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An Experimental Investigation on Indirect Solar Dryer for Drying Sliced Onions using Phase Change Materials (PCM)

Laeeq Ahmed Khan Aqil[1], Atul Bhattad[1*] and Srinivasa Rao Pittam[2]

[1]Department of Mechanical Engineering, Koneru Lakshmaiah Educational Foundation, Green Fields, Vaddeswaram, AP, India
[2]Department of Mechanical Engineering, Vardhaman College of Engineering, Hyderabad, TG, India
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*drathul@kluniversity.in

ABSTRACT

The food industry primarily utilizes sun dryers to extract moisture in order to preserve edible items such as cereals, vegetables, fish, etc. The performance of an indirect, single-pass, forced convection solar dryer with and without paraffin, a phase change material (PCM), integrated into the solar collector, was assessed in this work. Improving the drying efficiency of sliced onions was the main goal, especially when there was little to no sunlight. In this design, the heating-and-drying chamber could hold 1.5 kg of vegetables. A glass cover with dimensions of 100 × 300 cm² was used for the collector. A net served as the screen or tray inside the dryer. Three trays, each measuring 21 × 50 cm and framed with wooden edges. The findings showed that by prolonging the drying process past the sunlight period and sustaining high temperatures inside the drying chamber, adding lauric acid as a PCM greatly enhanced the dryer's performance. The current study carried out mathematical modeling with seven semi-empirical models and drying characteristics of onion slices. The study thoroughly examined important process variables for both dryer designs, moisture ratio (MR), and moisture removal rate. Tray 1 with PCM reached an MR of about 0.2 within 5 hours, while the same tray without PCM reached the same MR in approximately 6 hours. The Logarithmic model proved the best among all the different models fitted for onions dried with PCMs. Overall, the research results demonstrate the great potential of PCM integration to improve the efficacy and efficiency of solar dryers, especially in areas with fluctuating solar radiation.

Keywords: Solar energy; Drying kinetics; Thermal energy storage; Renewable energy; PCM.

1. INTRODUCTION

The process of drying is principal in the post-harvest management of agricultural products, particularly for items susceptible to rapid spoilage like onions. Solar drying systems, which are environmentally sustainable and economically viable, have gained traction for their ability to utilize renewable solar energy. Nonetheless, the effectiveness of these systems is hindered by challenges such as variable sunlight exposure, fluctuations in temperature, and operational inefficiencies during the night. To mitigate these limitations, the incorporation of phase change materials (PCM) into solar drying frameworks has surfaced as a viable strategy. PCM possesses the capability to accumulate surplus thermal energy during peak solar influx and subsequently release it when solar availability diminishes, thereby ensuring a more uniform drying process. This investigation delves into the drying kinetics, physicochemical characteristics, and thermal efficiency associated with PCM-enhanced solar dryers, aiming to augment both drying efficacy and product quality. The utilization of PCM within solar drying systems has demonstrated considerable promise in optimizing drying efficacy. PCM-filled solar dryers provide a controlled drying environment, reducing post-harvest losses. By absorbing and releasing solar energy, the phase change material stabilises temperatures and prolongs drying times past the hours of sunshine. The enclosed design shields crops from dust and insects, and the steady heat efficiently lowers moisture content, preventing microbial development and spoiling. Additionally, by preserving the product's nutritional content and sensory qualities, the consistent drying process prolongs the shelf life of agricultural products and reduces waste. Jahromi *et al.* (2022) illustrated that the inclusion of PCM enhances drying kinetics by stabilizing temperature levels, yielding thermal efficiency improvements ranging from 2.98% to 39% for dryers and from 15.6% to 62% for collectors when juxtaposed with systems lacking PCM. In a similar vein, (Lad *et al.* 2023) highlighted that PCM proficiently sustains the drying chamber temperature within an optimal range of 50°C to 55°C, effectively curbing nutrient degradation and browning in onions. Moreover, Salve and Fulambarkar, (2022) indicated that PCM prolongs the drying duration after sunset by retaining elevated chamber temperatures, a critical factor for achieving the targeted moisture content. Regarding quality preservation, Lad *et al.* (2023) observed that the integration of PCM mitigates the risks associated with excessive thermal exposure, which could otherwise result in nutrient depletion and browning. Yadav and Ramana, (2020) underscored that PCM-assisted drying markedly diminishes moisture content in a more uniform manner compared to conventional sun drying techniques, thereby enhancing product quality. Thermal assessments conducted by Chaatouf *et al*. (2021) demonstrated that PCM enhances thermal efficiency by approximately 3.12% during nighttime conditions, facilitating a more consistent drying experience. Similarly, Ramirez *et al*. (2020) emphasized PCM's function as a thermal buffer, which captures heat during peak solar hours and subsequently releases it, thereby lessening temperature variances.

