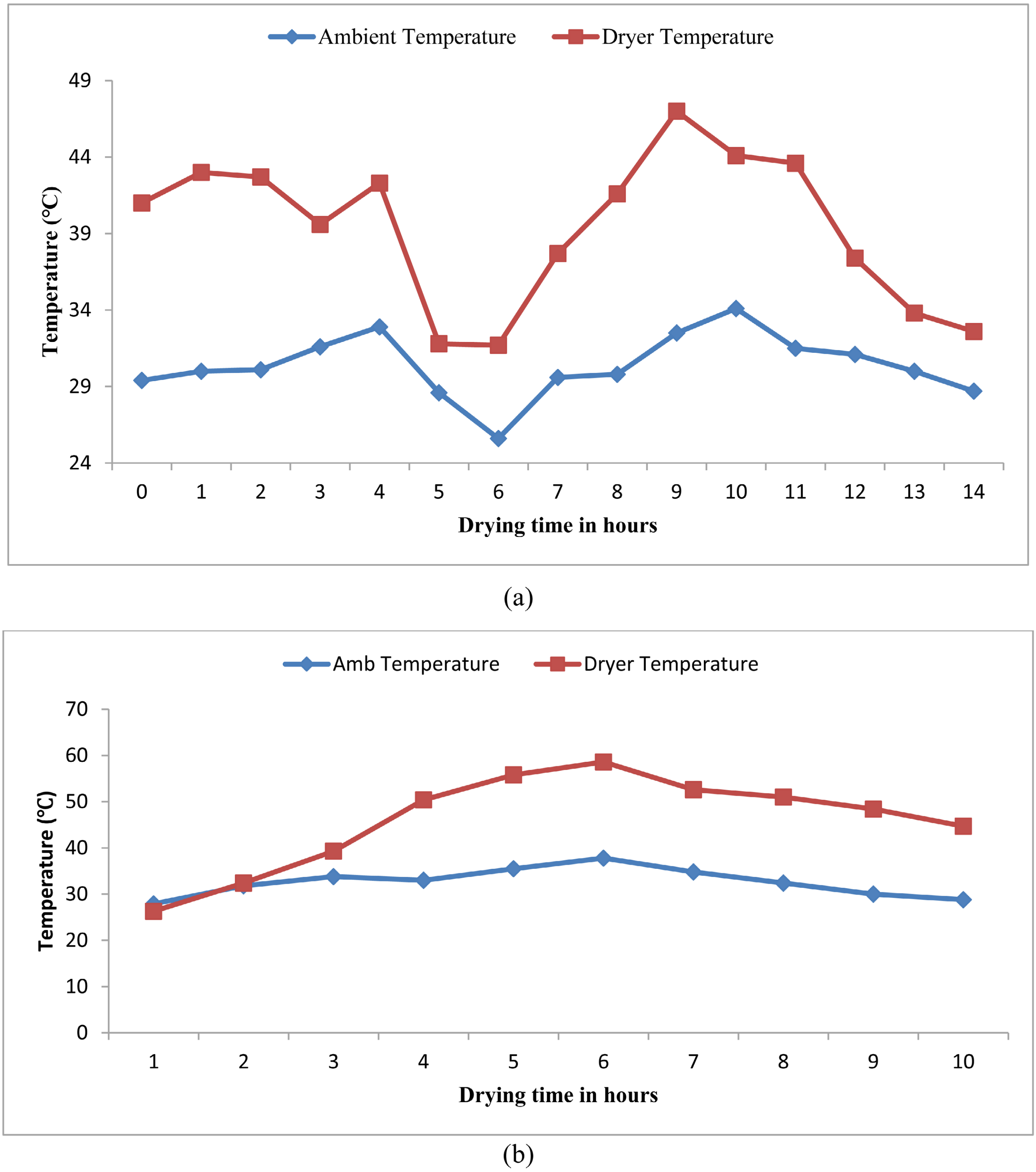


Figure 4. Dryer and ambient temperature profiles during the wet (a) and dry (b) season.

drying efficiency. In the dry season (**Figure 4(b)**), ambient temperature steadily increased from 27.9˚C at the start of the experiment (8:00 am) to approximately 37.8˚C by the 5th hour (1:00 pm), before showing a slight decline thereafter. During the same period, the dryer temperature exhibited a continuous rise, reaching its peak of around 60˚C also at 1:00 pm. The steady increase in ambient temperature is associated with lower humidity and clear skies, allowing for greater solar insolation and surface heating. This trend aligns with studies on effect of solar radiation variability on climate [33]. The dryer temperature rising to 60˚C indicates effective heat absorption and retention due to lower atmospheric moisture, which enhances drying efficiency. These findings are consistent with observations by [34] who reported reduced drying time with increase in atmospheric temperature.

