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Drying Characterization of a Hybrid Dryer for Cacao Pod Husk

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Cacao pod husks (CPH) are agricultural waste products that can be used to minimize wastages in the cacao supply chain but, like other agricultural waste, rot quickly and are worthless for other means of utilization. CPH can be used for more extended periods by being dried in this condition. Understanding the behavior of the CPH's moisture content reduction is crucial for creating the best drying conditions. Three methods of drying were examined: solar only, biomass only, and hybrid. The coco shell charcoals were used as a fuel source for biomass-only drying. Drying parameters such as drying temperature and relative humidity were analyzed. The study also develops drying modelling utilizing thin drying models by analyzing moisture ratio. Five thin drying models were used to describe the drying model for CPH. Nonlinear regression analysis was used to estimate the drying models using Minitab software. Using the concept of performance index, the best-fit drying model for CPH was the Modified Midilli I, which led to all three drying methods. The results also showed that solar-only drying has the highest peak dryer efficiency of 34.30 %, while biomass-only drying has the highest drying rate of 22 g/h.

1. Introduction

Cacao, known as cocoa, is crucial globally, mainly in tropical western Asia. Cook (2018) notes its seeds and fruit are widely used, with Beg et al. (2017) reporting annual production of 3.5 Mt and a forecasted 30% demand increase by 2020. However, this growth has led to significant waste (Suarez Rivero et al., 2023), about 700,000 t yearly, primarily from unutilized by-products (Barišić et al., 2020). The Philippines, particularly Davao City, is a leading producer, contributing 34.15 % to the nation's output, supported by critical producers Malagos Chocolates, MS3 Agri-Ventures, and Auro Chocolates (Arado, 2016). A substantial part of the waste includes cacao pulp, bean shells, and CPH, which comprise 70-75 % of the fruit's weight and are often discarded (Domingo, 2016). CPH has potential as a renewable biomass energy source (Martinez et al., 2015) due to its carbon-neutral nature and rich mineral content (Perea-Moreno et al., 2016), offering an environmentally friendly alternative to conventional fertilizers and fossil fuels (Lu et al., 2018). Despite the benefits, the transformation into biomass fuel demands consideration of its ash content, air flow rate, and carbon dioxide emissions (Tambunan et al., 2014). Biomass heating advancements still face challenges, like carbon monoxide emissions (Pal et al., 2016) and the necessity for material drying before combustion (Dzelagha et al., 2020). Innovative approaches, such as a biomass-fueled dryer for cacao beans (Atepor, 2020) that reduces moisture content significantly within hours and a hybrid drying method that combines solar and biomass energy, show promise in improving sustainability and efficiency in cacao production (Yassen and Al-Kayiem, 2016). This research focused on the performance evaluation of the hybrid drying system and the determination of the drying characteristics of CPH. Quantitative experimental research was utilized in this study using several data-gathering instruments. The hybrid drying system's solar collector, drying chamber, and biomass heater components were designed, fabricated, and tested in terms of its drying rate and efficiency to determine its

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overall performance. The hybrid drying system involved simultaneous solar and biomass drying operations. The experiment was conducted in Davao City.

2. Materials and Method

The study used analysis, simulation, and experimental designs to develop and test a dryer. It validated airflow and parameters using Computational Fluid Dynamics (CFD) and determined the best-fit drying model through statistical approaches based on the acquired data.

2.1 Computational Fluid Dynamics

The development of the hybrid drying system commenced with its design and validation using SolidWorks. This process involved the determination of the dryer's size and shape, followed by a comprehensive assessment using Computational Fluid Dynamics (CFD) analysis. The analysis was conducted using the sixth level of global mesh settings in the flow simulation, corresponding to various drying modes shown in Figure 1. Figure 1a illustrates the temperature distribution across the entire length of the dryer when operating solely on solar power. The temperature increase is primarily attributed to the absorber plate, a surface heat source that facilitates the transfer of solar irradiance at 600 W/m^2 to the flowing air. The air undergoes natural convective heat transfer at a constant coefficient of 25 W/m^2 °C. With an inlet velocity of 0.37 m/s and a final velocity of 0.65 m/s, the system effectively raises the air temperature from 293.2 K (25 °C) to 305 K (32 °C), demonstrating substantial heating efficiencies. In biomass mode, the dryer utilizes a biomass heater to generate heat. The simulation includes the flue gas with a mass flow rate of 0.1 kg/s and a temperature of 100 °C to replicate the hot flue gas from the heater, as depicted in Figure 1b. This multifaceted approach emphasizes the integration of renewable energy sources and underscores the intricate design considerations involved in developing a sustainable and efficient drying system.

