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Development and Validation of a Solar Cabinet Dryer with Solar Thermal Bed

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ABSTRACT

The model validation of an experimented indirect passive cabinet solar dryer with thermal storage bed for drying of high moisture perishables is presented. The system structural and supporting frames were fabricated using 25mm × 25mm × 2.5 mm and 50mm × 50mm × 4 mm mild steel angle iron respectively and then covered with 1.5mm thick mild steel sheet. Provision was made for insulation using sawdust while Ojano gravels served as storage heat material with black painted aluminum sheet as the absorber. Observed solar intensity for the month of March comparatively was higher to the simulated values but contrast to lower ambient and gravel bed temperatures. The experimental product drying temperature reduces linearly in conformity to the simulated result. Supplementary heat from storage bed was utilized for drying operation for a maximum of five and half hours after sunset. System annual drying output ranges from 27.89 to 67.48 kg depending on the month and annual drying duration. Statistical tools for model validation showed good quality fit between the predicted and the measured data. The work portrays the viability of solar dryers with thermal bed in drying high quality perishables with greener energy source. Thus, the incorporation of sensible heat materials to aid drying at solar radiation off peak period was suggested.

Keywords: Development, solar cabinet dryer, perishables, heat storage bed; validation.

1.0 INTRODUCTION

The use of solar energy is gradually gaining acceptance globally due to its environmental friendliness, long time economic benefits and ease for rural adaptation. Countries within the tropics are known to enjoy more solar energy than those found in the temperate climates. Studies have shown that the performance of solar energy systems is a function of the availability of solar radiation, solar tracking capability, and materials for construction among others. However, the fluctuations in the amount of solar energy receive across the day and seasons have necessitated the need for its storage for effective utilisation during the off peak periods. Thus, solar energy systems incorporated with thermal energy are known to be more proficient as various works have shown. The storage could be in phase change or sensible heat storage materials. An indirect natural convection solar fruit and vegetable dryer integrated with sand under the absorber plate as a heat storage material was investigated, and a reduction of 12

hours was achieved [1]. Passive solar dryer with bed heat storage reported by [2] attained moisture decreased from 73% to 10.2% for cassava. Transient analytical model for a solar crop dryer having reversed absorber plate type collector and packed bed thermal storage bed could dry 95 kg of onions in 24 hours drying period [3]. Evaluation of a developed maize solar dryer having black painted rock pebbles of volume 0.15 m^3 for heat absorption had savings in time by using the solar grain dryer as against the traditional open sun drying [4]. Test evaluation test using an active solar dryer with adjustable airflow rates and sensible heat storage unit for cassava, yam, sweet potatoes, cocoyam, ginger and turmeric in their chips shows drying period range of 24-29 and 42-50 hours for solar and, open sun drying method respectively [5]. Solar tunnel dryer with heat storage unit using local materials for drying leafy vegetables and other agricultural products could dry 17 kg of sliced cabbage from 95% moisture content wet basis to 9% in five days in a period characterized by intermittent downpours and permanent cloud cover [6]. Reduction time of 3 hours for drying 1 kg of grapes using sand as heat storage material in a multi-tray indirect-mode forced convection solar dryer is reported by [7].

The implementation of a natural/forced convection solar vegetable dryer incorporated with a heat storage unit gave higher drying capabilities compared to the natural convection system and the stored useful heat used for about six hours in drying during the night [8]. An indirect-mode forced-air solar kiln timber dryer with a slag bed roughened absorber and heat storage could dry tropical hardwoods to desire moisture content and of high quality within 2-5 weeks depending on weather conditions, species and thickness of the lumber [9]. Performance evaluation of a forced convection type solar dryer with thermal storage bed (gravels) having volume of 0.15 m^3 for drying ginger supplemented the system energy load demand for two hours during the night [10]. The quality of fruit and vegetable product dried without sandstone heat storage dryer has less nutrient content than product dried with heat storage dryer [11]. The performance evaluation of a passive solar crop dryer with a movable heat storage unit in Nsukka, Nigeria indicated a heat storage unit is requisite for continuous operation of solar dryers due to day and seasonal fluctuation in the amount of solar radiation received. There is need to validate the performance of the thermal heat storage bed for the developed and simulated model with particular reference to temperature of the gravel bed and profile on the trays including cumulative moisture removed Proximate analysis indicated that solar dried vegetables had significantly higher protein, fibre, ash, carbohydrate and vitamin C except for the fat content that was significantly higher for all the open sun dried samples than the solar dried and fresh products [12]. A novel numerical model to study the performance of mixed mode solar dryer with pebbles heat storage bed beneath the absorber plate for waffles. Experimental test results indicated that the presence of sensible heat storage material gave better absorber temperature, higher drying rate and efficiency. This work seeks to validate the predicated values for an indirect solar cabinet dryer meant for drying batch 6 kg of tomatoes slice [13].

