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Latent Heat Storage System Based Mixed Mode Indirect Solar Dryer for Drying Myrobalan

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A mixed mode indirect solar dryer (MISD) was designed with a PCM-assisted polycarbonate glazed sheet covered solar collector and a drying unit for drying myrobalan. The rate of heat loss coefficients was evaluated experimentally with a modified collector design. The novelty of this work is the application of a PCM-energy storage in a conventional solar dryer to reduce the drying time of myrobalan. The thermal storage in MISD increases the continuous thermal supply period by 19±4 % compared to without thermal storage during the off-sunshine hour. The drying time of myrobalan was reduced to 12 h in MISD compared to 41 h in the OSD method. This results in better dryer performance and reduced drying time. The total useful energy was 61.18 MJ, and 0.206 MJ was reduced energy loss. The dryer's average temperature and relative humidity were measured as 65.2 °C and 8.83 %, respectively. The results show that exergy efficiency increases, and exergy loss reduced in the MISD. An intensive experimental study on the thermo-physical properties of TES materials can be an additional advantage. Antioxidant values and the total phenolic content were evaluated by different methods. The best color and lower hardness values were achieved for a sample dried in MISD, as compared to other TD and OSD methods.

Keywords: Myrobalan, Solar dryer, Thermal storage, Antioxidant activity, TPC.

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1. INTRODUCTION

Drying agricultural products is one of the preservation techniques widely practiced. The primary objective of drying is to remove moisture to a pre-determined level and control the growth of microbes. Other chemical reactions are limited to extracting product moisture with heat and mass transfer processes [1]. Sun drying is an environmentally friendly and sustainable method that produces no hazardous emissions and is cost-effective for small-scale farmers to dry their products. The drawbacks of open sun drying (OSD) are the requirement of a larger area, higher labor cost, quality degradation of dried products, and environmental dependence (solar radiation, ambient condition, and wind flow). Solar drying is an excellent alternative to open sun drying techniques. Different solar dryer designs have been proposed to restrict post-harvest losses and improve product quality in recent decades. However, few solar dryer designs are popular among farmers and food-process industries. Depending on location, size, and product type, the solar dryer design varies. The natural convective, force convective and mixed-mode design in solar dryers is distinguished by air movement and heat transfer mode. Solar dryers are divided into two categories i.e., dryers with low temperatures and dryers with high temperatures [2].

Myrobalan was rich in antioxidant activity, total phenolic content, and high medical values to prevent and cure microbial and other infectious diseases [3]. It is abundantly available in the Bodoland (Assam) and Shillong (Meghalaya) of the northeastern region (NER)-India. The limited reviews are observed with solar dryer used to dry agricultural products with high value-added and fruits unutilized in NER-India. The work's motivation was that no studies and research reports were available on drying myrobalan in mixed mode indirect solar dryers with latent heat storage systems.

2. DESIGN AND FABRICATION OF MODIFIED MIXED MODE INDIRECT SOLAR DRYER

The built mixed mode indirect solar dryer (MISD) was setup in the terrace of the process control laboratory, CIT Kokrajhar, Assam at a latitude 26°51' North and longitude 90°22' East. Myrobalan was acquired from the local formers in Kokrajhar, NER-India. The dryer parameters like temperature, humidity, airflow, and weight are monitored using a data logger. The MISD consists of three important units: solar collector with aluminum sheet pipes and double-glazed glass, thermal storage unit with phase changing material, and drying chamber with dehumidifier. The solar collector structure constructed with galvanized iron (GI) sheet outside, mild iron (MI) sheet inside, and aluminum sheet as a thermal observer with physical dimensions as 1.52 m in length, 0.61 m in width, and 0.15 m in height. The collector mounted on an iron frame with an inclination angle of 23° along north-south for trapping maximum solar radiation. The unique feature of the collector was polycarbonate glazing cover and compared thermal conductance with the existing glass