The graphs in **Figure 5** illustrate the relative humidity profiles for ambient and dryer conditions during wet (a) and dry (b) seasons, highlighting the drying system's performance under varying environmental conditions. In the wet season

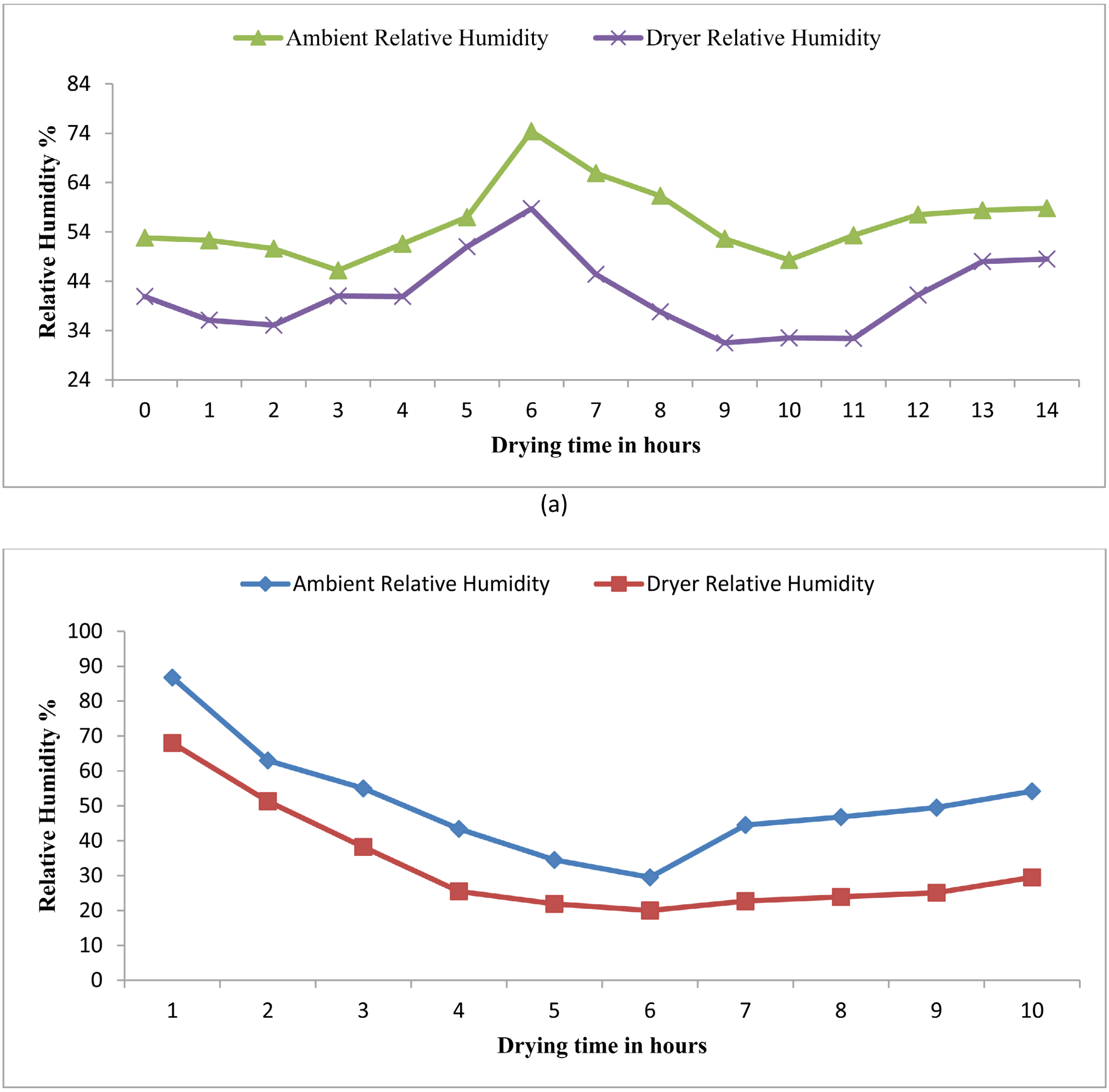
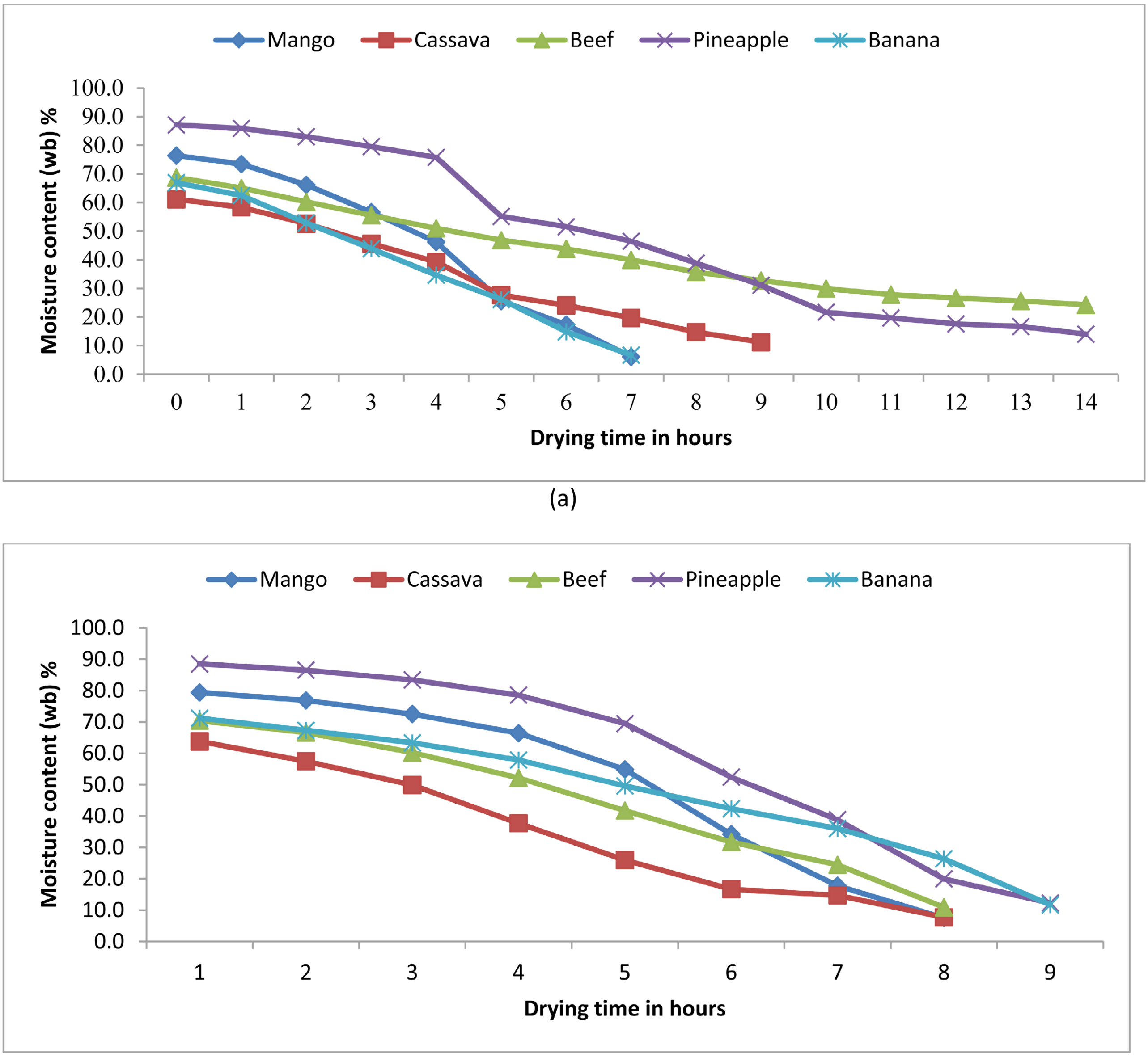