2.0 MATERIALS AND METHODS

2.1 Materials

The selection of materials for the development of a solar thermal system is fundamental to its performance. Plain glass of 4 mm thickness was adopted as a glazing material due to its better transmissivity characteristics, superior resistance to heat, low expansion/contraction and easy of accessibility, while aluminium plate served as an absorber plate for its light weight, relatively lower cost, ease of fabrication and energy effectiveness in usage over copper and silver. Absorber plate was coated with black paint over other coatings due to its higher solar absorptivity, low emittance at angles other than normal incidence; adherence and durability when exposed to weathering, sunlight and stagnation temperatures. For minimum heat losses, bottom and sides of the solar collector unit, and the drying chamber sides were lagged with **s**awdust. Preference was given to sawdust over other materials basically

due to its low cost and easy of availability. The drying cabinet structural frame was built from mild steel iron of 25 mm×25 mm×2.5 mm and covered with 1.5 mm thick mild iron sheet to provide the needed economic life span of the system. The outer wall of the drying chamber was painted white to give it a polish surface for minimizing heat loss by radiation. The drying chamber housed two drying trays. Angle iron of 25 mm × 25 mm × 2.5 mm was employed for constructing the drying trays frames and stainless steel wire mesh for holding the product to avoid rusting that meant contaminate the tomatoes slices. Ojano gravels located in Benue state previously investigated and confirmed to have demonstrated good potential for a better heat storage capacity and transfer characteristics for short term application was incorporated in the heat storage bed [14].

To provide the draft needed to amplify the convection currents to displace the humid air in the drying chamber, chimney was installed over the exit air opening at the top of the drying chamber cabinet as recommended [6]. The solar collector and cabinet dryer support frames were made from angle iron to provide the needed strength and rigidity. The solar collector and drying chamber supports were constructed from 50 mm × 50 mm × 4 mm iron angle considering the various dimensions of their supports, while the frames were required to withstand resistance to deflection, rigid in nature to transverse and cross-sectional loads of the system. The solar collector casing/housing was constructed from angle iron measuring 25 mm × 25 mm × 2.5 mm and then covered with 1.5 mm thick mild steel sheet. Provision for 50 mm thick sawdust as lagging material was made to minimise heat lost to the environment. To provide proper sealing, prevent leakages and allowance for contraction, silicon adhesive was used as the glazing gasket as suggested [15]. The indirect passive solar cabinet dryer consists of two major components, namely the solar collector unit and the system drying chamber. The solar collector unit of 1.5 m^2 was tilted at 13.01 degrees to the horizontal having glazing (glass) for the provision of greenhouse effect, gravel bed for heat storage underneath an aluminium absorber plate painted black for high heat absorptivity and storage for use as supplementary energy during solar radiation off peak periods. The base and sides of the gravel bed was insulated with saw dust to reduce conduction heat losses. Provision is made for loading and unloading of the product by use of two doors.



Figure 1: Pictorial View of Solar Cabinet Dryer

2.2 Methods

The various methods adapted for the research study ranged from design calculations, model validation, proximate analysis of dried product and experimentation.

2.2.1 Amount of moisture to be removed from the product

Moisture to be removed from the product was obtained from Equation 1.

$$m_w = m_p\left(\frac{m_i - m_f}{100 - m_f}\right) \quad (1)$$

2.2.2 Quantity of heat energy required for evaporating moisture from product

The quantity of heat required to evaporate moisture from the product to be dried is determined from Equation 2.

$$Q_T = m_w \times h_{fg} \quad (2)$$

$$h_{fg} = 2501 + 1.84t_{pr}$$

2.2.3 Bottom and edges heat losses of the solar collector, U_L

The system total heat loss is calculated from Equations 3, 4, and 5

$$U_b = \frac{K_{in}}{X_{ins-bot}} \quad (3)$$

$$U_e = \frac{K_{ins}}{X_{ins-sid}} \quad (4)$$

$$U_L = U_b + U_e \quad (5)$$

2.2.4 Volume of gravel heat storage material

The volume of the storage material, V_s is then calculated from Equation 6.

$$m_a \times c_{pa} \times \Delta T = m_w \times h_{fg} = Q_T$$

$$V_s = \frac{m_a \times C_{pa} \times \Delta T}{n_s \times C_{pr} \times \Delta T \times \rho_r} \quad (6)$$

The volume of the storage bed is taken as 40% of the calculated [11].

2.2.5 Thickness of gravel heat storage material

The thickness of the gravel bed heat storage material, R_t is determined from Equation 7.

$$R_t = \frac{V_s}{A_c} \quad (7)$$

2.2.6 Volumetric and mass air-flow rates

The volumetric flow rate of air is given as in Equation 8

$$\dot{V}_a = A \times v_a \quad (8)$$

The mass air-flow rate is obtained as follows from Equation 9:

$$m_a = \rho_a \times \dot{V}_a \quad (9)$$

2.2.7 Chimney height and diameter

The chimney surface area is calculated from Equation 10

$$A_v = \frac{\dot{V}_a}{v_a} \quad (10)$$

$$r = \sqrt{\frac{A_v}{\pi}}$$

2.2.8 Air pressure difference

The difference in air pressure is calculated as given in Equation 11.