Empirical investigations and mathematical modeling further corroborate the advantages of PCM-augmented solar dryers. Mojarrad *et al*. (2017) formulated models to forecast drying behavior under diverse conditions, thus enabling the optimization of the drying procedure. Experimental validation conducted by Yadav and Ramana, (2020) affirmed enhancements in drying duration and product quality relative to traditional drying methods. Despite these benefits, scholars have pointed out challenges such as elevated initial investment and increased system intricacy, which may hinder broader implementation, particularly in economically constrained areas. Nonetheless, the enduring advantages, including diminished drying time and enhanced product quality, provide a persuasive argument for the adoption of PCM-assisted solar drying systems as a sustainable approach in agricultural practices. Abdalla *et al*. (2023) stressed the efficiency of indirect solar drying in obtaining lower final moisture content compared to direct sun drying. Their study found that indirect sunlight drying reduced the moisture content of onions to 10% on a dry basis, compared to 16% with direct sun drying. The drying process largely happens during the decreasing rate stage, where the moisture removal rate lowers as drying continues. Additionally, Abdalla *et al*. (2023) emphasized the higher nutritional quality of dried onions, with an increased concentration of proteins, lipids, fiber, ash, and carbs. They also highlighted that indirect solar drying gives greater microbiological safety by shielding onions from contamination with extraneous elements and bacteria. Hanafy and Tarabye (2019) developed mathematical models to predict the drying behavior of onion slices. The Modified Page model, in particular, displayed great accuracy, with coefficients of determination (R^2) reaching 0.9961. Their study also evaluated the economic viability of solar dryers, indicating that these systems have a positive payback period, making them a cost-effective choice for onion drying. Walke *et al*. (2025) evaluated the influence of slice thickness on the drying process, finding that thinner slices (e.g., 2 mm) dry faster and are more appropriate for manufacturing onion powder. They also highlighted technical improvements, like the integration of IoT systems in solar dryers, which enable real-time monitoring and management of environmental conditions, hence boosting efficiency and product quality. Savitha *et al*. (2023) focused on the physical quality features of dried onions, stressing that the drying technique greatly affects color and taste preservation. They observed that sun conductive drying preserved more bioactive chemicals compared to alternative approaches, resulting to improved quality in the final product. Abdel-Galil and Mourad (2009) evaluated the link between design factors and the efficiency of solar dryers. They showed that raising the airflow velocity within the dryer may greatly enhance thermal efficiency. Their economic research further substantiated the cost-effectiveness of solar drying techniques for onion preservation. This research aims to enhance the drying efficiency and quality of onions using an indirect solar dryer integrated with phase change materials (PCM). By releasing stored solar energy during off-sunshine hours, this technique prolongs drying times, ensuring complete moisture removal and greatly lowering spoiling brought on by contamination and microbial development. Additionally, by uniformly drying products, PCM-enhanced dryers keep their nutritional value and sensory qualities, and their enclosed construction protects crops from outside contamination.

The study investigates the drying kinetics and moisture content reduction to optimize energy usage and drying uniformity. The research explores mathematical modeling to predict drying behavior and optimize design parameters, contributing to sustainable and effective drying techniques for agricultural products.

Table 1. Drying models used for mathematical modeling

Model name	Expression
Lewis or Newton	MR = exp(−kt)
Page model	MR = exp(−ktn)
Modified Page model	MR = exp(−(kt)n)
Henderson and Pabis	MR = a exp(−kt)
Wang and Singh	$MR = 1 + at + bt^2$
Two-term	MR = a exp(−kt) + b exp(−gt)
Logarithmic	MR = a exp(−kt) + c

2. MATERIALS AND METHODS

2.1 Experimental Procedure

In this design, the heating-and-drying chamber could hold 1.5 kg of vegetables. For that purpose, the chamber was built with dimensions of 23 × 37 × 60 cm^3, including an air outlet vent measuring 90 × 10 cm^2. A glass cover with dimensions of 100 × 300 cm^2 was used for the collector. A net served as the screen or tray inside the dryer. Three trays measuring 21 × 50 cm and framed with wooden edges were prepared using 2.5 cm × 2 cm wooden sticks. Transparent glass, 5 mm thick, was incorporated into the structure, while a 0.4 mm thick aluminum sheet was used for the metal components. The collector's glass cover measured 83 × 60 cm². Thermocouples and a display panel were installed at various points in the system to monitor temperatures. The drying chamber was connected to a heating chamber, which supplied hot air to facilitate the evaporation and removal of moisture from the vegetables. A spring-loaded weighing machine was used to manually record the weight loss of the vegetables at hourly intervals.

