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Article

Experimental Investigation of an Appropriate Thin Layer Drying Model of an Integrated Greenhouse and Flat Plate for Solar Coffee Dryer

Ewnetu Tefera * and Eneyw Gardie Damtie

School of Mechanical and Automotive Engineering, College of Engineering and Technology, Dilla University, P.O. Box 419, Dilla, Ethiopia
* Correspondence: Ewnetu.Tefera@du.edu.et

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Abstract: The predominant practice of coffee drying in Ethiopia involves an open sun system with direct exposure to solar radiation. This type of drying system leads to spoilage and quality degradation, and it also requires a longer drying time. This study presents an experimental investigation of the effectiveness of various thin-layer drying models in the context of a solar coffee dryer integrated with a greenhouse and flat plate collector system. The primary objective was to identify an appropriate drying model that best fits in the experimental results in the integrated dryer. Experimental setups were designed to simulate real-world drying processes, and data were collected on solar Irradiation, temperature, and moisture content over time. Both the greenhouse and the flat plate solar heater are encased in polyethylene plastic and transparent glass, measuring 1 m by 2 m and 1.6 m by 5 m in length and width, respectively. Seven models were evaluated for their accuracy in representing the drying behavior of coffee. Statistical analyses were employed to assess model performance. The findings highlight the importance of selecting an appropriate drying model to optimize the efficiency of solar coffee drying systems, ultimately contributing to improved quality and reduced post-harvest losses in coffee production. The drying result shows the average temperature difference between the greenhouse and the surrounding air was 10.7 °C. At the latitude of 6.4126 N and longitude 38.3008° E, 50 kg of wet, freshly harvested coffee with an initial moisture content of 54.23% was added to the system. After 80 h of drying in the integrated solar dryer, 24.14 kg of moisture was removed, and it takes 130 h in the open sun. The daily average solar insolation for the test periods of November and December was 673.267 W/m^2. Finally, to perform statistical analysis. Newton models were found to be the best explanation of coffee behaviour in the integrated flat plate and greenhouse dryer systems with $R^2 = 0.99$ and Two-Term in the open sun model with $R^2 = 0.979$. These models were tested by comparing the maximum value of the coefficient of determination R^2 and the minimum value of reduced chi-square X^2 and root mean square error RMSE between experimental and predicted moisture ratios.

Keywords: integrated solar dryer; drying models; moisture; coffee drying

1. Introduction

Drying is an essential procedure in food preservation, particularly for agricultural products such as coffee [1]. The global demand for high-quality agricultural products, especially coffee, has spurred the need for new and efficient agricultural practices [2]. Post-harvest processing, which includes drying coffee beans to the ideal moisture content using a consistent drying technique for quality and preservation, is one of the main challenges in Ethiopian coffee manufacturing [3]. Conventional, open-sun coffee drying techniques often result in uneven quality and potential spoilage [4].

Several drying methods are available today to address these issues, and they have gained popularity due to their effectiveness and sustainability [1,5]. Among these, integrated solar dryers that combine greenhouse and flat plate solar drying techniques have demonstrated potential for improving drying efficiency and preserving coffee bean quality. Thin layer drying models are also essential for understanding the drying kinetics of materials and the moisture removal process [6,7]. To maximize exposure to sunlight and promote uniform airflow, this technique typically involves spreading the material in a single, thin layer on trays. Compared to conventional methods, drying times are shortened because moisture evaporates rapidly as solar radiation heats the material's surface [8]. Solar drying does not evaporate only the moisture from the grain but provides safe storage and products controlled [9].

A crucial aspect of optimizing solar drying systems is understanding the drying kinetics involved. The chimney-type solar dryer performs better than the fan-type and open sun solar dryers [10]. Thin layer drying models provide a theoretical foundation for predicting moisture loss rates throughout the drying process [11]. These models are necessary to ensure the effectiveness of integrated solar dryers and to create efficient drying regimens. However, careful research and validation are needed to determine whether these models can be applied to specific crop types, such as coffee [12]. An appropriate drying model is critical for optimizing dryer design and operational parameters, ultimately leading to improved product quality.