$$\Delta P = (\rho_o \quad \rho_a) g H \quad (11)$$

Table 1: Design specifications of the solar cabinet dryer

Parameter	Value
Mass of water evaporated, kg	5.620
Quantity of heat energy required to evaporate moisture from the product, MJ	14.952
Bottom insulation thickness, m	0.050
Side insulation thickness, m	0.025
Heat lost through bottom and side insulation for 24 hours, kJ	276.48
Volume of gravel heat storage material bed, m^3	0.157
Length of gravel heat storage material bed, m	1.500
Thickness of gravel heat storage material bed, m	0.100
Height of drying chamber, m	0.300
Length of drying tray, m	1.000
Width of drying tray, m	1.000
Volumetric air flow rate, m^3/s	0.125
Mass flow rate, kg/s	0.153
Height of chimney, m	0.375
Diameter of chimney, m	0.040
Collector area for glazing, m^2	1.500
Pressure drop across the dryer, Pa	1.355

2.2.9 Validation of simulation model

The root mean square error (RMSE), Pearson correlation coefficient (r) and model efficiency (EF) were employed to validate the extrapolative power of the model [16, 17] and given in Equations 12, 13 and 14 respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}} \quad (12)$$

$$r = \frac{N\sum xy \times \sum(x)\sum(y)}{\sqrt{(N\sum x^2 - \sum(x)^2)(N\sum y^2 - \sum(y)^2)}} \quad (13)$$

$$EF = \frac{\sum_{i=1}^{N}(X_{obs,i} - X_{obs,mean})^2 - \sum_{i=1}^{N}(X_{i,model} - X_{obs,i})^2}{\sum_{i=1}^{N}(X_{obs,i} - X_{obs,mean})^2} \quad (14)$$

2.2.10 Experimental procedure

The solar cabinet dryer was tested from the month of March, 2020 to the month of August, 2020 (i.e a duration of six months) which covers the months of interest (optimum and design months) using fresh harvested and healthy tomatoes bought at Yelwa Tundu market, Bauchi. The experiment starts by cutting tomatoes into slices with a stainless sharp knife to a thickness of approximately 3 mm to a total weight of 6 kg and place 3 kg each on the drying tray at exactly 8:00 am. Digital thermometer (CE K type) capable of measuring temperature in the range of -50 to 1350°C was then attached at the base of the drying trays and also inserted at the top and middle of the gravel bed for temperature measurement.

3.0 RESULTS AND DISCUSSION

3.1 Monthly Simulated and Experimental Result for Solar Intensity, Ambient and Gravel Bed Temperatures.

The simulated and observed gravel bed temperature increased from 8:00 am steadily and reached an average maximum of 44.9 and 44.4°C for the month of August, while it was 59.3 and 58.8°C for the month of March respectively between the hours of 13:00 and 14:00 hours. The maximum solar intensity values of 575.4 and 1049.2W/m^2 were predicted for the months of August and March, whereas 569 and 1211.7W/m^2 respectively are obtained through experimentation. The observed data indicated the month of March comparatively having fairly higher experimental solar intensity values but lower ambient and gravel bed temperatures to the simulated values (Figure 2) contrast to the month of August where predicted values of solar intensity, ambient and gravel bed temperatures are relatively higher than the observed values (Figure 3). The experimental gravel bed temperature reaches its peak nearly an hour after solar intensity peak. The results revealed that the performance of the solar cabinet dryer is dependent on solar radiation, ambient temperature and the stored heat and is in accordance with values predicted. The gravel bed exhibited potential for absorbing, storing and gradually releasing heat to the drying chamber (thermal diffusivity).

However, the system performance was limited by the amount of solar intensity available, relatively high humidity and the mode of air flow (natural convection) in the design month (Figure 3). Nagaraj *et al.,* (2018) [18] achieved 65°C for sensible heat storage materials beneath the air collector at Oman condition and late evening drying. This work is similar to that of [19] who asserted that rock salt and pebbles maintained consistent drying chamber temperature in the absence of solar radiation by four more hours and increased the dryer efficiency by 13.83% while [20] achieved a 2°C temperature in the drying chamber above the ambient during off sun hours in Akure using a thermal storage bed. The works of [21] gave a daytime and night heat storage bed temperature of 48 and 29°C respectively. Temperatures of 56.3°C and 46.8°C were obtained for upper and lower limit of rock bed thermal storage respectively [22]. A solar collector fitted with pebbles as an absorber performed better than the sand-based collector as reported by [23] due to surface roughness and higher Reynolds numbers. Mean maximum heat storage

temperature of 59.8°C using stones as heat storage media in a heat storage system corresponding to maximum ambient temperature of 39.3°C was stated in the work of (N'Dri *et al.,* 2025) [24].