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cover type-solar dryer [4]. The polycarbonate glazed sheet of 6mm mounted as a solar observer and 5mm thick aluminum sheet was acting as a heat-absorbing bottom plate, and the aluminum tubes were used to increase the thermal conductance in the collector. The air circulating system used to maintain the optimal airflow in the collector to the drying unit. The collector was placed in a non-shadowed and open area to trap maximum solar radiation. The solar radiation falls on the polycarbonate glazed sheet the bottom plate, which was heated through heat conduction mechanism. Then, the heat was transferred from the bottom plate to pumped air from ambient conditions through the convection process. The hot air passes from the energy storage unit to the drying chamber. The circulating hot air from the solar collector initially contact with the energy storage unit. Due to high fluctuation in renewable energy sources, thermal storage facilities are in higher. Thermal storage setup in dryers can be classified as sensible type, latent type (phase-changing materials), and thermochemical type. Phase change materials (PCM) are preferred for thermal energy storage in dryers because of their ability to heat storage at constant temperature and availability in optimal food drying temperature ranges. The thermal energy storage (TES) was integrated into the collector where paraffin wax was melted and poured in to 30 aluminum tins of 2 mm thickness and 250 ml capacity. The tin cans were coated in black color to achieve quick heating of paraffin wax – phase change material (PCM) filled in tins. The significant advantage of paraffin wax is economical compared with other PCMs and neither poisonous nor explode in nature. To reduce the time of conduction and increase the convection efficiency, aluminum strips having 4 mm thickness were inserted during the filling of aluminum tins with melted paraffin wax. The physical dimensions of drying unit were 1.64 m in length, 0.61 m in breath, and 0.15 m in width (between collector glass and bottom plate) and inclined at an angle of 21° over the earth surface and fixed on a movable stand. In the drying unit, 4 aluminum trays (4 nos.) of 5 kg holding capacity were supported on an iron structure for drying the sample. Trays have 0.004 m holes for even distribution of circulating hot air, and the trays were kept in the distance of 0.2 m. The air vent in the dryer allows moist air to exit in the drying process.

3. MATHEMATICAL MODEL FOR DIFFERENT UNITS OF DRYER

The mathematical model of the modified mixed mode solar dryer (MISD) was derived for three important parts including, solar collector, drying chamber and thermal storage unit [5]. To validate the experimental data and the simulated model of any system, calculation of root mean square error (RMSE) and root mean square error percentage (RMSE%) was necessary. The experimental dryer temperature was measured continuously on a sunny day. With the mathematical model and identification techniques, the simulated model of the dryer was predicted. For MISD, the RMSE and RMSE% calculated as proposed by Zoukit [6]. To study the dryer performance, validation of experimental values and design of control schemes, modelling and simulation were performed. With the reference to the previous studies, for various solar dryers [7], an easy and effective simulation model identification was performed to predict the behavior of the MISD. In comparing the simulation model for dryer temperature with its experimental value, dryer performance was analyzed with the weather conditions of Kokrajhar. Estimation of error was carried out by calculating the mean variance between experimental values and the simulation values. The root mean square error (RMSE) and root mean square percentage (RMSE%) were calculated by,

$$\mathrm{RMSE} = \sqrt{\frac{\sum_j \left(Tc_{e.j} - Tc_{s.j}\right)^2}{N}}\,, \tag{1}$$

$$\mathrm{RMSE\%} = \sqrt{\frac{\sum_j \left(\frac{\left(Tc_{e.j} - Tc_{s.j}\right)}{Tc_{e.j}}\right)^2}{N}}\,. \tag{2}$$

