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ARTICLE

Machine Learning Based Random Forest Prediction for Solar Dryer under Thailand Climatic Conditions

Jakkrawut Techo[1], Panupon Trairat[1] and Karthikeyan Velmurugan[2,*]

[1]Division of Industrial Technology, Faculty of Agricultural Technology and Industrial Technology, Nakhon Sawan Rajabhat University, Nakhon Sawan, Thailand

[2]Department of Technology Engineering, Faculty of Industrial Technology, Kamphaeng Phet Rajabhat University, Kamphaeng Phet, Thailand

*Corresponding Author: Karthikeyan Velmurugan. Email: karthikeyan_v@kpru.ac.th

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ABSTRACT: In this study, selective and non-selective absorber-coated trays were employed to dry carrots and pears. Two trays with a selective absorber coating (1 mm thickness) were used, each loaded with 600 g of sliced carrots and pears. Similarly, two additional trays with a non-selective absorber coating were utilised. Furthermore, the performance of both selective and non-selective absorber-coated trays was compared with conventional open sun drying. The selective absorber-coated tray demonstrated higher thermal energy absorption and enabled the drying of carrots within 2 days, resulting in a weight loss of 529 g. In contrast, owing to the higher fructose content in pears, approximately 7 days were required to achieve a weight loss of 480 g. Overall, more effective drying was observed in the selective absorber-coated tray compared with the non-selective absorber-coated tray and open sun drying. A two-way ANOVA was performed to evaluate the effectiveness of the drying process across the examined methods. The higher F-statistic value of 63.566 indicates significant biological differences between carrots and pears, validating the comparison of their drying behavior. In addition, the F-statistic value of 5.099 for the drying method suggests a notable variation between selective and non-selective absorber-coated trays. It is concluded that the selective absorber-coated tray facilitates enhanced heat transfer to both carrots and pears. Following the ANOVA analysis, a Random Forest (RF) regression model was applied to the selective absorber-coated tray. Notably, the solar dome inner cover temperature exhibited a feature importance of 0.958, indicating its dominant role in increasing the tray temperature and improving drying performance. The average difference between actual and predicted tray temperatures was 0.16°C, demonstrating that the RF model is stable and reliable, with an R^2 value of 0.975. The integration of machine learning approaches in solar dryers can support predictive maintenance and reduce operational costs.

KEYWORDS: Selective absorber; carrots and pears drying; two-way ANOVA; machine learning; random forest prediction

1 Introduction

In the past, farmers experienced significant losses due to excessive yield and uncontrolled market consumption, leading to the wastage of high-moisture crops owing to their limited shelf life [1]. In recent decades, air transport has increased the visibility of these crops and enabled their transport and presentation in the global market; however, such losses have not been eliminated. To address this issue, many farmers have adopted drying processes to remove moisture from crops, thereby enhancing shelf life, increasing profitability, and reducing post-harvest losses [2].

1.1 Drying Crops

Initially, crop drying was primarily carried out using electric and gas-based burners; however, these methods were not cost-effective and raised environmental concerns, particularly related to global warming. To reduce dependency on fossil fuels, solar thermal collectors were widely adopted to harness solar energy and transfer heat into a closed chamber, commonly referred to as an indirect heating process [3]. During the early stages, indirect solar dryers gained popularity; however, their relatively high operational costs limited widespread adoption among farmers. To overcome this limitation, solar greenhouse and dome dryers have been introduced in recent years, as they offer improved efficiency along with comparatively lower installation and maintenance costs [4]. Furthermore, to better understand the effectiveness of moisture removal, various drying techniques, operational mechanisms, and associated benefits of solar greenhouse and dome dryers have been extensively investigated.