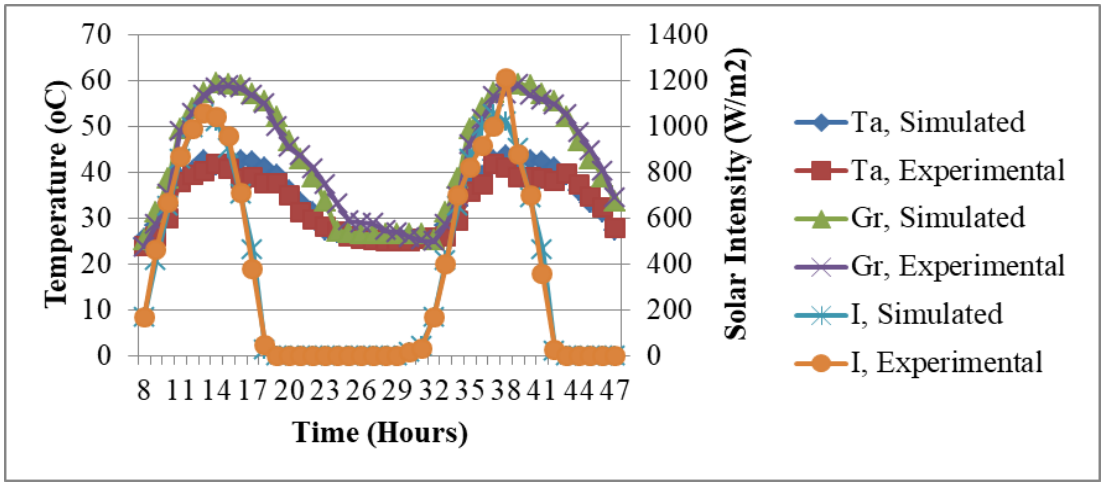


Figure 2: Comparison of the monthly simulated and experimental solar intensity, ambient and gravel bed temperatures for the month of March

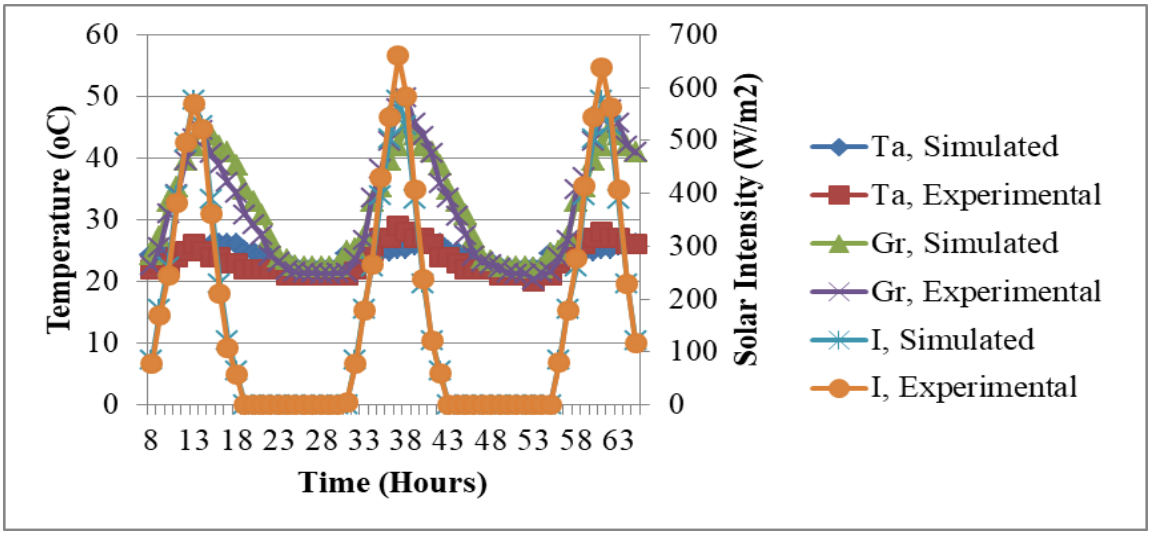


Figure 3: Comparison of the monthly simulated and experimental solar intensity, ambient and gravel bed temperatures for the month of August

3.2 Monthly Simulated and Experimental Product Drying Temperatures.

Figures 4 to 7 is the relationship of tray I and II for the simulated and experimental values in the optimum and design month. The predicted product air drying temperature exhibited better values with exception between the hours of 12:00 and 14:00 on day 2 and 3 where there is a slight variation in data values compare to the experimental data in the design month (Figures 6 and 7). The experimentation period was characterized with low solar intensity, intermittent rain showers and relatively high humidity thus, giving rise to inability of the gravel bed to absorb, store and release adequate heat for drying operation. Figures 6 and 7 revealed maximum simulated and observed product drying temperatures of 49.4 and 49.0°C respectively in the design month while the optimum month, elevated product drying temperatures were

found between the hours of 8:00am to 12:00 for the predicted system and 13:00 and 15:00 hours for system experimentation for day 1 and 2 of drying with values of 66.0 and 70.1°C respectively (Figures 4 and 5). Simulated and observed product drying temperatures on trays varied with drying time due to variations of solar intensity, relative humidity and ambient temperature with relatively higher product drying temperature on tray 1.

The design efficacy of the system was confirmed by its ability to provide drying temperatures not exceeding that required for such a temperature sensitive crop. Integration of painted rock pebbles in a passive solar grain dryer demonstrates significant potential for improving drying efficiency in for solar dryers in tropical conditions [25]. Evaluated mixed mode passive solar fish dryer at Nsukka achieved a maximum drying chamber, ambient and absorber plate temperatures of 68, 30 and 72°C respectively [21] and whilst [26] obtained maximum solar dryer chamber temperature of 82°C, collector efficiency of 62% and ambient temperature of 30°C which are in agreement to this work. Stratification of a two trays air temperature reaching a maximum value of 6.9°C has been observed in the drying chamber of a two tray millet solar dryer [27]. The work of [22] yielded average temperature gradient between four trays of about 10°C. Notably, there is insignificant difference in the product drying temperatures for the trays, accordingly in conformity with the work [28]. Developed solar collector system with pebbles and sand as absorber materials provides the modest temperature heat required for drying of crops [23]. Contrast to this work is that of [29] which obtained average temperature difference of 6.5°C between the exit air temperature from the collector and the air temperature at the bottom of the lower tray in the drying chamber.