(a) (b)

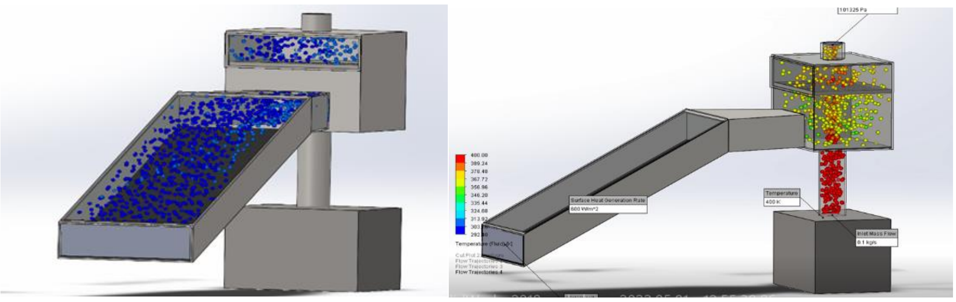

Figure 1: Particle Flow Simulation of Hybrid Dryer a) Solar Mode b) Biomass Heater Mode

2.2 Final Prototype Design

The final prototype design of the dryer can be seen in Figure 2. Since the solar collector and the drying chamber utilize the sun as the primary drying source, both components were installed with glass panels so that convection works optimally. Furthermore, to improve the temperature within the system, foam insulation was installed along the walls of the solar collector and the drying chamber. This modification excluded the biomass heater as the temperature reached very high values. Computer fans powered by a motorcycle battery were also installed at the solar collector's inlet to force airflow into the drying chamber where the CPH was situated.

Figure 2: Final Assembly of Hybrid Dryer

2.3 Experimental Design

Before starting the data gathering, a baseline value for the initial moisture content of the CPH is required. Hence, an oven test involved the oven toaster, which provided a constant temperature. The initial moisture content was obtained by letting the CPH dry inside the oven at 100 °C and checking the weight of CPH every five (5) mins, as shown in Figure 3. As seen in Figure 3a, a large piece ranged between 40 g - and 45 g, a medium piece ranged between 20 g - 25 g, as depicted in Figure 3b, and a small piece ranged between 5 g and -10 g, as shown in Figure 3c. The test will only stop when the weight of CPH does not change for three (3) or more consecutive readings (Culaba et al., 2021). Before the oven drying test, three CPHs sliced into similar dimensions and weight classes were used to provide a more accurate average reading for the initial moisture content.

(a) (b) (c)

Figure 3: Sample sizes used for determining the initial moisture content of CPH a) large, b) medium, and c) small

The CPH was initially prepared to commence the data acquisition procedure. The husk was fractionated into different sections according to their size and weight specifications. To determine the drying characteristic of CPH more precisely, various sizes were employed to demonstrate the correlation between the quantity of moisture and its size. In this study, one of the main goals is to evaluate the drying process of CPH. The moisture content of the CPHs before and after the drying process was done in triplicates and monitored for 8 h since only the solar hours were considered in the experiments. A digital weighing scale with a tolerance of 0.1 g was used to measure the moisture content and determine how much moisture was lost during drying. Additionally, temperatures and relative humidities were monitored using thermometers with a tolerance of 0.2 °C for solar mode and K type thermocouple for biomass mode with a tolerance of 0.6 °C, as well as a hygrometer with a tolerance of 5 % for relative humidity measurements.

2.4 Drying Models

Utilizing various thin drying models, the aim is to predict the optimal drying pattern and determine which model would best fit the curve of the CPH moisture ratio (MR), which is the ratio of moisture content at any time t, M_f, and initial moisture content, M_i.

$$MR = \frac{M_f}{M_i} \tag{1}$$

To achieve this, the study employed several sophisticated statistical tools. Five different drying models were tested to determine which demonstrated the optimal fit for the CPH drying curve. The models were Modified Page II, Modified Midilli I et al., Haghi and AngizII, Sripinyowanich and Noomhorm Model, and Parabolic Model (Ertekin and Firat, 2015). Drying modeling and statistical analysis were done using Minitab and Microsoft Excel applications. Aside from determining the best-fit model for the CPH drying, relevant constants and exponents were also obtained.