The capacity of a greenhouse to maintain ideal drying conditions for agricultural products and absorb solar energy is greatly influenced by its design [13,14]. Recent research on diverse methods for performance enhancement by incorporating turbulence generators, fins, phase change materials (PCMs), and nano-fluids as working mediums, improving solar radiation harvest through reflectors, and utilising mini- and micro-channels for fluid flow [15]. Flat plate collectors are essential for enhancing the efficiency of solar drying systems [16]. The air passing through the drying chamber is heated by the thermal energy they produce from absorbing sunlight. A multitude of variables, including the angle of inclination, material properties, and surrounding environment, can affect the performance of flat plate collectors [17]. The studies in mixed-mode solar drying and indirect-mode solar drying were conducted to examine the influence on drying kinetics and physicochemical properties of cooked and raw chicken breast meat and the mixed-mode dryer achieves faster equilibrium moisture content [18].

1.1. Physical Characteristics Fresh Harvested Coffee

The coffee beans used in this study are Arabica (Coffea arabica), known for their superior quality and Flavors. The beans were sourced from Yirga Chefe, Gedeo Zone, Ethiopia, which is recognized for its optimal growing conditions. Fresh Arabica coffee beans display a vibrant green coloration, indicating that they are unroasted and at the optimal stage for processing. The beans have a smooth and firm texture, with a hardness that reflects their high moisture content. This texture is crucial for maintaining quality during the drying process. The initial moisture content of the fresh Arabica beans was measured to be approximately 54.23% using a moisture analyser. This measurement is crucial for determining the appropriate drying conditions. Arabica beans are typically oval-shaped and smaller than their Robusta counterparts.

Integrating various greenhouse designs with flat plate coffee dryers is a promising approach to increasing the efficiency of solar drying systems for coffee production. According to the literature, optimizing the drying process for agricultural products requires careful evaluation of drying models, collector performance, and greenhouse design.

This research should focus on the experimental investigation of the Integrated flat plate and greenhouse solar dryer and identify an appropriate drying model best fit to the experimental moisture ratio value of coffee drying.

2. Methods

2.1. Coffee Drying Property

The drying of coffee products is a complex heat and mass transfer process that depends on external variables such as temperature, humidity, and air stream velocity, as well as internal variables like surface roughness or smoothness, chemical composition (sugars, starches), physical structure, and the size and shape of the products [19]. The rate of moisture movement from the product to the outside air varies between products and is significantly influenced by whether the material is hygroscopic or non-hygroscopic.

Specific design criteria and parameters of interest were established through a series of engineering design calculations, considering a general design for a direct free convection greenhouse and flat plate solar dryer for coffee drying. Numerous design characteristics, assumptions, and relevant criteria were considered when evaluating the solar dryer's design.

2.2. Experimental Procedure

This experiment utilizes an open-flow loop, a test duct with entrance and exit sections, and recording various drying parameters. The flow system consists of an entrance section on the flat plate side and an exit section on the greenhouse side. The flat plate solar collector setup features a single layer of glazing glass that measures 1 m × 2 m and is 4 mm thick aluminum absorber plate and 1.6m by 5 m greenhouse size with polyethylene plastic cover.

To capture direct shortwave solar energy, the drying chamber was constructed using RHS frames and covered with clear polyethylene plastic. Analytical calculations were performed to determine the geometry and mounting of the built-in flat plate solar air heater and greenhouse dryer, which were assembled on a simple iron frame positioned at an angle of 21.4° to the south.

Convective airflow through the drying chamber was facilitated by the installation of a vent at the upper rear end of the greenhouse. The experiment measures temperature, solar radiation, and coffee moisture content. The mean ambient temperature ranges from 23.6 °C to 29.8 °C from November to December. For safe drying, the final moisture percentage of the coffee should be between 11% and 12%, and the coffee was dried at 70 °C without losing quality [20]. The design considerations which should consider manufacturing the experimental set-up are described in Table 1. The systematic diagram of the experimental set-up and the manufactured experimental set-ups are illustrated in Figure 1 and Figure 2 respectively.

Table 1. Design considerations.