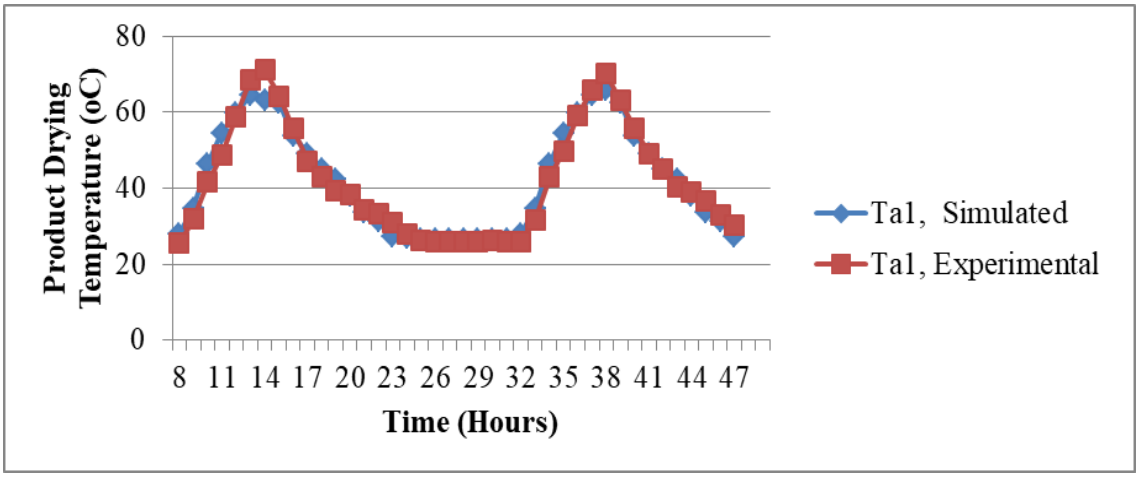


Figure 41: Comparison of the monthly simulated and experimental product drying temperature for tray I for the month of March.

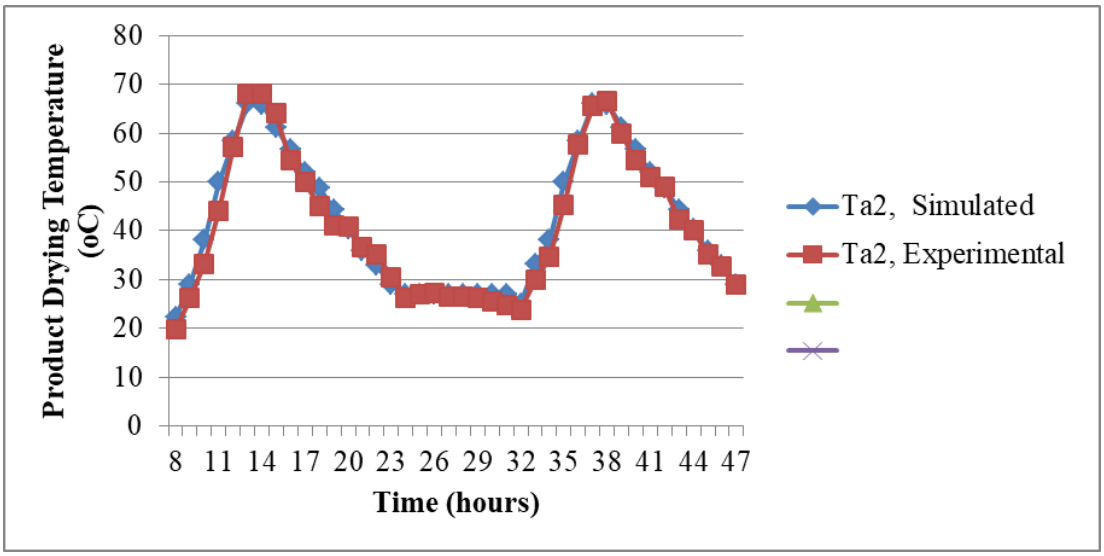


Figure 5: Comparison of the monthly simulated and experimental product drying temperatures for tray II for the month of March