2.2 Selection of Phase Change

Materials Organic PCMs were chosen to utilize their superior qualities compared to inorganic PCMs. These benefits encompass enhanced chemical stability, non-corrosiveness, and increased latent heat per unit mass. Organic PCMs are also recyclable, exhibit congruent melting, and demonstrate minimum or no supercooling, removing the need to chill them below their freezing point to commence crystallization. The drying chamber's maximum input air temperature was 55 °C. Lauric acid was selected as the phase change material for this work. Lauric acid's beneficial thermal properties and useful features make it a suitable Phase Change Material (PCM) for solar drying research. Its melting point, which is normally between 40 and 50 degrees Celsius, fits very nicely with the temperature needs of many agricultural drying procedures, allowing for effective moisture removal without resulting in thermal damage. Moreover, efficient heat storage and temperature stabilisation within the dryer are made possible by its high latent heat of fusion. Long-term performance is guaranteed by the chemical stability of lauric acid, and it is a safe and practical choice due to its non-toxicity and affordable price. The PCM storage box has a capacity of 1.5 kg and was filled to 80% of its volume. The box was located at the base of the drying chamber, and 1.5 kg of PCM was utilized in the tests.

2.3 Drying kinetics and Moisture Content (MC)

The kinetics of drying, along with the moisture content present in the material at a specific moment in time, can be anticipated through the use of empirical correlations established in previous research (Safarov *et al*., 2020; Inyang *et al*., 2018). In the context of the current investigation, several models derived from existing studies and comprehensively represented in Table 1 will be utilized and analyzed for their applicability and accuracy. Determining relevant parameters within these models is predominantly achieved through empirical experimentation, ensuring the models are grounded in practical application. A comprehensive understanding of the common thin-layer drying models and their corresponding equations and critical parameters is essential for optimizing drying processes and enhancing product quality in industrial settings.

In the proposed theoretical frameworks, the parameters a, b, c, and n represent the drying coefficients, while k denotes the drying constant expressed per minute units. Various empirical and theoretical models have been delineated in the academic literature and employed to model foodstuff drying kinetics (Hii *et al*. 2023; Akter *et al*. 2022). Although the relevance of a specific model is contingent upon the characteristics of the material and the underlying mechanisms at play during the drying process, it is frequently asserted that the models above are routinely utilized to elucidate the kinetics of fruits and to engineer industrial drying apparatuses (Compaoré *et al*. 2019). Consequently, these models were applied to approximate the kinetics of onions. Drying models are employed to estimate the duration of the drying process for various products under a range of conditions. This practice facilitates the generalization of drying curves pertinent to the specified design and operational parameters of ITSD. Non-linear least squares regression analysis utilized the Levenberg-Marquardt algorithm within the OriginPro software environment.

2.4 Drying Characteristics of Onions

The initial moisture content (MC) of a material can be estimated on both wet basis (wb) and dry basis (db). The wet basis moisture content is calculated as Eq. .1, while the dry basis moisture content is determined by the formula Eq. 2, where mi represents the initial mass of the product, and md denotes the final dried mass. Additionally, the drying rate (DR) of the material in an Integrated Thermal System Dryer (ITSD) is estimated by taking the difference in moisture content at two successive times and dividing it by the time interval (dt). This is expressed as Eq. 3. A system's drying efficiency, especially that of a solar dryer, is assessed by measuring and analysing a number of important characteristics. These variables offer a thorough comprehension of the dryer's operation.

$$MC_i = \frac{(m_i - m_d)}{m_i} \quad \dots (1)$$

$$MC_i = \frac{(m_i - m_d)}{m_d} \quad \dots (2)$$

$$DR = \frac{dMC}{dt} = \frac{(MC_{t+dt} - MC_t)}{dt} \quad \dots (3)$$

The experimental determination of moisture ratio (MR) is employed to identify the best-fit model from the existing literature. A dimensionless metric known as the moisture ratio shows how much moisture is still present in the product at any particular moment in comparison to the starting and equilibrium moisture concentrations. It facilitates comprehension of the drying process's evolution over time. MR can be expressed as Eq. 4:

$$MR(db) = \frac{(MC_t - MC_e)}{(MC_i - MC_e)} \quad \dots (4)$$

where, MC_t represents the moisture content (db) at a specific moment in time, and MC_e denotes the equilibrium moisture content (db) of the sample. Eq. 5 can be simplified, as proposed by Akpinar (2010), to:

$$MR(db) = \frac{(MC_t)}{MC_i} \quad \dots (5)$$

Non-linear least squares regression analysis was conducted utilizing the Levenberg-Marquardt algorithm, implemented within the Sigma Plot software environment. This robust method is particularly effective for fitting complex models to data, allowing for estimating parameters that minimize the difference between observed values and those predicted by the model. A key metric in this analysis was the coefficient of determination (R^2), the primary criterion for accurately identifying the most suitable model to represent the drying curve. R^2 values range from 0 to 1, with values closer to 1 indicating a strong correlation between the model and the observed data, thus reflecting the model's explanatory power. In addition to R^2, reduced chi-square (χ^2) and the root mean square error (RMSE) were used to assess the model's goodness of fit further. The reduced chi-square provides a normalized measure of the fit by accounting for the degrees of freedom, allowing for a more nuanced comparison between models with different numbers of parameters. Meanwhile, RMSE quantifies the average magnitude of the errors between predicted and observed values, offering insight into the precision of the model's predictions. The calculations for these parameters can be derived using the following Eqs. 6 and 7:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-Z} \quad \dots (6)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{\frac{1}{2}} \quad \dots (7)$$

2.5 Effective Moisture Diffusivity

The pace at which moisture permeates the product during drying is indicated by this metric. A basic characteristic affects the kinetics of drying. The effective moisture diffusivity ($Deff$) of the tray with and without PCM was computed using Fick's second law of diffusion, which can be simplified by the first-term approximation of the Crank model. Starting with the calculation of moisture ratio, MR, it can be computed as the ratio of moisture content at any time, Mt, to the initial moisture content, $M0$. The equation based on Crank's model for MR is expressed as:

$$MR = (8/\pi^2)\exp(-(\pi^2 Defft)/(4L^2)) \quad \dots (8)$$

where, t is the drying time and L is the thickness of the material. By taking the natural logarithm on both sides, the equation could be linearized:

$$\ln(MR) = \ln(8/\pi^2) - (\pi^2 Defft)/(4L^2) \quad \dots (9)$$

This linearized form allows us to plot $\ln(MR)$ against t, where the slope (m) of the line is related to $Deff$ through the relationship:

$$m = -(\pi^2 \mathrm{Deff})/(4L^2) \quad \dots (10)$$

Rearranging this expression, $Deff$ can be expressed as:

$$Deff = -(4L^2 m)/(\pi^2) \quad \dots (11)$$

For each tray, we calculated MR from the data provided and then took the natural logarithm of MR. Values of $\ln(MR)$ were plotted versus drying time (t) for each tray (with and without PCM). A linear regression was carried out to obtain the slope (m) of the line. With the known thickness of the material slices, L (0.005 m), $Deff$ for each tray was computed using the above equation. The values of effective moisture diffusivity have been plotted against drying time to analyze each tray's behavior under different drying conditions with and without PCM.

3. RESULTS AND DISCUSSIONS

Figure 1 delineates the correlation between drying duration and the concomitant decrease in moisture content (MC, based on dry weight) of onion slices positioned on trays with and without phase change materials (PCM). The initial MC for all trays was approximately 6 kg/kg. During the preliminary phase of the drying process (the first 60 minutes), the thermal energy supplied by the drying air primarily served to elevate the temperature of the drying apparatus and the onion slices, resulting in a diminished moisture extraction rate. Following this initial interval, the moisture removal rate accelerated due to the increased moisture diffusion facilitated by the higher moisture contents within the onion slices.