Location	Dilla, Ethiopia
Product	Coffee
Initial moisture content (%) wet basis	54.23%
Desired final moisture content (%) wet basis	11.5%
Maximum permissible drying temperature	60 ^{o}C
Wind speed	1 m/s
Average ambience air temperature	23
Drying time (sunshine hours) td	9.9 hr
Incident solar radiation, I	566.213 w/m^2
Vertical distance between two adjacent trays	10 cm
Estimated Dryer efficiency	70%

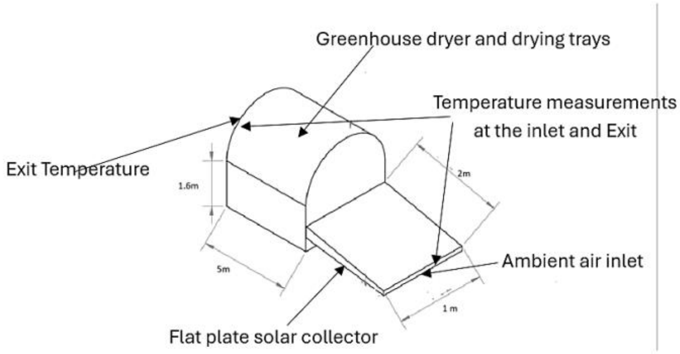

Figure 1. Schematic diagram of the prototype.

Figure 2. The manufactured integrated solar Coffee dryer.

2.3. Mathematical Modelling Method

The temperature and moisture content changes of a single layer of coffee sample particles are described using thin-layer drying models [21]. These mathematical models fall into two categories: physics-based models, which are derived from universal physical laws, and observation-based models, which are based on experimental data [22]. In this research, observation-based modes were used.

2.4. Mathematical Model Results

The experimental moisture ratio values were fitted with all seven selected mathematical model values. As shown in Table 2, the best fit of the experimental moisture ratio and the mathematical modeled moisture ratio values were identified by analyzing the experimental drying curves. Regression analysis was performed, and the best-fitting Mathematical model was selected by comparing R^2, RMSE, and X^2 values.

$$x^2 = \frac{\sum_{i=1}^{N}\left(MR_{i\,\exp mean} - MR_{i\,\mathrm{pre}}\right)^2}{N-n} \tag{1}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}\left(MR_{i\,\mathrm{pre}} - MR_{i\,\exp}\right)^2}{N}\right]^{1/2} \tag{2}$$

$$R^2 = 1 - \sum_{i=1}^{N}\left(MR_{i\,\mathrm{pre}} - MR_{i\,\mathrm{exp}}\right) \tag{3}$$

Table 2. Drying kinetics using mathematical models.

Model Name	Model
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Modified Page	$MR = \exp(-kt)^n$
Henderson and Pabis	$MR = a \exp(-kt)$
Logarithmic	$MR = a \exp(-kt) + c$
Two-term	$MR = a \exp(-k_1 t) + b \exp(-k_2 t)$
Diffusion approximation	$MR = a \exp(-kt) + (1-a)a \exp(-kbt)$

3. Results and Discussion

3.1. Experimental Result

The experiment was conducted between 8 AM and 5 PM, which was an optimal daytime temperature in Ethiopia. The maximum temperature recorded in the greenhouse chamber ranged from 30.9 °C to 47.02 °C and the ambient temperature, which varied between 23.6 and 29.8 degrees Celsius.

The average temperature inside the greenhouse reached 45.34 °C, as shown in Figure 3. The mixed-mode solar dryer has a higher temperature than the open-sun drying system, as the temperatures inside the greenhouse were considerably higher than those outside. Figure 4 shows solar irradiance plotted against the time of day, with the highest measured value of 950 W/m² occurring on the sixth day at 3:00 PM. The average ambient temperature recorded was 26.37 °C, and the average solar irradiance over the testing periods was 598.44 W/m².