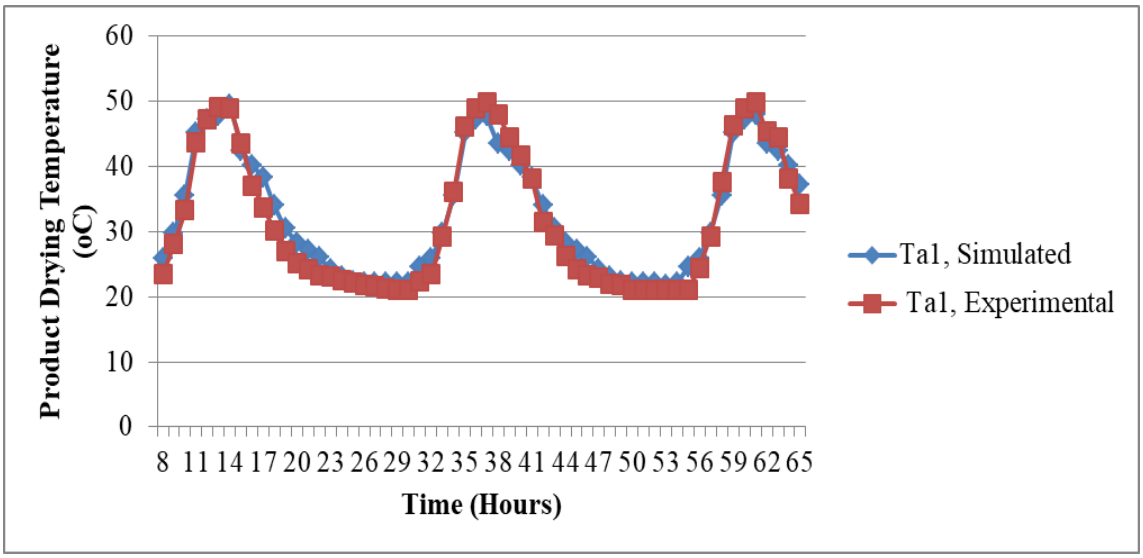


Figure 6: Comparison of the monthly simulated and experimental product drying temperatures for tray I for the month of August

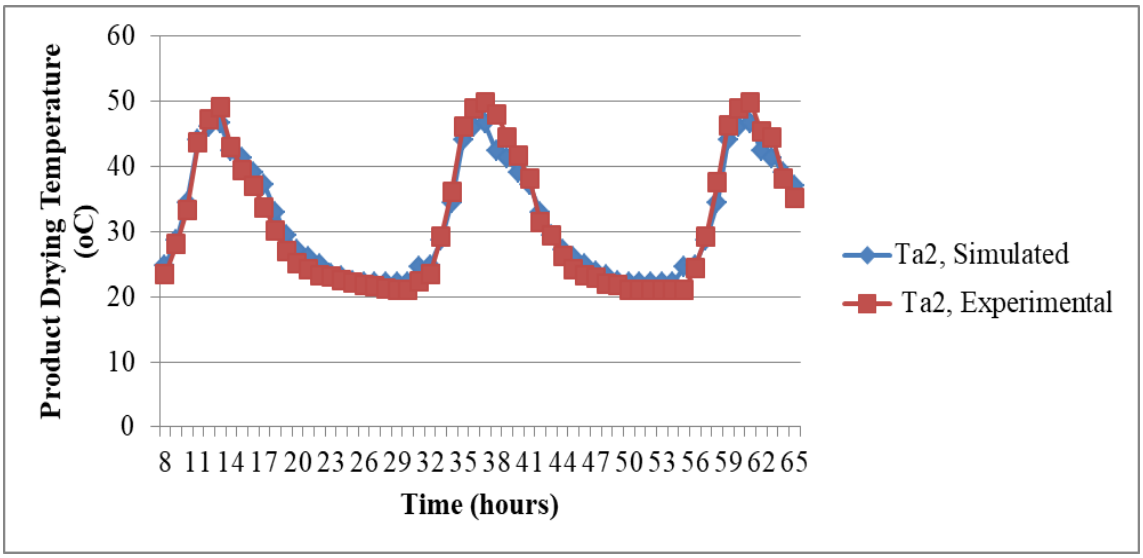


Figure 7: Comparison of the monthly simulated and experimental product drying temperatures for tray II for the month of August

3.3 Monthly Simulated and Experimental Result for Cumulative Mass of Moisture Removed.

The cumulative moisture removed from tomato slices are illustrated in Figures 8 to 11 for both optimum and design months. These figures show a steady increase in moisture removal between 10:00 and 15:00 hours, coinciding with the period of maximum solar intensity available to the system. After this peak period, moisture removal gradually declines due to the reduction in solar intensity received. The mass of moisture removed decreases linearly over time as the product loses moisture. On the first day, the system slightly underperformed compared to the predicted moisture removal but ultimately achieved the overall target for March (Figures 8 and 9). In the design month of August, despite average performance, the observed moisture removal reached 2.78 kg per tray after 58 hours of drying, closely matching the predicted 2.81 kg (Figures 10 and 11). The lower performance during the design month is attributed to unexpectedly low solar intensity, high relative humidity, and the reduced effectiveness of the heat storage unit in absorbing, storing, and releasing heat needed for off-peak solar drying.

Approximately 7.19 and 11.03% (drying between the hours of 6:00pm to 8:00am) of cumulative mass of moisture removed was achieved using supplementary heat stored from the bed in the months of March and August respectively (Figure 8 to 11). Remarkably, the predicted model resulted in higher product drying temperature with a heat storage medium and thus, the total cumulative mass of moisture removed in terms of percentage should be in excess of these figures (7.19 and 11.03%) when consideration is given to the drying hours of 8:00am to 6:00pm. Thus, the used of supplementary heat from the thermal storage bed achieved a significant reduction in the total drying time. The result of moisture content removed in a three tray solar potatoes dryer shown a significant difference between the trays [30]. A significant difference between mass of moisture removed on tray I and II was reported by [26], a dissimilar trend as obtained in this research which is attributed by the small vertical distance between the trays. The work of [29] found total loss in mass for trays 1, 2 and 3 as 208, 158 and 160 grams, respectively.