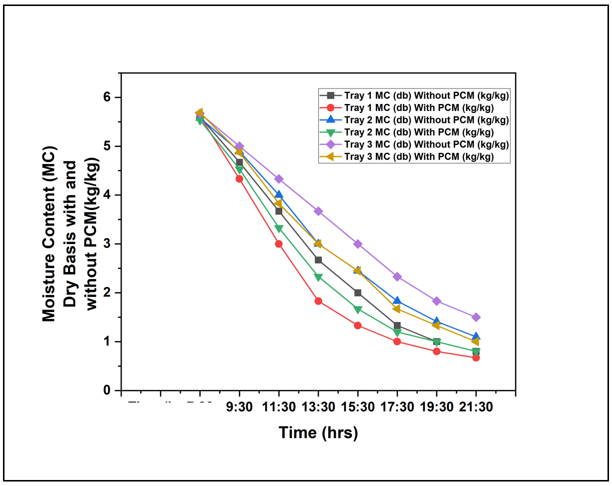

Fig. 1: Influence of PCM on moisture content in various trays

The incorporation of PCM markedly affected the efficiency of the drying operation. Trays integrated with PCM demonstrated a more rapid reduction in moisture throughout the drying timeline, particularly during the late afternoon and evening periods when solar radiation decreased. For example, Tray 1 containing PCM reached a final MC of roughly 0.5 kg/kg, in contrast to 1 kg/kg observed in the absence of PCM. A similar pattern was noted for Trays 2 and 3, wherein PCM enabled continuous thermal energy release, resulting in lower final MC levels. The ultimate moisture content (MC) was strongly influenced by the spatial configuration of the trays in the drying chamber. Trays positioned nearer to the phase change material (PCM) source or those receiving augmented airflow exhibited superior drying speeds and uniformity relative to those at a greater distance. As the moisture content decreased, the rate of moisture diffusion also declined, resulting in a slowdown in the drying rate towards the conclusion of the operation. PCM's integration and strategic organization improved drying efficiency by sustaining stable temperature conditions and optimizing energy usage.

Figure 2 presents some results that relate the drying time with different MRs of onion slices corresponding to samples dried in trays with or without PCM. The start MR for all trays lies at 1, representing the initial moisture take-up by onion slices being subjected to this process. During the first inceptive drying stages (first 2 hrs), MR goes down slightly because the entire system normally takes up this time or a little more for heating parts of the dryer and the main product, the onion itself. This stage is characterized by a lower moisture removal rate, common in drying processes as the initial energy input is used mainly for heating.

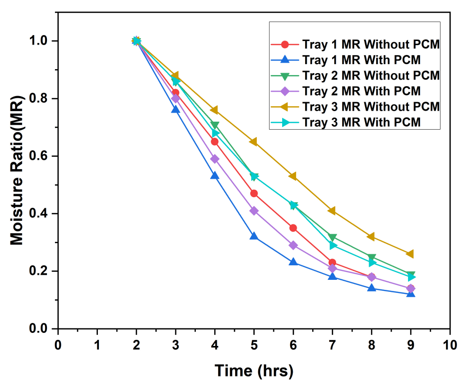

Fig. 2: Influence of PCM on moisture ratio in various trays

Results show that in every test run, trays with incorporated PCMs showed a consistent increase in the rate of reduction in MR when compared to trays without PCMs. This can be especially attributed to the fact that beyond the initial 2 hours, the thermal energy stored within the PCMs began to assist when there were fluctuations in ambient solar energy. For example, Tray 1 with PCM reached an MR of about 0.2 within 5 hours, while the same tray without PCM reached the same MR in approximately 6 hours. The fact that Tray 1, which had PCM installed, obtained a Moisture Ratio (MR) of 0.2 in 5 hours as opposed to 6 hours for the non-PCM system, highlights the considerable efficiency improvements made possible by PCM integration. The PCM's capacity to speed up moisture removal is clearly demonstrated by this 16.67% drying time decrease, underscoring its value in establishing a more reliable and effective drying environment. The PCM technology enables a quicker and more consistent drying process by sustaining constant drying temperatures even during variations in sun light. This trend shows PCM's efficiency in maintaining a consistent drying environment, thus hastening moisture removal. This can be similarly seen in Tray 2 and Tray 3, whereby the test pieces placed in trays equipped with a PCM system tend to perform better drying than those without the system above. This is highly desirable, especially at the end stages of drying, usually beyond 4 hours from commencement, when the solar intensity is reduced. In these periods, the stored heat in the PCM allows for the continued release of thermal energy, thus maintaining a constant MR reduction. At the end of the drying period, the MR values for trays with incorporated PCM reach much lower values than those without PCM, indicating an improvement in the drying efficiency.

Drying performance is also influenced by the placement of trays inside the dryer. Trays closer to the PCM, such as Tray 1, have faster drying rates with lower final MRs due to the improvement in heat distribution. Tray 3, being far from the melting point of the PCM, presents a slow moisture removal rate even with the presence of the PCM. This shows that optimization of the tray placement in the drying chamber is of the essence for the effective utilization of PCM.

Drying Rate (DR) refers to the quantity of moisture evaporated per unit time. A comparison done for trays with and without phase change materials will emphasize the influence of the PCM on the drying performance. The DR for various parameters is illustrated in Figure 3. For Tray 1, the DR values showed a progressive reduction in the presence of PCMs, indicating that the moisture removal rate is uniform with the aid of the thermal buffering effect of PCMs. This resulted in a more consistent drying process than Tray 1 without PCM, which started with a greater drying rate but declined quickly, suggesting rapid initial moisture loss followed by lower heat transfer efficiency. The situation with Tray 2 is similar, where PCM stabilized the drying pace, decreased fluctuations, and lengthened the duration, which is good for preserving product quality. In the absence of PCM, Tray 2 showed a higher initial drying rate but quickly decreased, indicating that the drying conditions were not maintained. In the instance of Tray 3, with the application of PCM, the drying rate exhibited the most sluggish drop, underlining the requirement of giving longer and homogenous heat for stable drying. In contrast, Tray 3 without PCM demonstrated a quick decline in the drying rate after the first phase, leading to unpredictability in drying performance.