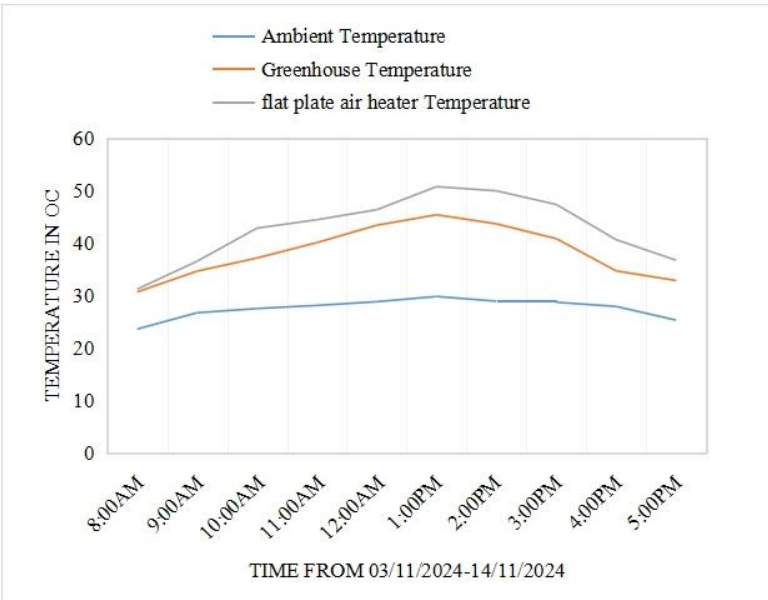

Figure 3. Ambient, Greenhouse and flat plate Temperatures.

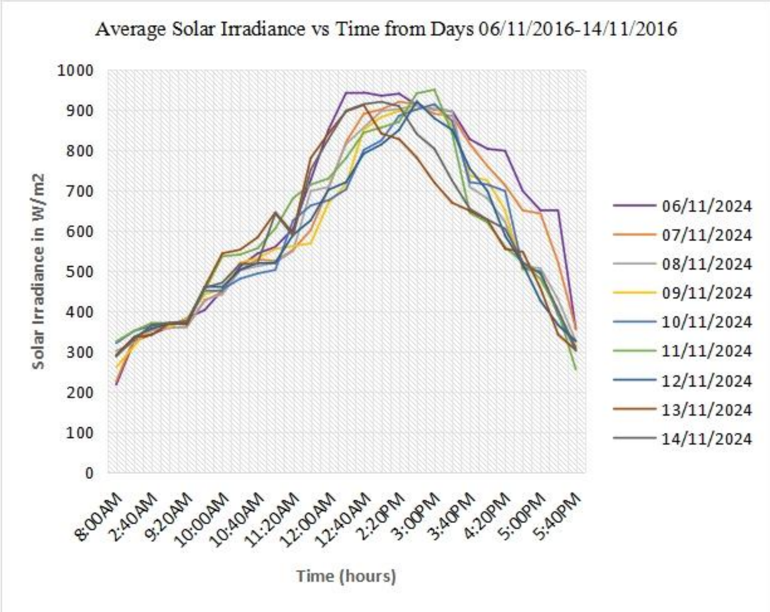

Figure 4. Solar irradiation measurement values.

3.2. Moisture Content of Open Sun Drying

To conduct this test, an equal amount of coffee sample was spread out the integrated solar dryer and in the open-sun dryer. The initial moisture content of 54.23% was reduced to a final level of 12.2% after 13 days of drying in the open sun dryer with an average of 10 h drying time per day and the same sample coffee takes 8 days in the integrated drying system. From Figure 5, the high moisture content was steadily reduced on the first day, through time the grain's surface hardens [23], and the moisture loss from the coffee reduces and it remains constant at 12.2% moisture content at the final drying day.