2.5 Statistical Analysis

The moisture ratio results were used to estimate drying curves using standard models and nonlinear regression. Each curve was tested for statistical fit using Minitab 18. The best-fit curve was determined by evaluating several factors, including R^2, RMSE, MRD, and Φ. For optimal results, elevated R^2 value alongside reduced RMSE and MRD values are desired. The drying model with the highest Φ will be considered the best. The relevant formulas from Eq(2) to Eq(7) are shown below (Mitrevski et al., 2014).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_i\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_i\right)^2} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \quad (3)$$

$$E_i = M_i - \overline{M_\iota} \quad (4)$$

$$\overline{M_\iota} = \frac{\sum_{i=1}^{n} M_i}{n} \quad (5)$$

$$MRD = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{E_i}{M_i}\right| \quad (6)$$

$$\Phi = \frac{R^2}{(RMSE)(MRD)} \quad (7)$$

3. Results and Discussion

3.1 Drying parameters

The initial moisture content was obtained to be 81.79 %. The average moisture content for solar, biomass, and hybrid drying is 52.57 %, 22.02 %, and 45.03 %. The moisture content was reduced in 8 h to final average moisture contents from solar only, biomass only, and hybrid to 26.19 %, 8.42 %, and 18.14 %, with the highest reduction observed in biomass mode, as shown in Figure 4a. The temperature in the drying chamber reached a maximum of 88 °C in biomass mode, 48 °C in solar mode, and 52 °C in hybrid mode. The variation in solar intensity impacts the lower temperature in the dryer. Figure 4b depicts the sample validation of simulated results to measured ones for drying temperature in solar mode. A standard deviation of 6.67 °C can be observed due to solar fluctuations during the testing using thermometers with a tolerance of 0.2 °C. Given this observation, considering advanced control systems can effectively mitigate the influence of temperature variations, thereby ensuring a more consistent drying outcome despite fluctuations. The average drying rates were 10 g/h in hybrid mode, 6.5 g/h in solar mode, and 8 g/h in biomass mode. It was found that the highest drying rate, 22.5 g/h, was observed in biomass mode due to the higher temperature, compared to 10 g/h in solar mode and 13 g/h in hybrid mode. These results show biomass mode is the most effective option for drying CPH.

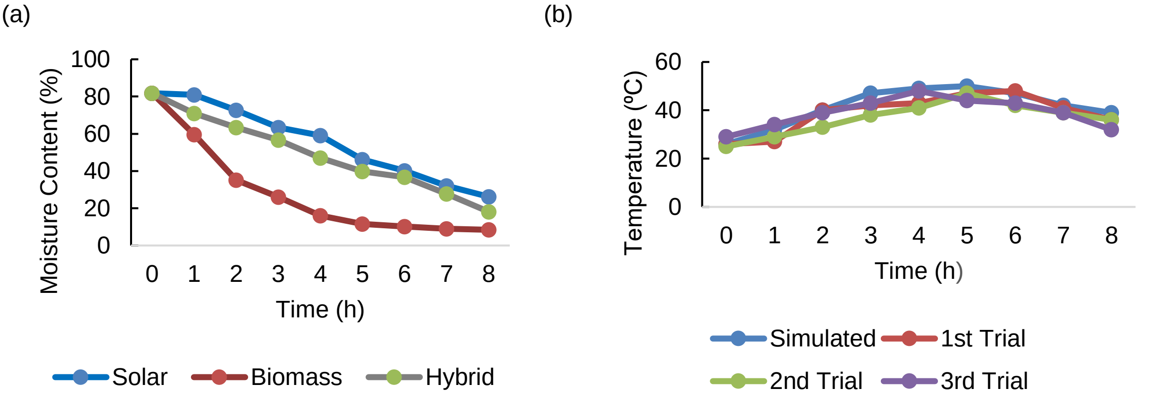

Figure 4: Drying Parameters a) Moisture Content Reduction for Solar, Biomass, and Hybrid Mode, b) Comparison of Temperature for Solar Mode

3.2 Drying Models

In the comprehensive analysis summarized in Table 1, the study has conducted a detailed review of statistical findings pertinent to drying modeling techniques. The Modified Midilli I model distinguishes itself as a superior performer, indicated by its exceptional R^2 value of 0.9978 within the biomass mode. This demonstrates its unparalleled accuracy and predictive capability, rendering it an outstanding option for applications in biomass drying. Concerning the solar mode, the analysis identified premier thin drying models suited for efficient drying of CPH. The Modified Page II model illustrated a significant performance index of 114.69, narrowly surpassed by the Haghi and Angiz II model at 115.72.