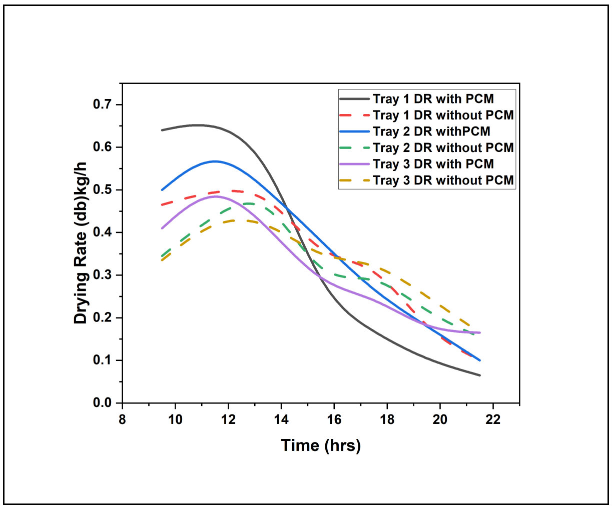

Fig. 3: Effect of PCM on drying rate in various trays

3.1 Statistical Analysis and Mathematical Modelling Tools

Experimental data of onions, on a dry weight basis under two drying conditions, viz., with and without phase change material, were analyzed. Data on moisture content were converted to moisture ratio and fitted to seven chosen drying models which include Lewis model, Page model, Modified Page model, Henderson and Pabis model, Wang and Singh model, Two-term model, and the Logarithmic model. Because of its natural adaptability and efficiency in describing the normal drying behaviour of agricultural items like onions—particularly the marked dropping rate period—the Wang and Singh model fits onions dried without PCM better than other models. When direct heat transfer and internal moisture diffusion mainly fuel drying, as is the case in non-PCM systems, this model well captures the progressive decline in moisture removal over time. It is an excellent option for simulating the drying kinetics under these circumstances due to its relative simplicity and capacity to faithfully depict this drying dynamic. According to Table 1, these models find common use in drying agricultural and food commodities because of their efficiency in describing moisture reduction dynamics. Among the statistical tests performed to check for goodness of fit in the proposed models were R^2 and RMSE. Results are presented in Tables 2 and 3, including model parameters and statistical metrics. The R^2 of all models varied from 0.9650 to 0.9991 and RMSE in the range of 0.000001 to 0.359941, which proves that a good fitness between experimental and predicted moisture ratios exists. These high R^2 values, which are close to unity, indicate that the model's predictions and the actual experimental data fit each other almost perfectly, confirming the models' ability to properly depict the system's drying kinetics. Establishing the validity of the authors' findings and deriving insightful conclusions on the influence of PCM integration on the sun drying process depend heavily on this strong statistical validation. Furthermore, the strong R^2 values highlight how well the models can forecast drying behaviour, allowing for precise drying time predictions and aiding in drying process optimisation for improved product quality and efficiency.

Table 2. Modeling of moisture ratio with drying time during drying of onion without PCM

Tray	Model	Parameters	R^2	RMSE
Tray 1	Lewis	0.2606	0.9874	0.0332
	Page	0.1936, 1.2229	0.9987	0.0108
	Modified Page	0.2612, 1.2229	0.9987	0.0108
	Henderson and Pabis	1.0378, 0.2716	0.9904	0.0290
	Wang and Singh	-0.2116, 0.0125	0.9977	0.0143
	Two-term	0.5199, 0.2716, 0.5179, 0.2716	0.9904	0.0290
	Logarithmic	1.1992, 0.1992, -0.1814	0.9956	0.0196
Tray 2	Lewis	0.2758	0.9965	0.0171
	Page	0.2429, 1.0974	0.9990	0.0094
	Modified Page	0.2754, 1.0974	0.9990	0.0094
	Henderson and Pabis	1.0169, 0.2810	0.9971	0.0156
	Wang and Singh	-0.2308, 0.0155	0.9996	0.0061
	Two-term	0.5018, 0.2810, 0.5151, 0.2810	0.9971	0.0156
	Logarithmic	1.0744, 0.2463, -0.0669	0.9982	0.0122
Tray 3	Lewis	0.2888	0.9982	0.0122
	Page	0.2717, 1.0475	0.9988	0.0099
	Modified Page	0.2882, 1.0475	0.9988	0.0099
	Henderson and Pabis	1.0066, 0.2909	0.9983	0.0119
	Wang and Singh	-0.2413, 0.0169	0.9983	0.0118
	Two-term	0.5028, 0.2909, 0.5037, 0.2909	0.9983	0.0119
	Logarithmic	1.0404, 0.2675, -0.0401	0.9988	0.0101