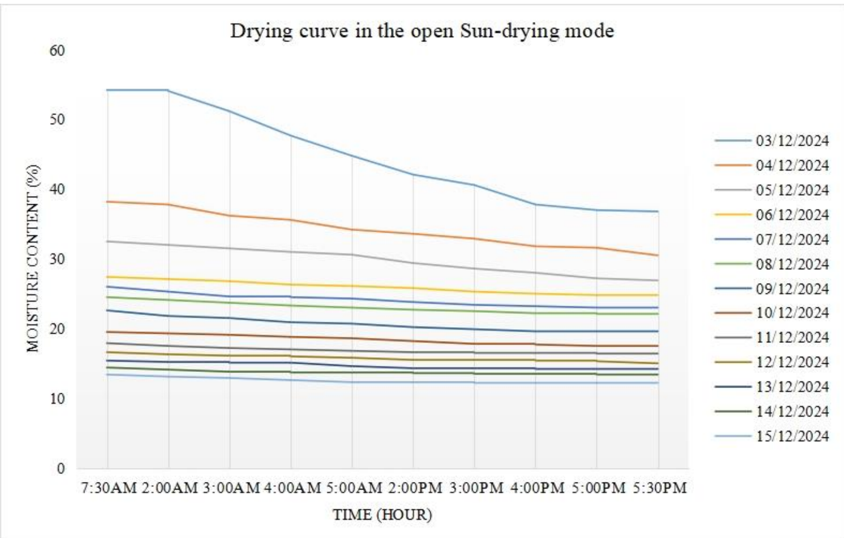

Figure 5. Drying curve in the open Sun-drying mode.

3.3. Moisture Content in the Integrated Flat Plate and Greenhouse Solar Dryer

The same sample to the open sun dryer coffee was spread in the integrated solar dryer with the initial moisture content of 54.23% and reduced to 10.8% in 8 drying days of 10-hour average drying time per day. The temperature in the dryer chamber ranged between 38.6 °C and 34.53 °C, as shown in Figure 6. This dryer saves 50 h compared to the open sun dryer per drying batch. For small scale drying, solar collector-integrated HGSD under natural convection are better as they give faster drying with less investment [24]. Different Research on solar dryer technology proliferates since it reduces the drying period while keeping nutritional values in the agricultural products [25].

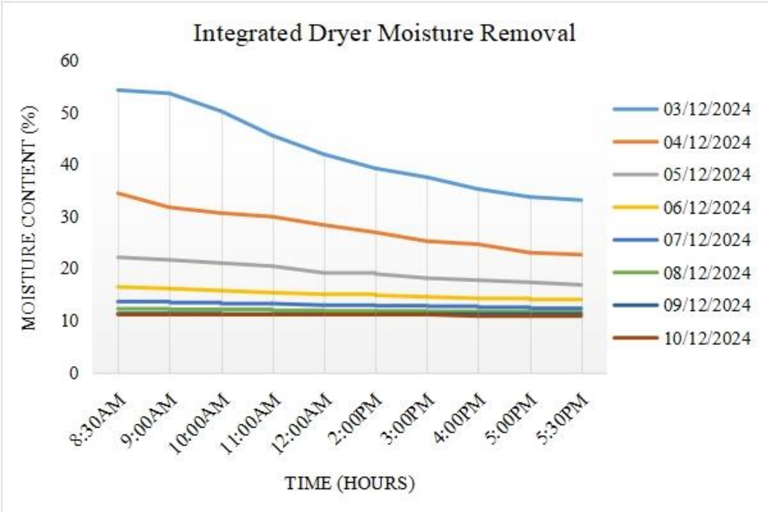

Figure 6. integrated dryer moisture removal.

3.4. Mathematical Model Results

For open-sun and integrated dryers, the experimental data of moisture content versus time was transformed into a dimensionless parameter known as the moisture ratio versus time to normalize the drying curves, as shown in Figures 7 and 8 respectively. The moisture content from the experimental data was used to compute the moisture ratio. Statistical analysis was conducted for open sun and integrated greenhouse and flat plate solar dryers. The model's equation was applied to the gathered data to determine the drying constants k and the product constant n, as well as the constants a, b, and c for both the open sun and the integrated flat plate and greenhouse solar dryers, as shown in Table 3.

$$MR = \frac{M - M_e}{M_o - M_e} \tag{4}$$

Table 3. Models parameters result.