Figure 5. Dryer and ambient humidity profiles during the wet (a) and dry (b) season.

(**Figure 5(a)**), ambient humidity fluctuates significantly, peaking around 74% attributed to presence of dense moisture-laden air, while dryer humidity remains consistently lower. These trends imply that the drying system effectively counteracts high ambient humidity in the wet season but requires adjustments to sustain efficiency over extended periods. The dry season (**Figure 5(b)**), exhibits a steady decline in both ambient and dryer humidity indicating superior efficiency with reduced energy demands due to naturally favourable conditions. The dry season's steady decline in both ambient and dryer humidity aligns with reduced atmospheric moisture and lower dew point temperatures. These conditions facilitate faster drying rates and improved system performance due to the higher vapour pressure deficit, which enhances moisture migration from the material being dried to the air [34]. Optimizing the system with adaptive controls can enhance energy savings during the dry season while improving its ability to counteract high ambient humidity and boost performance in the wet season.

Figure 6 shows the relationship between moisture content reduction and drying time for various agricultural products during wet (a) and dry (b) seasons highlighting product-specific drying behaviors. Variations in moisture content reduction are due to differences in initials moisture content and structural differences among the agricultural products. It can be generally observed that as drying time increases, product moisture content is reduced. Agricultural products with higher initial moisture content, such as pineapple, banana, and mango, exhibit slower initial drying rates due to the need for significant moisture removal to establish a vapour pressure gradient. However, their porous structures and high sugar content accelerate surface evaporation once drying begins. This is consistent with findings by [35], who noted that products with high sugar levels exhibit a faster moisture loss during intermediate drying stages due to enhanced capillary action. Cassava & banana with dense, starchy tissues slow moisture diffusion, causing a gradual curve [36]. Compared to the starchy (cassava, banana) and sugary (mango, pineapple) plant based products, which primarily undergo moisture loss through diffusion driven mechanisms, beef exhibits significantly different drying characteristics due to its unique composition. The high protein and fat content in beef contributes to surface case hardening during drying, particularly under high temperature or low humidity conditions [37]. This phenomenon results in the formation of hardened outer layer that impedes internal moisture migration, thereby reducing drying efficiency [38]-[40]. Additionally, fat migration during drying can further complicate moisture transport by creating hydrophobic barriers that interfere with water evaporation pathways [39] [41] [42]. These effects contribute to slower and less uniform drying in meat products. In contrast, plant materials like cassava and banana typically exhibit more predictable drying behavior governed by internal moisture diffusion, with fewer barriers to moisture release [43] [44]. In the wet season, mango and banana lead in drying efficiency due to their porous structures facilitating faster water removal even under high humidity conditions. Their minimal moisture content by 7 - 8 h