1.2 Solar Greenhouse and Dome Dryer

Generally, a solar dome dryer utilizes polycarbonate material due to its cost-effectiveness and durability under extreme weather conditions. In Indonesia, a 3.5 m solar dome was specifically designed to facilitate efficient loading and unloading of agricultural products, with a volume of 125 m^3. A north-to-south orientation was adopted to enhance operational efficiency. Notably, higher temperatures were achieved within the dryer during the sun's east-to-west movement due to its specific design and engineering configuration. During daylight hours, solar irradiance served as the primary energy source for drying. Depending on moisture levels and solar intensity, air blowers were operated to regulate humidity, with their operation controlled through a feedback loop integrated with smart sensors. Additionally, indirect drying using an electrical heater improved productivity; however, greater emphasis was placed on direct solar drying due to its energy efficiency [5]. Similarly, UV-resistant polycarbonate sheet-based dome dryers have been evaluated under real-time operating conditions. These systems, with a diameter of 5 m^2 and a height of 2.5 m, utilized removable stainless-steel mesh trays for effective drying. Smart sensors were employed to monitor temperature and humidity within the drying chamber, thereby optimizing airflow conditions. For auxiliary power, a 660 Wp solar panel coupled with a 12 V battery was installed to ensure uninterrupted operation. It was observed that the solar dome dryer reduced relative humidity to 54.5%, whereas open sun drying reached 79.8%. Moreover, fungal and bacterial growth were observed in the open drying method [6]. A banana drying process was performed in Vietnam and the effects after drying with different types of pretreated bananas were studied to find the effectiveness for a longer storage period. An untreated banana exhibits texture changes after prolonged storage and is susceptible to fermentation and quality degradation [7]. To reduce the investment cost, a greenhouse-based solar dryer was developed using a transparent plastic film and the structures were made from plywood. Though the developed dryer's shelf life was lower than that of commercial dryers, it was cost-effective and easy to install in any location. The side and centre wall height of the dryer was 1.3 and 1.5 m, respectively and it was a sloped-roof dryer. Natural and forced convection airflow was maintained using a solar-powered air blower, resulting in variations in indoor temperature. Reportedly, the lowest Root Mean Square Error (RMSE) of 0.012944 was achieved as compared to the existing models and effective moisture reductions were observed [8].

In Thailand, a dome-type, structure-based indirect solar drying system with an auxiliary conventional gas-burner air-heating system has been studied. Given the high moisture and sugar content of the examined pineapple, an indirect drying system was implemented to prevent browning and pigmentation issues. A dome-type solar receiver was placed atop the rectangular drying chamber to prevent direct heating of the pineapple, and a gas burner was installed to maintain the drying process for 24 h without interruption. Precisely, ca.55°C was maintained and the wind velocity was 1.5 m/s to avoid the humidity stagnation in the drying chamber. Notably, the drying duration was reduced from 32 to 12.5 h. According to the market availability of the dried pineapple, within three months, the investment cost will be recovered [9].

A single-slope greenhouse dryer was performed under tropical climatic conditions of the north-eastern part of India. Bay leaf and a neem leaf were dried, considering their high-value domestic demand during the monsoon period. A comparative performance analysis was conducted between the upper and lower drying trays. It was found that upper-tray drying was faster than lower-tray drying. Notably, neem leaf dries faster than bay leaf due to its thickness variation. The highest efficiency, 92.2%, was achieved on the upper tray, whereas the bottom tray reached 78.01%. It was estimated that the 15-year shelf life for the developed dryer and the payback period will be 0.65 years [10].

Similarly, cassumunar ginger was dried using a large-scale polycarbonate-based greenhouse solar dryer under tropical climatic conditions. The single batch of drying takes 300 kg of ginger and approximately 80% of the moisture content was reduced within 10 h of drying. The solar dryer was completely operated at off-grid and air inlet/outlet operations were performed using a solar PV system. The simulation results were in strong agreement with the experimental results, with RMSD and MBD of 5.3% and 3.17%, respectively. Beneficially, the solar dryer attained 38.9% of thermal efficiency [11]. A rumen was dried under Colombian climatic conditions using a solar greenhouse dryer. A 10,000 kg of wet biomass was dried and its initial humidity was 60%. Notably, the drying process was performed using natural convection, achieving a moisture content of 14.1%. During the wet season, biomass drying takes approximately 6 consecutive days to reduce moisture levels for storage. The greenhouse dryer's internal air temperature reached a maximum of 49.6°C, exceeding the ambient temperature and suitable for real-time drying. A decrease in moisture content significantly increases the biomass temperature, resulting in higher efficiency achieved and is suitable for large-scale deployment [12].

1.3 Machine Learning Approach

A smart dome dryer was utilised to automate airflow control based on humidity and moisture levels within the drying chamber. Such automation was achieved using pre-trained datasets, particularly in tropical regions where humidity fluctuations are highly unpredictable. Under controlled conditions, drying efficiency was significantly improved. To achieve faster and more effective drying, the dome's internal temperature and humidity were adjusted to meet the thermal energy requirements of the products [13]. A greenhouse dryer operating under Iranian climatic conditions was used to dry mint leaves. To enhance system performance, machine learning techniques such as Multilayer Perceptron (MLP), Radial Basis Function Neural Network (RBF), and Gaussian Process Regression (GPR) were implemented. Within 3–4 h, mint leaves lost sufficient moisture for long-term storage. The RBF model demonstrated superior prediction accuracy compared to MLP and GPR. Notably, Mean Absolute Percentage Errors (MAPE) of 1.4% and 1.82% were achieved for temperature and mass predictions, with R^2 values of 0.99 and 0.98, respectively. Furthermore, a normal error distribution and a 95% confidence level confirmed the robustness and reliability of the proposed models for real-time applications [14].