	Open Sun			Integrated Solar		
Model	**X^2**	**RMSE**	**R^2**	**X^2**	**RMSE**	**R^2**
Newton	0.022973	0.150985	0.8661	0.000282	0.016798	0.99553
Page	0.014533	0.120089	0.91042	0.009951	0.099756	0.92331
Logarithmic	0.02109	0.144663	0.8792	0.010998	0.104869	0.915457
Henderson	0.022602	0.14387	0.88914	0.001925	0.04387	0.945160
Modified Page	0.080898	0.283329	0.633287	0.076239	0.273339	0.773317
Two-term	0.006977	0.399127	0.979677	0.193599	0.438304	0.942743
Diffusion approximation	0.021453	0.145905	0.882064	0.001435	0.037735	0.945377

The measured data is generally plotted near the seven predicted values in both the open-sun and integrated dryers. In the open sun dryer, the straight-line representing the predicted data, with R^2 = 0.979677, X^2 = 0. 0.006977, and RMSE = 0.399127 was recorded in the Two-term model and R^2 = 0.99553, X^2 = 0.000282, and RMSE = 0.016798 was recorded in the Newton model in the integrated solar dryer. This is because the (X^2) and the (RMSE) were lower and higher for the Page model than the others, as indicated in Table 3. The experimental moisture content reduction rate must best fit the model values, to be the best dryer for agricultural drying without affecting the quality [25].

The consistency of the constructed model is further confirmed by plotting the predicted moisture ratio against the measured moisture ratio, as shown in Figure 7. From Table 3, the Newton model represents the combined flat plate and greenhouse solar dryer, while the Two-term model describes the open sun dryer. Generally, the measured data are scattered close to the straight line representing the predicted data. The Integrated dryer gives best curve fit to the experimental value than the open sun dryer as seen from Figures 7 and 8.

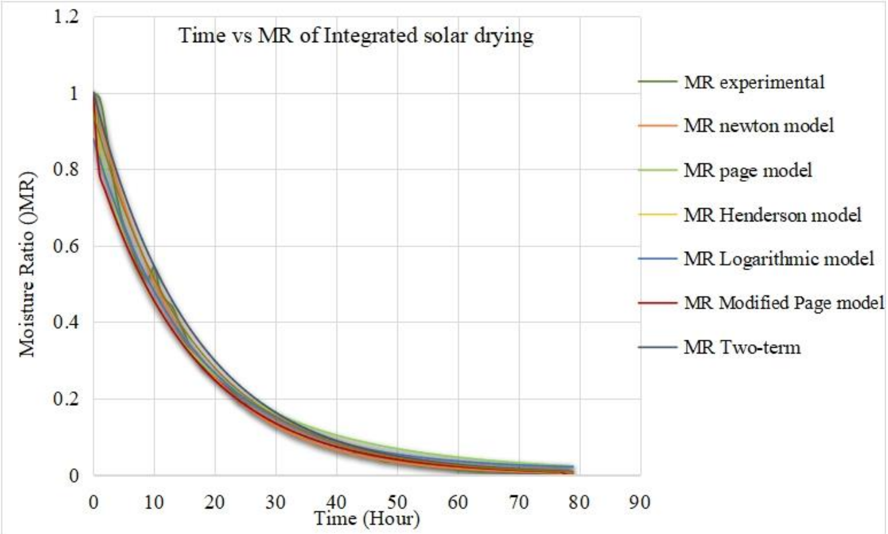

Figure 7. Time vs MR of Integrated solar drying.