In the case of onions dried without PCM (Table 2), from statistical tests, the Wang and Singh model best fitted Tray 2 data with the highest value of R^2 being 0.9996 and the lowest value of RMSE being 0.0061. The Page and Modified Page models also showed high values for R^2 and low values for RMSE, almost equal to that given by the Wang and Singh model. Thus, the model of Wang and Singh was picked out to be the best for all the statistical data. Figure 4 illustrates a comparison of the drying curve of the Onion with the Wang-Singh model. Among all the different models fitted for onions dried with PCMs, the Logarithmic model proved to be the best. R^2 values were above 0.9950, while RMSE values were less than 0.0216 for all trays from Table 3. More precisely, the best fit was obtained by Tray 3 using the Logarithmic model with an R^2 value of 0.9978 and an RMSE of 0.0144. This Logarithmic model best expressed the characteristics of gradual moisture reduction and energy modulation in PCM-assisted drying, illustrated in Figure 5.

Table 3. Modeling of moisture ratio with drying time during drying of onion without PCM

Tray	Model	Parameters	R^2	RMSE
Tray 1	Lewis	0.3383	0.9917	0.0276
	Page	0.3122, 1.0686	0.9929	0.0256
	Modified Page	0.3365, 1.0686	0.9929	0.0256
	Henderson and Pabis	1.0188, 0.3449	0.9924	0.0265
	Wang and Singh	-0.2824, 0.0227	0.9960	0.0191
	Two-term	1.0867, 0.3688, -0.0867, 32.5718	0.9945	0.0224
	Logarithmic	1.0036, 0.3610, 0.0190	0.9926	0.0261
Tray 2	Lewis	0.3628	0.9945	0.0226
	Page	0.3446, 1.0457	0.9950	0.0216
	Modified Page	0.3610, 1.0457	0.9950	0.0216
	Henderson and Pabis	1.0130, 0.3677	0.9948	0.0220
	Wang and Singh	-0.2956, 0.0244	0.9957	0.0201
	Two-term	1.0176, 0.3757, 0.0000, -0.9518	0.9959	0.0196
	Logarithmic	0.9973, 0.3865, 0.0200	0.9951	0.0214
Tray 3	Lewis	0.3826	0.9970	0.0166
	Page	0.3811, 1.0036	0.9970	0.0166
	Modified Page	0.3824, 1.0036	0.9970	0.0166
	Henderson and Pabis	1.0048, 0.3844	0.9971	0.0165
	Wang and Singh	-0.3059, 0.0258	0.9939	0.0238
	Two-term	1.0099, 0.3949, 0.0002, -0.7035	0.9983	0.0127
	Logarithmic	0.9835, 0.4133, 0.0277	0.9978	0.0144

3.2 Determination of Effective Moisture Diffusivity

Figure 6 shows the variation of effective moisture diffusivity with drying time for trays with and without PCM. The values of Deff determined are picked from Fick's diffusion model as presented in Eq. 15. For Tray 1, the value ranges from 1.5×10^{-10} m^2/s to 1.2×10^{-9} m^2/s, and for Tray 2, it ranges from 2.0×10^{-10} m^2/s to 1.0×10^{-9}. Using PCM with the drying system gave higher Deff values than those without, indicating the system's superior performance in the drying process. This has been explained by better temperature management along the drying line by the PCM. The average of Deff for all the trays increased with drying time, showing gradual improvement in moisture diffusivity with increasing drying time.