4. MATHEMATICAL MODELING OF THIN LAYER DRYING

The heat and mass transfer processes in the solar dryers are highly complex. Mathematical modelling has been carried out to overcome the improper drying and optimize the drying process. Performing the dryer's complete factorial experiment with all variables is time taking and difficult to find the correct drying method, controlling the process, studying the drying kinetics, and optimizing engineering process, using the process variables, the rate of moisture removed in any product can be shown by drying kinetics. Drying models are built on understanding the drying rate of the products. Myrobalan of uniform size was procured from the local market and cleaned with running water to remove all dirt and dust. After washing, clean white towel was used to draw the excess water from myrobalan fruits. Before performing the drying process, the fruit sample was cut axially in to two halves to determine the initial moisture content (IMC) and final moisture content (FMC) of the sample dried. The IMC and FMC of myrobalan were measured using a moisture analyzer – infrared type (Satorius (MA 35), SLI - Germany). The IMC and FMC were calculated as of 88±1 % (w.b.) and 6.2±1.4 % (w.b.), respectively, for myrobalan fresh sample. In this work, the drying kinetics of myrobalan was investigated in the three different drying methods, modified mixed mode solar dryer (MISD) as shown in Figure 3, tray dryer (TD at 60 °C), and open sun drying method (OSD). In MISD and TD, a 0.2 kg myrobalan sample was placed in trays for drying. An equal quantity of 0.2 kg of myrobalan sample was placed on the ground to dry in the OSD method. While performing the drying of myrobalan in three different methods, a load cell sensor was used to measure the moisture content of the fruits in terms of the mass of the fruit. Similarly, the moisture content of the fruits has been calculated physically through a weighing machine at every 1-hour interval throughout the drying process and compared with the values from load cell censor. The AOAC method was used to calculate the moisture content in the samples. The sample (400 g) was dried in hot air over (at 110 °C) to chive the constant weight. On a dry basis, the sample's initial moisture content and final moisture content are estimated. Five popular models listed in the Table 1, were used for estimating the drying kinetics of myrobalan slices. Through the nonlinear regression analysis, experimental data was executed using the Origin Pro 8.0 software. The best drying model for the drying of myrobalan slices was selected by the values of coefficient of determination (R^2) and Root Mean Square Error (RMSE).

Table 1 – Different empirical model for thin layer solar drying

Model Name	Expression
Modified Page [8]	$MR = \exp[-(kt)]^n$
Henderson and Pabis [9]	$MR = a\exp[-(kt) + (1-a)\exp(-kt)]$
Two term exponential [10]	$MR = a\exp[-(kt) + (1-a)\exp(-kt)]^n$
Midilli [11], [12]	$MR = \dfrac{M - M_e}{M_0 - M_e} = ae^{-(\kappa\tau^n)} + bt$
Wang and Singh [13]	$MR = M_0 + at + bt^n$

5. QUALITY ANALYSIS OF DRIED SAMPLE TOTAL PHENOLIC CONTENT AND RADICAL SCAVENGING ACTIVITY

To measure the total phenolic content (TPC) and antioxidant activity of fresh and dried myrobalan slices, Saikia et al., 2022 [14] was followed.

6. RESULTS AND DISCUSSION

On a sunny day, the first week of October 2021, between 8 AM to 8 PM, drying experiments were performed at the CIT Kokrajhar-BTAD, Assam, NER-India. The plotted data in Fig. 1 were used to validate the experimental data of the MISD with a simulation model. A drying time of 720 minutes, constant air velocity of 0.62 m/s was considered. At ambient conditions, the experimental temperature value was compared with the simulated temperature value obtained through system identification data-driven technique. From Fig. 1, a close association between experimental and simulated values can be observed.