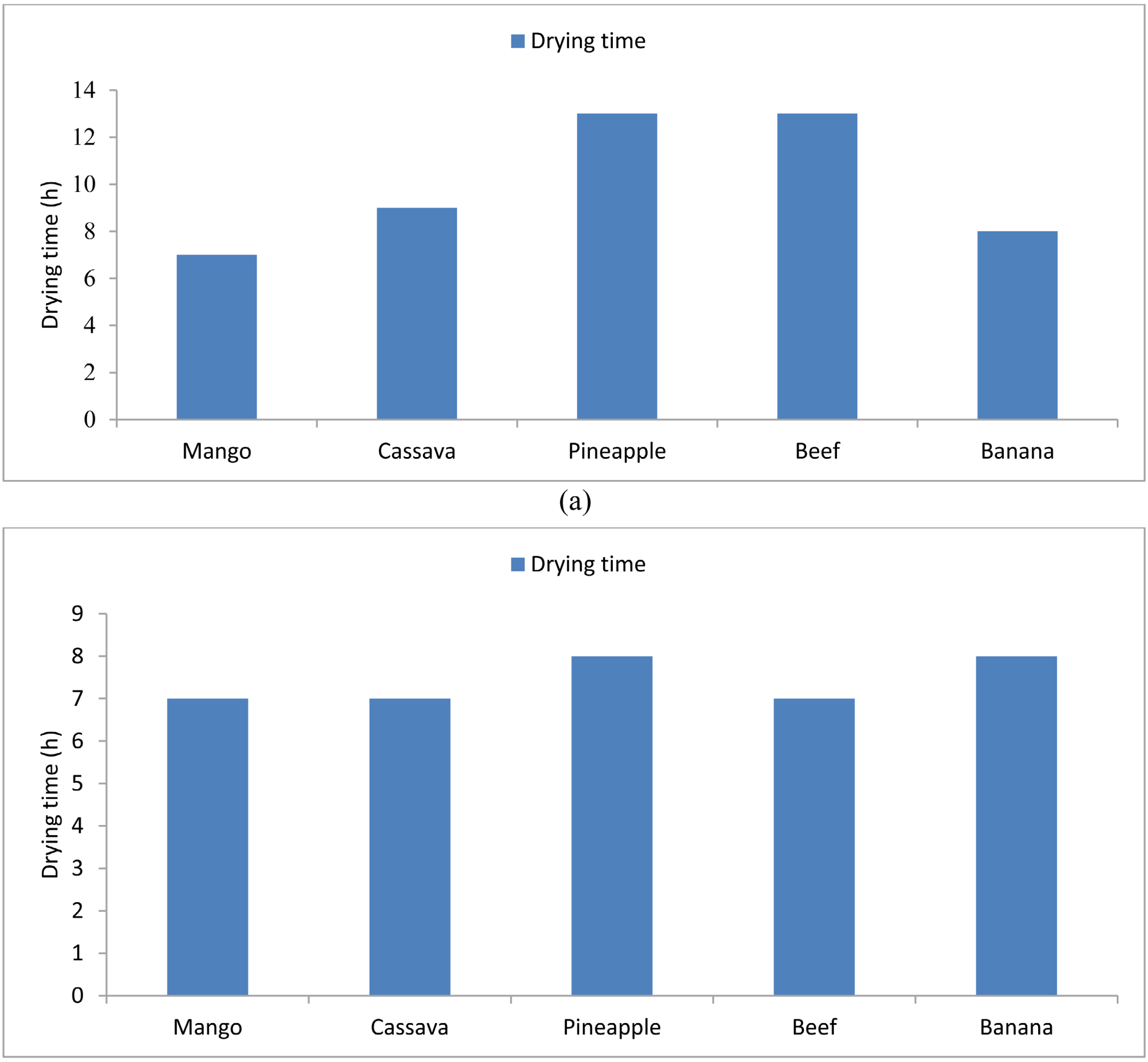
(a)

(b)

Figure 6. Moisture content curves for the dried agricultural products during the wet (a) and dry (b) season.

highlights their adaptation to ambient conditions. Cassava's dense structure causes a delayed response, reaching minimal moisture at 9 h. Pineapple and beef, requiring longer drying times (13 h), reflect their higher water retention and complex drying behavior under humid conditions. In the dry season, the moisture reduction for all products is more consistent and faster, reflecting the favorable ambient conditions. Cassava, mango and beef lead in drying efficiency, reaching minimal moisture content by 7 h, while pineapple and banana require more time (8 h), due to their higher water retention. These trends demonstrate the system's improved efficiency in dry conditions, supported by studies such as [34], which highlight the role of low humidity in enhancing drying system performance.