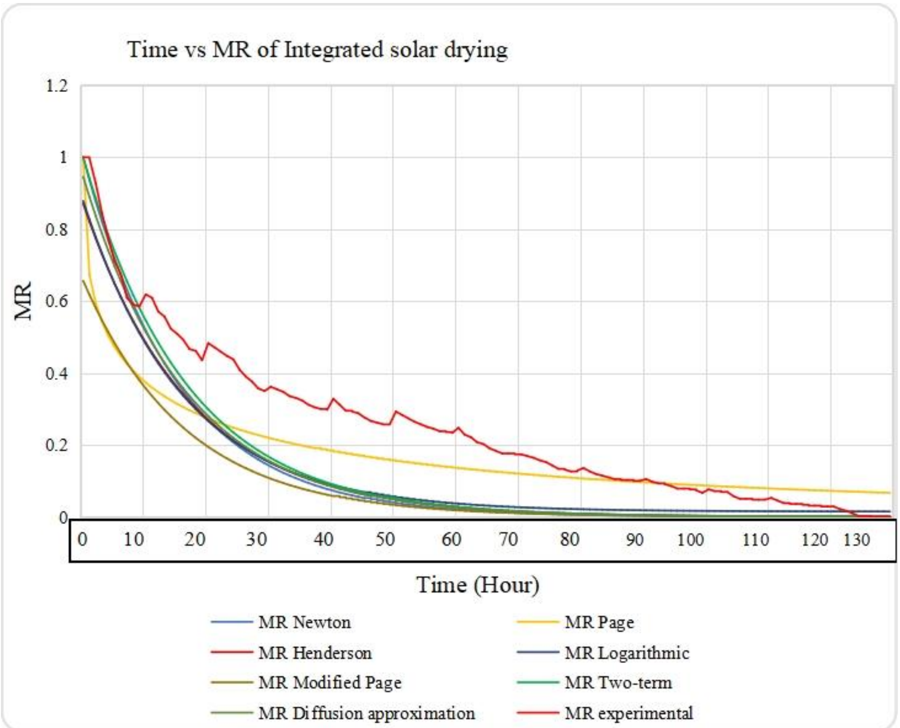

Figure 8. Time *vs* MR of Integrated solar drying.

4. Conclusions

The experiment was conducted from open sun and the newly designed integrated flat plate and greenhouse solar dryers, and the Temperature, Solar Irradiance and Moisture loss values were recorded. The dryer consisted of a 1 m by 2 m flat plate combined with a 5 m by 1.6 m greenhouse. The maximum outlet temperature in the newly designed Integrated solar dryer system was recorded as 45.34 °C for a maximum ambient temperature of 29.8 °C. A batch of coffee weighing 50 kg, whose initial moisture content is 54.23% wet basis, needs to be dried to 11.5% moisture content using a newly Integrated flat plate and greenhouse solar dryer and an open solar dryer system. Evaluation of the performance of the drying systems was based on percentage moisture loss rate. A total dying period of coffee in an integrated dryer system takes 80 h to remove 54.23% of moisture content and in an open sun drying method 130 h take to reduce the moisture from 54.23% to 12.2% and 10.8% in the open sun and integrated dryers respectively.

To determine the optimal drying model, by compared R^2, X^2, and RMSE values. The Newton model emerged as the best option for integrated solar drying, while the Two-term model was more suitable for open sun drying. The model is selected based on low root mean square error (RMSE), X^2 and a high coefficient of determination (R^2), the Newton model outperformed the other models in terms of correlation with experimental data in the Integrated dryer system. This research provides valuable insights into enhancing solar drying systems for coffee production, ultimately promoting sustainability and improving the standard of living for coffee growers. The findings indicate that the combined flat plate and greenhouse solar dryer significantly improve drying efficiency compared to conventional open sun drying methods, reducing drying time without compromising coffee quality.

Recommendation

Future research directions for integrated flat plate and greenhouse solar coffee dryers should focus on enhancing material development for improved thermal efficiency, optimizing system designs through innovative flat plat solar collector configurations and by adding thermal heat storage inside the greenhouse.

List of abbreviations

R^2	Coefficient of Determination
RMSE	Root Mean Square Error
X^2	Chi-Squared (or Chi-Square)
k	drying constants
n	Product Constant
MR	Moisture ratio
MR_{exp}	Experimental Moisture ratio
MR_{pred}	Predicted Moisture ratio
M	Initial moisture content
Mo	Moisture content at any time
Me	Final equilibrium moisture content
HGSD	Hybrid greenhouse solar dryer

Availability of data and materials: The data that support the findings of this study are available from the literature, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. Data are, however available from the authors upon reasonable request and with permission of the researcher.

Author Contributions: E.T.C. contributed to the study conception and design, material preparation, experiment, data collection, and analysis, and E.G. contributed documentation.

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Conflicts of Interest: The authors declare no conflict of interest.

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