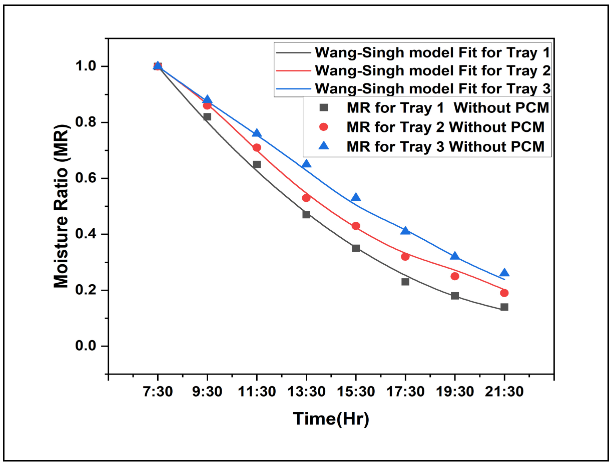

Fig. 4: Comparison of drying curve of Onion with Wang-singh model without presence of PCM

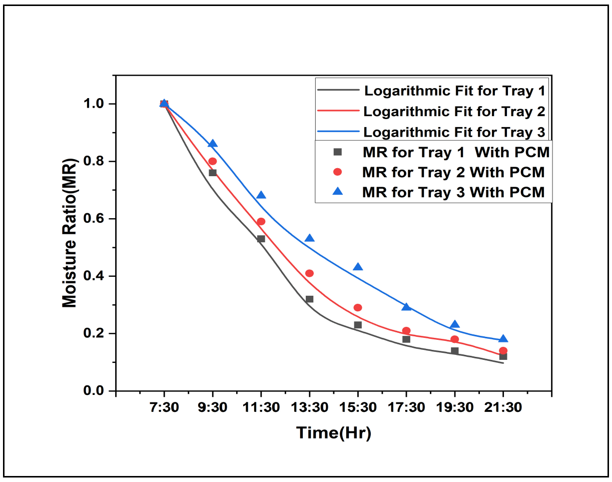

Fig. 5: Comparison of drying curve of Onion with Logarithmic with presence of PCM

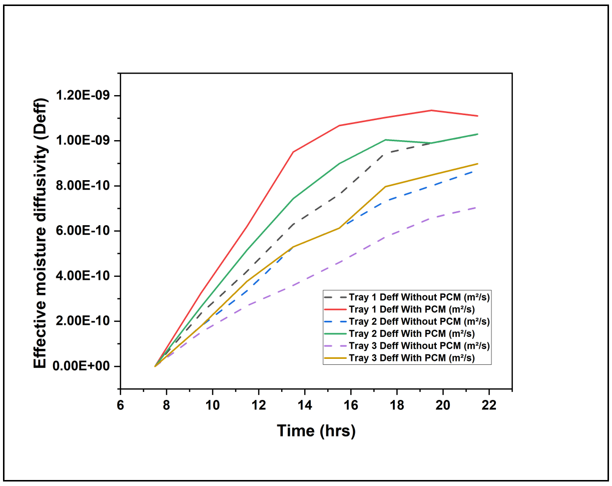

Fig. 6: Variation of effective moisture diffusivity with drying time for trays with and without PCM

The estimated Deff values in this work compare very well with those available in the literature; for example, (Zogzas and Maroulis, 1996) estimated the Deff values in several food materials from 10^{-8} m^2/s to 10^{-12} m^2/s. (Evin, 2012) found the Deff values for G. tournefortii range from 10^{-12} m^2/s to 10^{-6} m^2/s. It should be noted that the results of the present study compare very well with those in the literature, showing their validity and consistency with established data. As shown in Figure 6, PCM inclusion tremendously impacts the drying process by improving moisture flow. This can be reflected through the higher effective diffusivity in every assisted tray.

4. CONCLUSION

Drying is a valuable approach to reducing post-harvest losses in agriculture, offering numerous benefits such as lower moisture content, extended shelf life, and inhibition of microbial growth. The study investigates the reduction of drying kinetics and moisture content to optimize energy usage and drying uniformity. The research explores mathematical modeling to predict drying behavior. Drying models are employed to estimate the duration of the drying process for various products under a range of conditions. The following conclusions were drawn from the study:

- The incorporation of PCM markedly affected the efficiency of the drying operation. Trays integrated with PCM demonstrated a more rapid reduction in moisture throughout the drying timeline.
- Tray 1 with PCM reached an MR of about 0.2 within 5 hours, while the same tray without PCM reached the same MR in approximately 6 hours.
- The R^2 of all models varied from 0.9650 to 0.9991 and RMSE in the range of 0.000001 to 0.359941, proving a good fitness between experimental and predicted moisture ratios exists.
- In the case of onions dried without PCM, the Wang and Singh model fits best for Tray 2 data, with the highest value of R^2 being 0.9996 and the lowest value of RMSE being 0.0061.
- Among all the different models fitted for onions dried with PCMs, the Logarithmic model proved the best. R^2 values were above 0.9950, while RMSE values were less than 0.0216 for all trays.
- The use of PCM with the drying system gave higher values of Deff than those without, indicating a superior system performance in the drying process.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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