From **Figure 7**, it is observed that mango is the best performing product in the



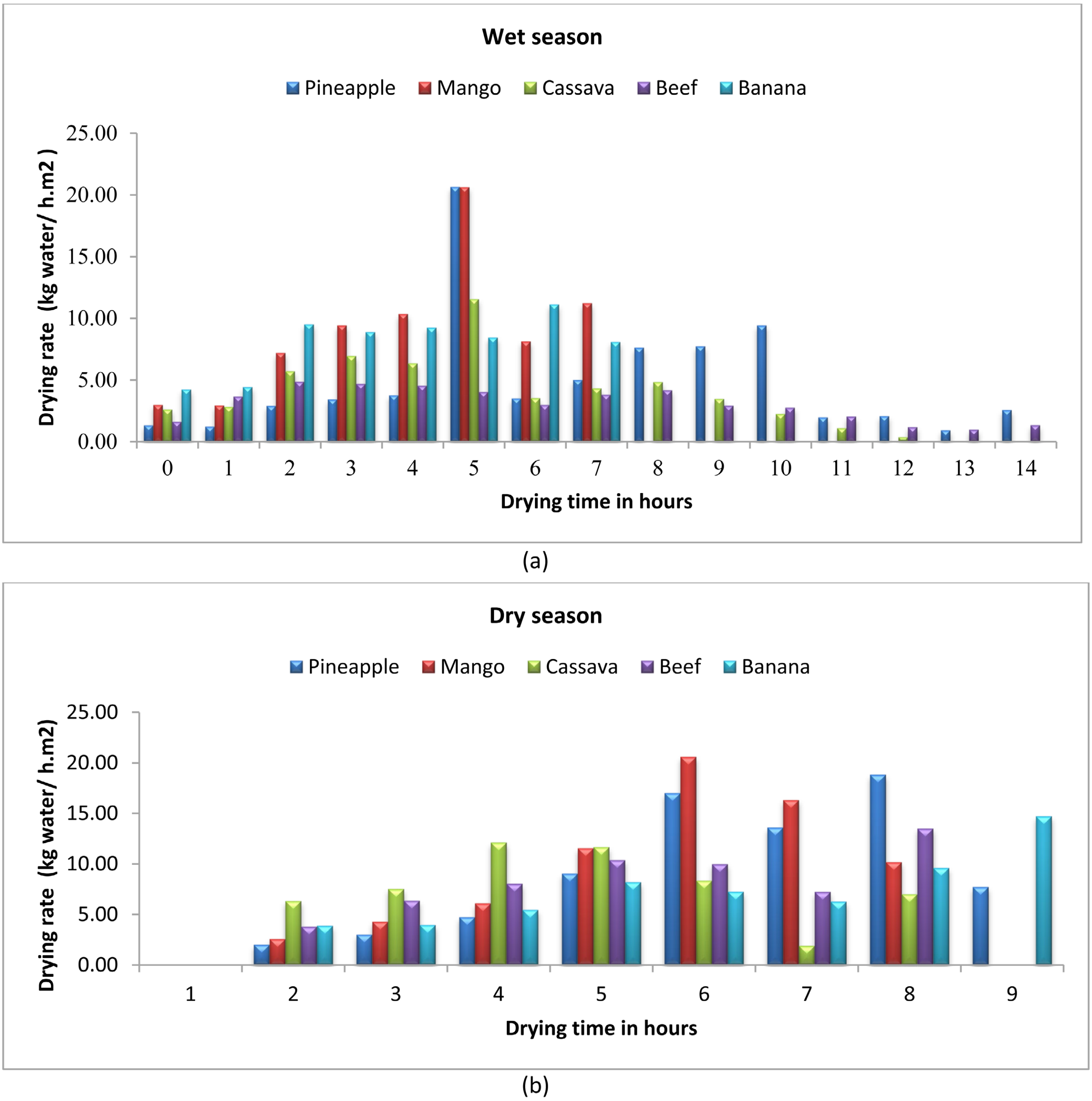
(a)

(b)

Figure 7. Drying time of the dried agricultural products during the wet (a) and dry (b) season.

solar dryer with the least drying time (7 h) during both seasons. This could be due to high sugar content and porous structure that enable rapid moisture evaporation. This aligns with findings from research on forced-convective solar tunnel dryers that found that mango exhibited high effective moisture diffusivity, significantly outperforming denser crops like potato and okra [45]. Additionally, studies from Tanzania showed that solar drying retains mango's sugars, indicating minimal structural collapse that preserves pathways for moisture escape [46]. Pineapple is the slowest drying product taking 13 and 8 hours during wet and dry season respectively. This is attributed to its thick fibrous flesh and high initial moisture content that prolong drying [4]. Banana and cassava have intermediate drying in both seasons with a less significant difference in drying time. This is attributed to their dense starch-rich matrix that imposes great resistance to internal moisture migration.