From the literature above, it is evident that solar greenhouse dryers and dome dryers play a significant role in crop drying. Most studies focus on increasing productivity and efficiency through forced convection. Notably, no studies have examined drying carrots and pears under Thailand's climatic conditions. Carrots are a root vegetable, and pears are a pome fruit, which are entirely different in nature, and their dominant sugars are sucrose and fructose/sorbitol, respectively. The existing studies avoided carrots and pears for drying application mainly due to their sticky nature (higher sucrose and fructose/sorbitol), carrot edges hardening issues and high pigment sensitivity. However, the demand for carrots and pears during the off-season signalled higher prices for consumers. Considering this issue, moisture was removed from carrots and pears using a selective absorber-coated tray. Secondly, a comparative analysis is conducted on the fruits, but no research has compared carrots and pears using a selective and a non-selective absorber tray. Apart from these, most of the existing studies are widely performed in experimental or numerical methods to find the effectiveness of the solar dryer and few studies have been conducted with machine learning approaches. With a machine learning approach, solar dryers can gain attention from farmers and commercial users, as the operation of the solar dryer can be predicted and drying quantity and duration can be estimated under various climatic conditions. This predictive operation will reduce the dependency on fossil fuels during the monsoon period. In addition to a selective absorber-coated tray, we built a Random Forest (RF) regression model and compared the predicted tray temperature with experimental results for validation. A selective absorber coating and RF regression model analysis will increase the usage of the solar dryer in Thailand.

2 Materials and Methods

In this study, a dome-type solar dryer was investigated under Thailand's climatic conditions to evaluate its effectiveness in removing moisture from carrots and pears. The dimensions of the solar drying chamber tray base were 111 cm × 191 cm, and the center peak height of the dome above the tray was 46 cm. A parabolic roof geometry with a UV-stabilized polycarbonate sheet (4 mm thick) was utilised. According to the manufacturer, the top cover exhibited a transmittance of greater than 85%. Two DC fans were used for air circulation, with one functioning as an air inlet and the other as an air outlet to regulate moisture levels. A 10 Wp solar panel powered both fans. The drying area was divided into four trays; two trays were left unmodified, while the remaining two were coated with a selective absorber to evaluate the influence of thermal enhancement. Considering the direct contact of carrots and pears with the coated surface, a food-grade, water-based modified acrylic copolymer (RAL 9017 black paint) was applied. This coating was certified under ISO 22196 and ISO 21702 standards for food contact safety. A thin layer of approximately 30 μm thickness was uniformly sprayed onto the trays. Following the coating process, the trays were placed inside the solar dryer for 48 h under outdoor conditions for thermal stabilization. Each tray provided a drying area of 54 cm × 93 cm. Prior to drying, carrots and pears were washed with clean water, and excess surface moisture was removed using a cotton cloth. The samples were then sliced to a uniform thickness of 1 mm to enhance heat and mass transfer during the drying process. This thickness was selected to minimize case hardening and ensure uniform moisture removal. Thicker slices tend to dry rapidly on the outer surface while retaining moisture internally, which may lead to fungal growth during prolonged storage. Each tray was loaded with 600 g of sliced samples. The unmodified trays contained 600 g each of carrots and pears, while an additional 600 g of each sample was placed on the selective absorber-coated trays. For comparative analysis, a third set of 600 g samples was dried under uncontrolled environmental conditions using the open sun drying method. Under typical operating conditions, a duration of 2–7 days is generally sufficient to achieve drying for carrots and pears. However, to evaluate consistency and performance, the experiment was conducted over a period of 20 days. The experimental procedure was initiated at 06:00 due to early solar availability and continued until 18:00. Solar irradiance was measured using a solar power meter with an uncertainty of ±1%. At the same time, temperature profiles were recorded using K-type thermocouples calibrated against a mercury thermometer to ensure accuracy. The pyranometer included an internal logging system; therefore, temperature data were recorded using a Graphtec data logger. Both solar irradiance and temperature were recorded at 1-min intervals. The inner cover temperature of the solar dome was measured to assess the thermal buffering effect within the chamber. Additionally, temperatures of both modified and unmodified trays were recorded for comparison. Ambient temperature was measured under shaded conditions, whereas air temperature was recorded under non-shaded conditions to analyze environmental influences on drying performance. At the end of each experimental day, the weight of the samples was measured using a Mettler Toledo electronic balance with an uncertainty of ±0.001 g. After measurement, the dried samples were carefully returned to the trays and placed back into the dryer for continued drying. No specific storage method was employed during nighttime, as the experiment aimed to replicate real-time operational conditions. Uniform spacing between slices was maintained to ensure consistent drying throughout the experiment.