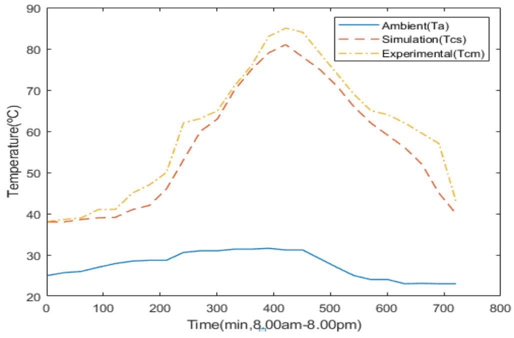

Fig. 1 – Validating experimental data with simulation model drying chamber temperature due to solar radiation

The total useful energy obtained from the collector of MSD to the drying chamber during drying was 61.18 MJ, and the loss was estimated as 0.206 MJ. Higher amount of energy consumed by the pump was 5.38 kW. During the drying process (8 AM to 8 PM), the average temperature and relative humidity was recorded as 65.2 °C and 8.83 %, respectively.

Five empirical models were considered to fit the experimentally obtained drying data. From the data in Table 2, it can be seen that all drying models were fitted closely, but the modified page was found to be more suitable as the value of R^2 was higher and the value of RMSE was lower as compared to other models.

Table 2 – Thin layer drying model for drying myrobalan in MISD

Model	Drying method	Constants	R^2	RMSE
Modified page	OSD	$k = 0.014$, $n = 1.4$	0.9985	0.0095
	MISD	$k = 0.007$, $n = 0.9$	0.9998	0.0061
	TD (60°C)	$k = 0.013$, $n = 1.3$	0.9989	0.0096
Henderson and Pabis	OSD	$a = 1.0700$, $k = 0.0029$	0.9955	0.0381
	MISD	$a = 0.9902$, $k = 0.0088$	0.9998	0.0088
	TD (60°C)	$a = 0.9836$, $k = 0.0071$	0.9997	0.0072
Two term exponential	OSD	$a = 0.998$, $k = 0.01$	0.9981	0.0897
	MISD	$a = 1.900$, $k = 0.02$	0.9989	0.0091
	TD (60°C)	$a = 1.713$, $k = 0.01$	0.9976	0.0086
Midilli Model	OSD	$a = 0.9997$, $k = 0.0003$ $n = 1.397$, $b = 0.00002$	0.9993	0.0124
	MISD	$a = 1.005$, $k = 0.0118$ $n = 0.9511$, $b = -0.00004$	0.9994	0.0074
	TD (60°C)	$a = 0.9950$, $k = 0.0089$ $n = 0.957$, $b = -0.000001$	0.9996	0.0059
Wang and Singh	OSD	$a = -0.0019$, $b = 0.0000008$	0.9936	0.0452
	MISD	$a = -0.0059$, $b = 0.000008$	0.9745	0.0766
	TD (60°C)	$a = -0.0044$, $b = 0.000004$	0.9629	0.0937

The reduction in moisture ratio (MR) was increased rapidly due to high moisture content and higher temperature. A better correlation of R^2 with RMSE was obtained when comparing the experimental value to the predicted value.

The acceptability of food depends on various factors and the color as well as texture of the food products often indicative of the product quality which increases the demand for the product. In the current work, quality parameters like TPC, antioxidant activity, TFC, texture, and color of the dried product were measured and compared with fresh slices of myrobalan.

The raw and dry myrobalan slices TPC values varies from 77.11 mg to 34.98 mg (GAE/gm of the sample), whereas the TPC of dried myrobalan slices in MISD, TD (at 60 °C) and OSD was recorded as 55.67, 43.06 and 35.97 mg (GAE/gm of the sample). The difference in the TPC values of dried samples is with variances of the drying period of each method. As per the report of Esparza-Martínez et al., [15], drying at maximum temperatures over long periods enhances the phenolic compounds solubility, causing the cellular structure breakdown and release of phenolic chemicals linked to the cell wall. The study's outcome was similar to the results of Krishnan et al., [16], where TPC has decreased nearly half a fold in a vacuum dryer (ultra-sonicated) at 60 °C compared to the fresh slices.

The antioxidant activity of myrobalan slices was assessed using a free radical scavenging test. The results showed that the antioxidant activity of fresh sample was 128.58±1.4 μ mol of TE/gm of the sample, and samples dried in OSD showed the lowest value of 62.37±0.6 μ mol of TE/gm of a sample.