From **Figure 8**, it is observed that all products show the highest drying rates between 12:00 PM and 3:00 PM, coinciding with maximum solar irradiance and ambient temperature. After 3:00 PM, drying rates drop sharply due to reduced solar energy and lower temperatures and by late evening (6:30 PM onward), rates approach zero, and indicating minimal moisture removal. Banana has the highest initial drying rate (likely due to high surface moisture) but declines rapidly. Beef and cassava show slower but more sustained drying, typical of dense, starchy


Wet season

(a)

Dry season

(b)

Figure 8. Drying rates for the different agricultural products during the wet (a) and dry (b) season.

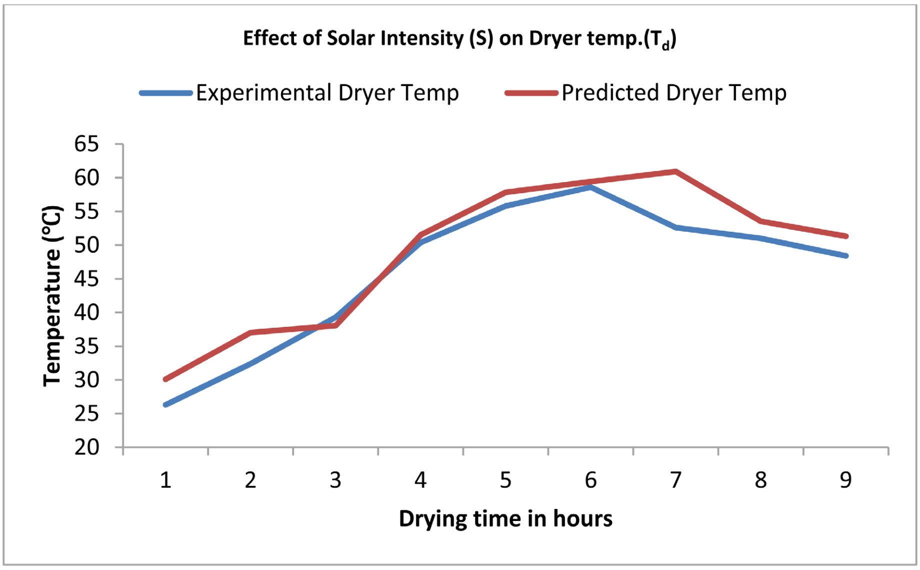
materials. Pineapple and mango (high sugar content) dry faster initially but stabilize earlier than cassava. It is also observed that cassava, mango, and pineapple exhibit peak drying rates around 5 PM despite declining solar radiation and ambient temperatures. This could be due to the fact that solar dryers often incorporate thermal storage materials like dark absorber plates that retain heat even after peak solar noon [47]. This stored energy continues to drive moisture evaporation later in the afternoon, causing a lag between peak insolation and peak drying rates [48]-[50]. For example, if the dryer's internal temperature peaks at 3 PM but remains high until 5 PM due to thermal inertia, drying rates may peak later. This observation also suggests that the dryer is well insulated. Well-insulated dryers maintain elevated temperatures longer than ambient conditions, sustaining evaporation rates even as external temperatures drop. It can also be explained by product specific moisture dynamics. Cassava's thick cellular structure slows moisture migration to the surface [51]. The falling rate period (FRP) dominates, meaning drying depends on internal diffusion**,** not just ambient heat. Heat absorbed earlier penetrates deeper by 5 PM, releasing trapped moisture later. According to [52], sugary tissues (like mango/pineapple) bind water tightly, requiring sustained heat to overcome moisture adhesion. Delayed peak drying aligns with prolonged energy input needed to break these bonds. Even with lower temperatures, afternoon air is often drier (lower relative humidity) than midday, enhancing the moisture gradient and evaporation potential [4].