Nonetheless, the Modified Midilli I model excelled, achieving the highest performance index of 136.30. This reaffirms its efficacy and reliability as the preferred model for solar drying processes. Regarding biomass mode, an in-depth analysis revealed that the Modified Midilli I and Haghi and Angiz II models yield the most favorable outcomes, with performance indices of 75.86 and 41.14, respectively. These results highlight the models' consistent and robust performance, effectively catering to the drying rate requirements of CPH within biomass heater configurations. When examining hybrid drying methodologies, the Parabolic Model, Haghi and Angiz II, and Modified Midilli I emerged as leading options, with 86.64, 107.66, and 116.50 performance indices, respectively. This evidence demonstrates the Modified Midilli I model's superior adaptability and precision, establishing it as the optimal choice for hybrid drying contexts and affirming its pre-eminence across various drying modalities. The comprehensive analysis underscores the exceptional versatility and superior performance of the Modified Midilli I model across assessed CPH drying modes. Its consistent ability to provide the most precise fit in any drying context establishes it as the definitive solution for specialists and researchers seeking dependable and efficient CPH drying modeling strategies. This strong endorsement is supported by performance indices analysis, which convincingly demonstrates the exceptional predictive capabilities of the Modified Midilli I model and its consistent suitability across various drying conditions.

Table 1: Summary of Results of Statistical Analysis

Parameters	Modes	Modified page-II	Modified Midilli I	Haghi and Angiz-II	Sripinyowanich and Noomhorm	Parabolic
R^2	Solar Only	0.9945	0.9956	0.9949	0.9908	0.9890
	Biomass Only	0.9891	0.9978	0.9967	0.9796	0.9877
	Hybrid	0.9872	0.9959	0.9965	-0.4534	0.9943
RMSE	Solar Only	0.0171	0.0161	0.0171	0.0229	0.0251
	Biomass Only	0.0314	00146	0.0173	0.0429	0.0332
	Hybrid	0.0271	0.0158	0.0141	0.3159	0.0182
Φ	Solar Only	114.69	136.30	115.72	84.26	75.55
	Biomass Only	16.04	75.85	41.14	15.59	19.20
	Hybrid	62.19	116.51	107.66	47.49	86.64

4. Conclusions

The importance of determining the drying rate of CPH under each drying method is to give a concise answer on which drying mode is the most efficient. The drying rate for each technique was identified through various determinations of initial moisture content and reduction. The percentage of final moisture content is also essential in determining the most optimum drying method. As mentioned in the hypothesis, the drying mode predicted to be the optimum was the hybrid mode. However, in interpreting the drying rate graphs for each drying mode, the biomass heater mode is superior among the three. Not only does the biomass heater mode dry the CPH, where the moisture content is at the lowest among the three, but its average drying rate also sits higher when compared to solar and hybrid modes. Without question, biomass heater mode gave the optimum drying rate for CPH. Based on the findings, Modified Midilli I is the best-fit drying model for the drying of CPH for the three modes of operation: solar-Only, biomass-Only, and hybrid Mode. The Modified Midilli I presented the highest performance index value for the three drying modes, the ranking parameter. It can be concluded that the drying characteristics of CPH follow the drying model of Modified Midilli I.

Nomenclature

E_i – moisture residual, kg/kg
M_i – initial moisture content, -
M_f – moisture content at any time t, -
MR_i – moisture ratio, -
$\overline{MR_i}$– average moisture ratio, -
$MR_{pre,i}$ - i^{th} experimental moisture ratio, -
$MR_{exp,i}$ - i^{th} predicted moisture ratio, -
MRD – mean relative deviation, -
n- number of constants, -
N – number of observations, -
R^2 – coefficient of determination, -

RMSE – root mean square error, -
Φ– performance index, -

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