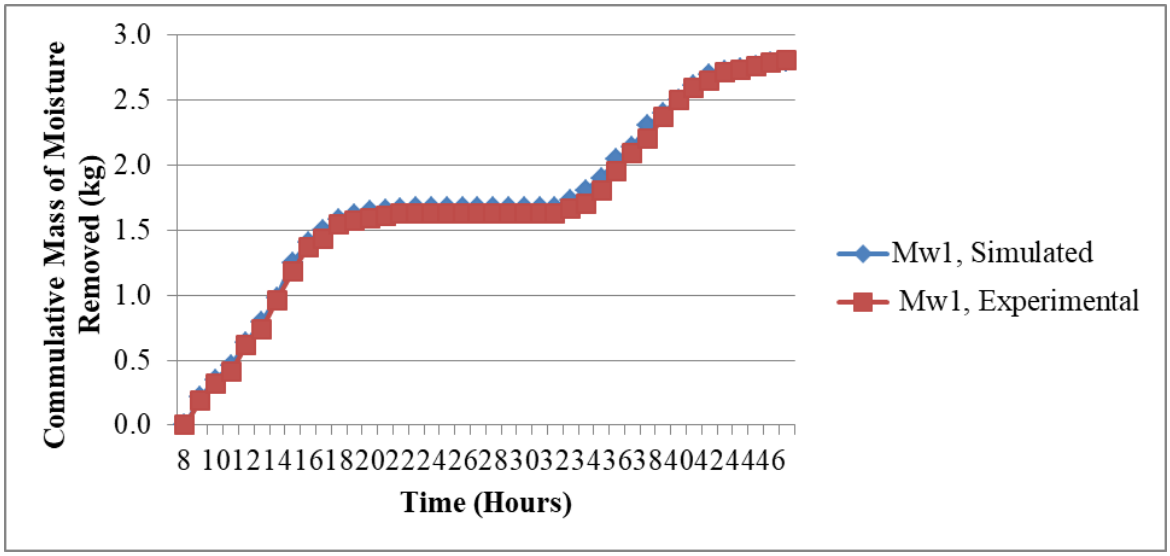


Figure 8: Comparison of the monthly simulated and experimental result for mass of moisture removed for tray I for the month of March

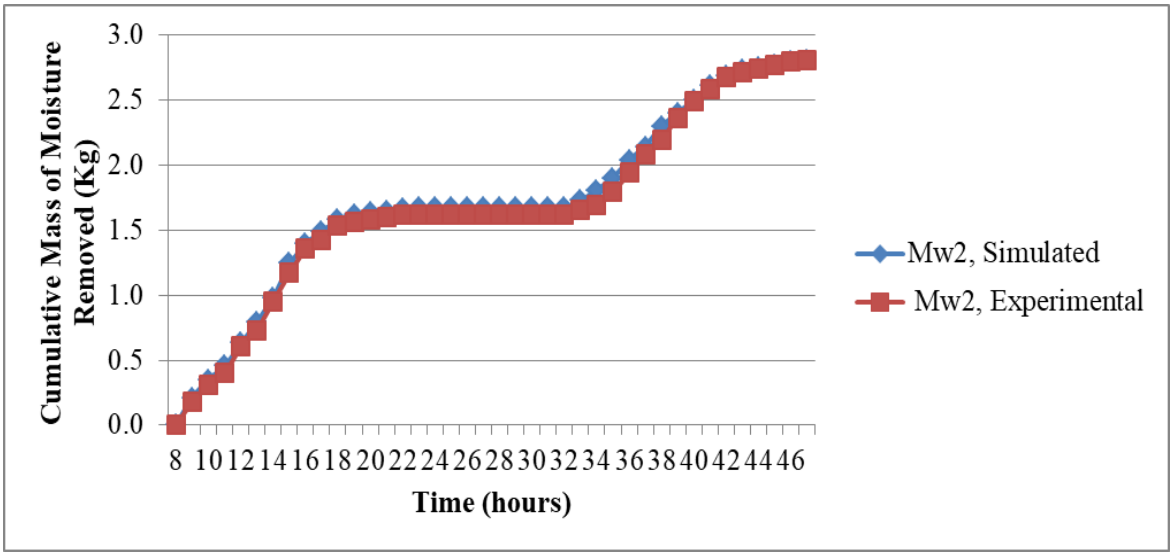


Figure 9: Comparison of the monthly simulated and experimental result for mass of moisture removed for tray II for the month of March