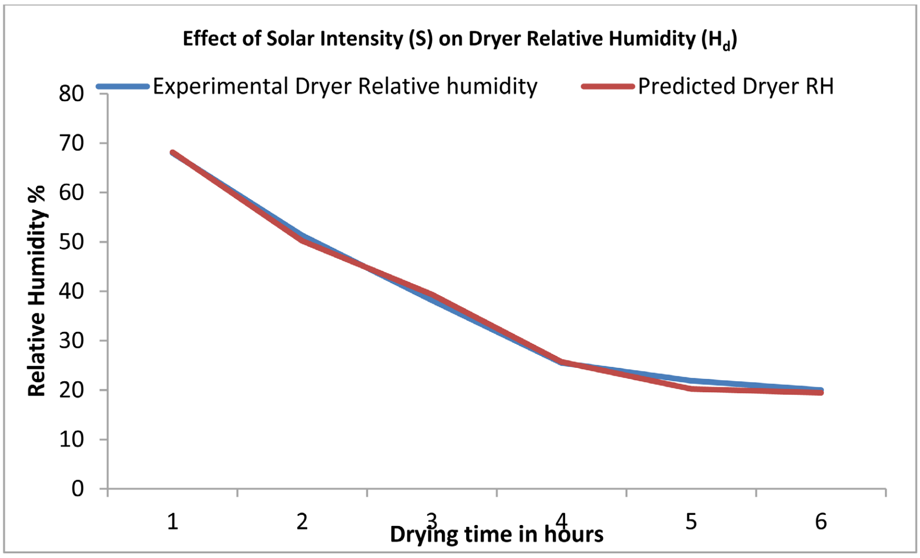
3.3. Model Fitting

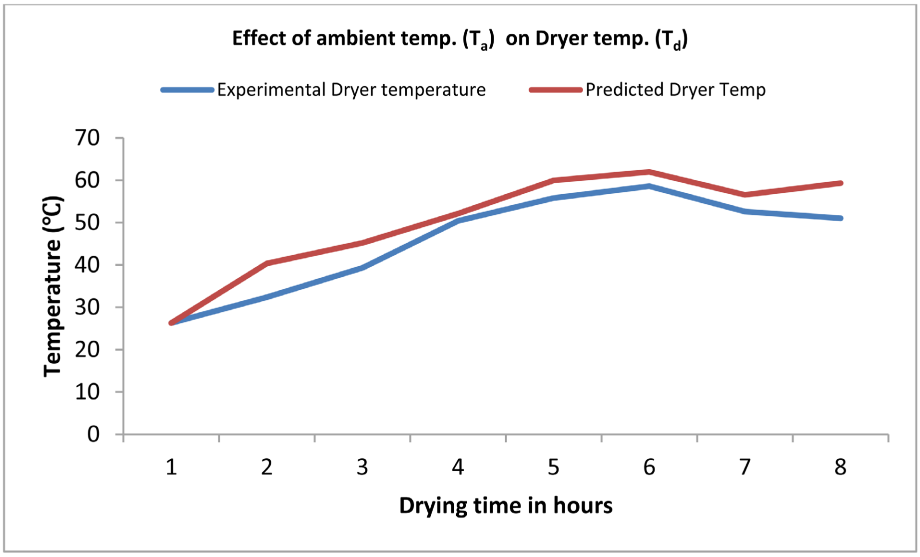
Models in **Table 2** were developed and validated to predict dryer temperature, dryer relative humidity and moisture content for various dried agricultural products. The independent variables considered in the modelling process were solar

Table 2. Models to predict the effect of ambient conditions on dryer conditions in the wet season and dry season.

Model name	Dry season		Wet season	
	Model expression	R^2	Model expression	R^2
Effect of Solar Intensity (S) on Dryer temp. (T_d)	$T_d = 0.0002S^2 - 0.1724S + 73.9886$	0.8271	$T_d = 0.0164S + 30.377$	0.492
Effect of Solar Intensity (S) on Dryer Relative Humidity (H_d)	$H_d = -0.0002S^2 + 0.2281S - 3.3325$	0.6572	$H_d = -0.0147S + 46.235$	0.394
Effect of ambient temp. (T_a) on Dryer temp. (T_d)	$T_d = 3.4398T_a - 69.004$	0.7375	$T_d = 1.8143T_a - 15.874$	0.5361
Effect of ambient temp. (T_a) on Dryer Relative Humidity (H_d)	$H_d = 0.4482\,T_a^2 - 34.445T_a + 680.96$	0.7957	$H_d = -0.1876\,T_a^2 + 9.8152T_a - 86.015$	0.3959
Effect of ambient RH (H_a) on dryer RH (H_d)	$H_d = 0.9263H_a - 12.784$	0.9286	$H_d = -0.0231\,T_a^2 + 3.0327H_a - 57.9069$	0.2318
Effect of ambient RH (H_a) on dryer temp. (T_d)	$T_d = -0.6224H_a + 77.193$	0.9243	$T_d = -0.4376H_a + 63.7529$	0.3845


Effect of Solar Intensity (S) on Dryer temp.(T_d)
Experimental Dryer Temp
Predicted Dryer Temp
Temperature (°C)
65
60
55
50
45
40
35
30
25
20
1
2
3
4
5
6
7
8
9
Drying time in hours


Effect of Solar Intensity (S) on Dryer Relative Humidity (H_d)
Experimental Dryer Relative humidity
Predicted Dryer RH
Relative Humidity %
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
Drying time in hours


Effect of ambient temp. (T_a) on Dryer temp. (T_d)
Experimental Dryer temperature
Predicted Dryer Temp
Temperature (°C)
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
Drying time in hours