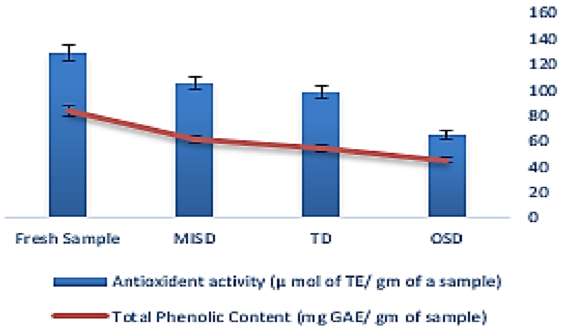

Fig. 2 – Antioxidant activity and TPC of fresh slices and slices dried in different techniques

Fig. 2 shows the best antioxidant and TPC value achieved with MISD technique in drying of myrobalan. Systematic breakdown of cell walls was occurred at uniform and regulated drying conditions of MISD, which progressively activated the discharge of oxidative and hydrolytic enzymes. As a result, bioactive components in the dried sample decreased substantially but found to be higher than the samples dried in OSD and TD [25].

7. CONCLUSIONS

The effectively designed and tested solar collector models using polycarbonate glazing sheet and thermal storage units measured experimental data compared to the glass covered solar dryer. The heat loss coefficient in MISD decreased, resulting in a 17±0.4 % improvement in total thermal gain in the process compared to SD. The myrobalan drying time in MSD was reduced to 12 h compared to 41 h in the OSD method, and the continuous drying period increased by more than 3 h during off-sunshine hours using a thermal storage system. The result of the exergy analysis of the MSD was exergy loss was reduced, and the exergy efficiency increased beyond unity. Thin layer drying kinetics was evaluated for dried samples. The modified page has shown a better correlation while comparing the predicted value to experimental value with larger R^2, and lesser RMSE obtained compared to other models. Continuous supply of heat in the drying process improves the sample quality. According to the experiments, the quality and discoloration of the dried product were improved and mitigated. The result of the exergy analysis of the MSD was exergy loss was reduced, and the exergy efficiency increased beyond unity.

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Сонячна сушарка змішаного режиму на основі системи акумулювання прихованого тепла для сушіння міробалану

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Непряма сонячна сушарка змішаного режиму (MISD) була розроблена із сонячним колектором, полікарбонатним листом, вкритим шаром скла з додаванням PCM, та сушильним блоком для сушіння міробалану. Швидкість коефіцієнтів тепловтрат оцінювалася експериментально на основі модифікованої конструкції колектора. Новизна даної роботи полягає у застосуванні PCM-акумулятора енергії в звичайній сонячній сушарці для скорочення часу сушіння міробалану. Термоакумуляція в MISD збільшує період безперервного теплопостачання на 19±4 % порівняно з випадком відсутності теплового накопичувача протягом години без сонячного світла. Час сушіння міробалану зменшився до 12 годин у MISD порівняно з 41 годиною за методом OSD. Це призвело до кращої продуктивності сушарки та скорочення часу сушіння. Загальна корисна енергія склала 61,18 МДж, а втрати енергії були зменшені на 0,206 МДж. Середня температура та відносна вологість сушарки склали відповідно 65,2 °C та 8,83 %. Результати показують, що ефективність ексергії підвищується, а втрати ексергії зменшуються в MISD. Додатковою перевагою може стати інтенсивне експериментальне дослідження теплофізичних властивостей TEC матеріалів. Антиоксидантні показники та загальний вміст фенолів оцінювали різними методами. Найкращі значення кольору та менші значення твердості були досягнуті для зразка, висушеного в MISD, порівняно з іншими методами TD та OSD.

Ключові слова: Міробалан, Сонячна сушарка, Акумулятор тепла, Антиоксидантна активність, TPC.