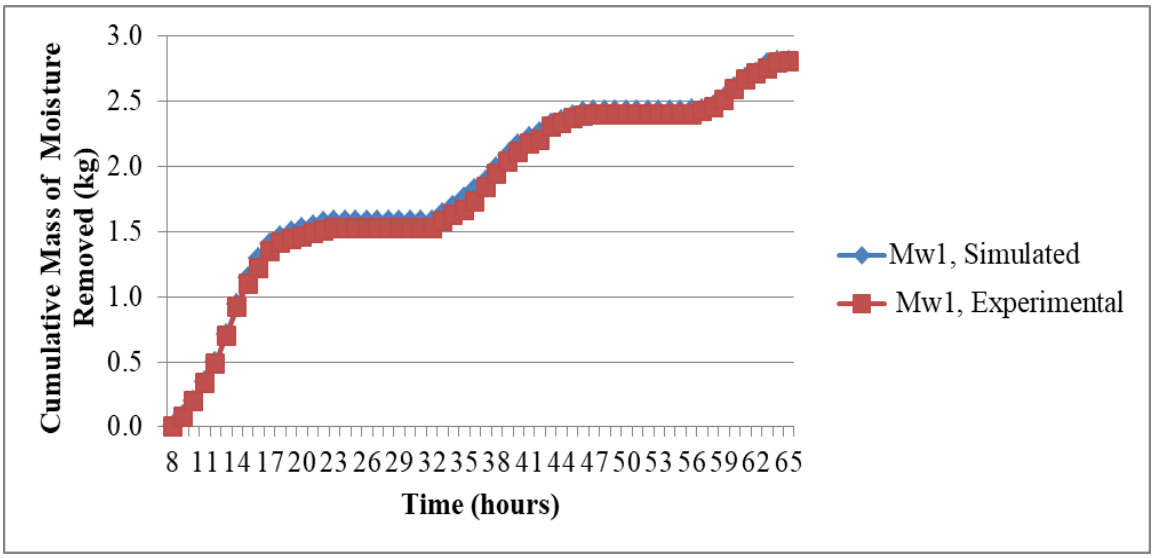


Figure 10: Comparison of the monthly simulated and experimental result for mass of moisture removed for tray I for the month of August

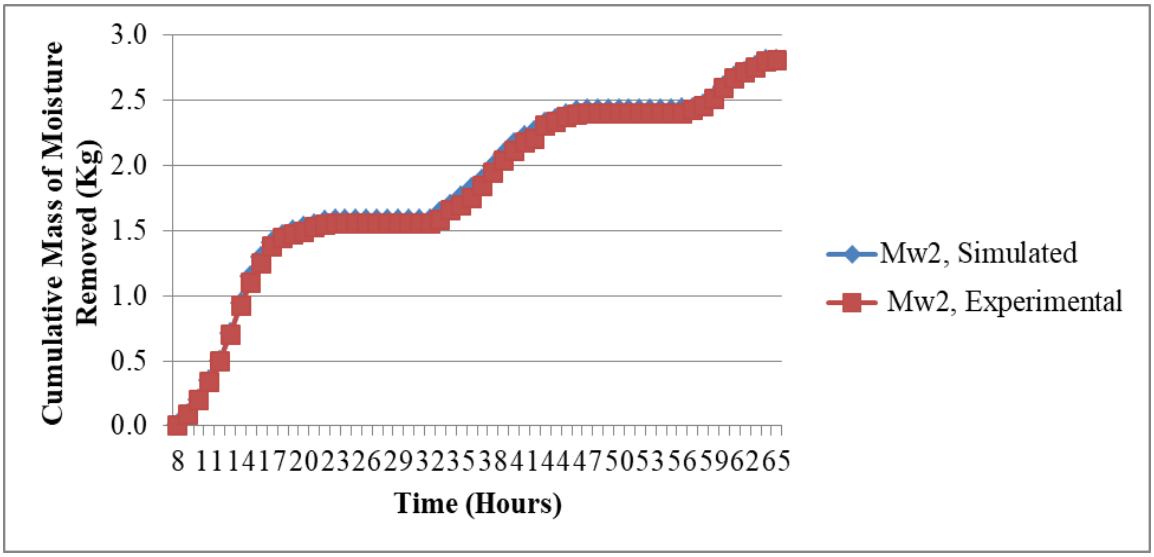


Figure 11: Comparison of the monthly simulated and experimental result for mass of moisture removed for tray II for the month of August

3.4 Model Validation

The model was considered optimal when the root mean square error (RMSE) was minimized, and both the correlation coefficient (r) and model efficiency approach one. The poorest predictive performance, reflected by the highest RMSE and lowest correlation coefficient, was observed during the design month, except for the product drying temperature in March, which had an RMSE of 2.75°C (Table 2). The strong agreement between predicted and observed results confirms the model's validity and its ability to accurately represent the dynamic behavior of the real system.

Table 2: Statistical Table of Values for Validated Variables

Statistical tool	Month	Gravel bed tempt.,°C	Drying product tempt., °C	Cum.moisture removed, kg
RMSE	Aug	2.43	2.04	0.06
	Mar	2.03	2.75	0.05
r	Aug	0.96	0.97	0.96
	Mar	0.99	0.99	0.99
EF	Aug	0.93	0.93	0.95
	Mar	0.97	0.97	0.99

4.0 CONCLUSION

Based on the findings from this study, it can be concluded that the inclusion of a thermal storage bed helps maintain the drying chamber temperature above ambient levels, thereby supporting the drying process during nighttime hours. Optimizing the system design also reduces temperature stratification across the trays, leading to more uniform product drying and moisture removal. A comparison between model predictions and experimental results shows a strong linear correlation, demonstrating the model's accuracy and validity in capturing the system's dynamic and transient behavior. However, to further enhance system performance, heat absorption techniques such as painting the gravel bed black to maximize heat retention could be implemented.

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