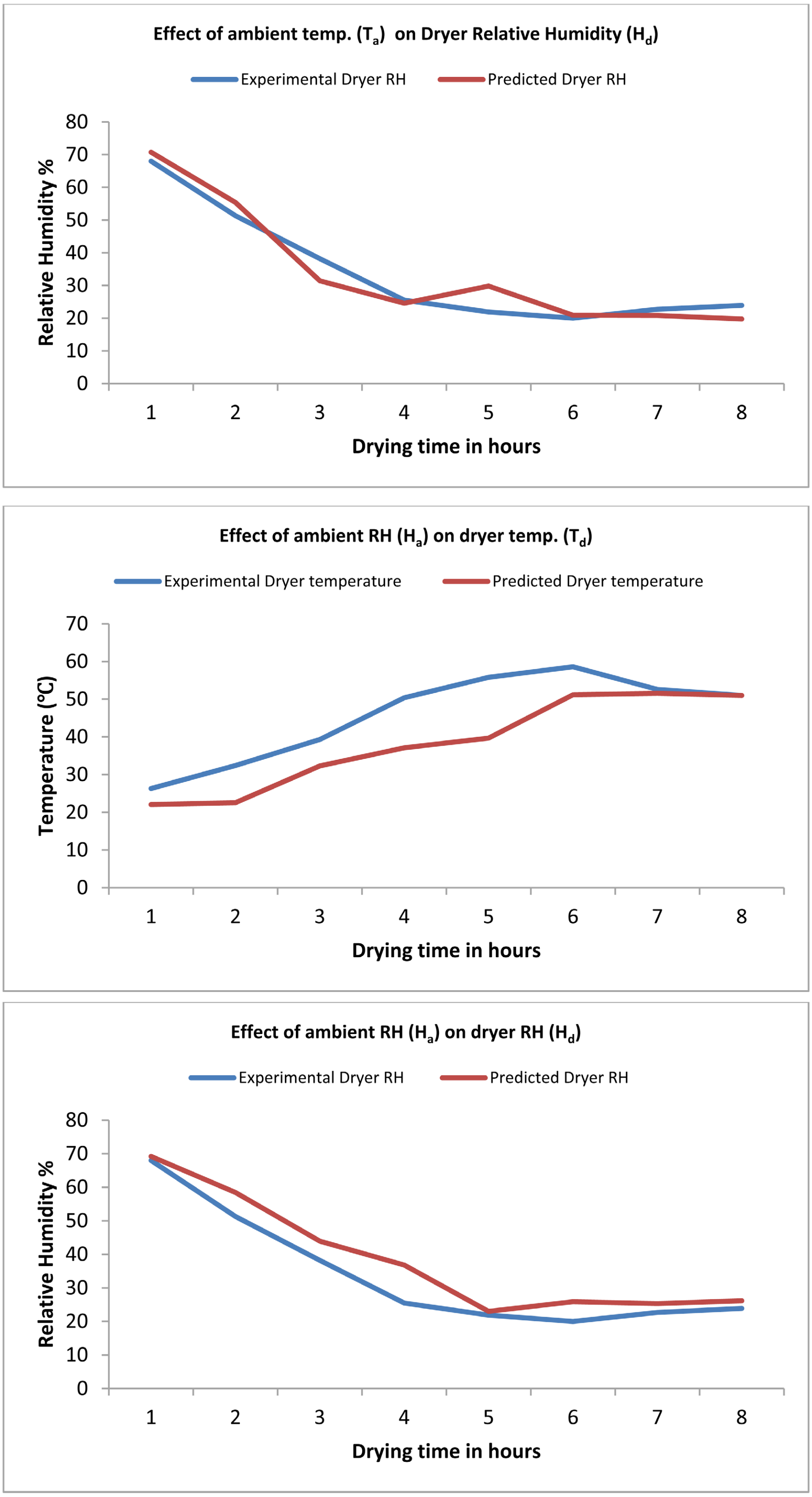


Figure 9. Comparison of predicted and experimental data by established models during the dry season.

intensity, ambient temperature and ambient relative humidity. These variables directly influence the energy available for drying (solar intensity), the air's moisture-holding capacity (ambient temperature), and the moisture gradient driving evaporation (relative humidity) [31]-[33] [46]. The air flow rate was excluded because the dryer uses a single constant-speed fan, thus its influence becomes uniform and does not contribute to variability [53] [54].

Figure 9 indicates comparison of predicted and experimental data by established models for mango during the dry season. The established models provided satisfactorily a good conformity between experimental and predicted data ($R^2 > 0.8$). Predicted data generally fitted well on the experimental curves, with intersection points at which the model exactly matches the experimental data showing the suitability of these models in describing drying behavior of mango during the dry season.

4. Conclusions and Recommendations

The study quantitatively demonstrates the effectiveness of solar drying for various Ugandan food products, highlighting its potential to achieving controlled drying. Characterization of the drying system revealed that during the dry season, the dryer achieved peak performance with temperatures reaching 60˚C and relative humidity dropping below 30%, attaining mango's drying time of 7 h due to its high sugar content and porous structure. Pineapple, characterized by its high initial moisture content, required 8 - 13 h, depending on the season. Products like cassava and banana exhibited intermediate drying times with less pronounced seasonal variations, attributed to their dense starch structures and moderate water retention. Beef, with high protein and fat content, displayed slower drying rates due to its low moisture diffusivity. Model predictions for dryer performance and moisture content yielded R^2 values exceeding 0.8 for most parameters, confirming the reliability of the predictive models and their ability to characterize product-specific drying behavior under varying environmental conditions. Farmers may priotize drying starchy crops like cassava and banana during the dry season when solar intensity is highest, while value added products like beef and fruits can benefit from improved dryers with thermal storage or hybrid energy sources during the wet season. This study underscores the importance of adaptive drying control strategies tailored to product type and seasonal conditions by incorporating thermal energy storage or auxiliary heat sources like biomass to optimize performance, reinforcing the role of solar dryers as a sustainable solution for food preservation in Uganda.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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