2.1 Two-Way ANOVA Approach

To evaluate the thermal reliability of the experimental setup, a two-way ANOVA was performed on the 20-day weight loss data of carrots and pears. The weight loss data were converted into a moisture ratio, which is more suitable for analyzing drying performance across different experimental conditions. The sum of squares (SS) was calculated to determine the variation between fruit types. Degrees of freedom were then estimated for fruit types, drying methods, and residuals. The F-value was calculated to assess the ratio of variance between groups relative to within-group variance. An F-statistic value greater than 1 indicates a significant variation between the examined groups. Additionally, the probability associated with the F-statistic was calculated to determine whether the observed results were due to experimental effects or random variation. The confidence level was set at $p < 0.05$. If $p \geq 0.05$, the results were considered statistically insignificant, indicating that the experimental methods did not provide meaningful differences in drying performance.

2.2 Machine Learning Based Random Forest Regression

Following experimental and statistical validation, a machine learning approach was implemented. The thermal profile of the solar dryer and solar irradiance were recorded at 1-min intervals between 06:00 and 18:00, resulting in a total of 4326 data points for each parameter. To minimize overfitting and variance, a Random Forest regression model consisting of 100 decision trees was employed, and the results were averaged. Four input features were considered: solar irradiance, ambient temperature, air temperature, and inner cover temperature. The target variable was the temperature of the selective absorber-coated tray. The model was developed using default hyperparameters from the scikit-learn library, with a mean squared error criterion and an expected R^2 value of approximately 0.9, eliminating the need for additional tuning. The dataset was divided using an 80/20 training-to-testing split ratio. Model performance was evaluated using the coefficient of determination (R^2), comparing actual and predicted tray temperatures. Feature importance was determined using the mean decrease in impurity method, which captures non-linear relationships between variables. In contrast, Pearson correlation analysis was used to evaluate linear relationships. An open-source Python environment was used, incorporating major libraries such as pandas, NumPy, matplotlib, seaborn, scikit-learn, and SciPy. This approach ensured that the developed model was robust, reliable, and suitable for predictive analysis.

3 Results and Discussion

3.1 Carrots and Pears Drying and Weight Loss

The market prices of carrots and pears in Thai local markets are highly unstable, as they are predominantly imported from China and other regions. During the monsoon season, domestic carrot production decreases due to root rot, while pear prices increase during summer owing to unfavourable growing conditions. Consequently, both commodities experience higher demand during the off-season, resulting in elevated prices. Long-term storage of carrots and pears is challenging due to their biological characteristics, and they require controlled low-temperature environments. However, extended storage over several months remains difficult. To address this issue, carrots and pears were dried using three different methods: selective absorber-coated trays, non-selective absorber-coated trays within a solar dome dryer, and conventional open sun drying.

Fig. 1a illustrates the internal configuration of the solar dome dryer equipped with four trays. The arrangement included both selective and non-selective absorber-coated trays containing carrots and pears. Fig. 1b presents the open sun drying setup. In both cases, 600 g of samples were used, representing the initial (0th day) condition. After 20 days of drying, the physical characteristics of the carrots changed significantly due to the 1 mm slice thickness. The carrots dried using selective absorber-coated trays exhibited uniform shrinkage, as shown in Fig. 2a and a consistent golden texture, whereas those dried using non-selective trays showed comparatively less uniformity, as shown in Fig. 2b. Similarly, pears dried using selective absorber-coated trays developed a desirable golden-brown appearance, attributed to higher drying temperatures, as shown in Fig. 2c, compared to those dried on non-selective absorber-coated trays shown in Fig. 2d. During the initial three days, a sticky texture was observed due to rapid moisture removal; however, after approximately 7 days, the samples became non-sticky, indicating suitability for long-term storage. In contrast, the open sun drying method adversely affected both carrots and pears due to uncontrolled environmental exposure.

Samples were subjected to rain and high humidity, leading to deterioration in texture and the development of fungal growth, as shown in Fig. 3a and b, respectively. Fig. 3c presents the weight loss trends across the three drying methods. At the end of the first day, the weight of carrots dried in the selective absorber tray reduced to 126 g, compared to 161 g in the non-selective tray and 182 g in open sun drying. Carrots required approximately 2 days for effective drying, after which weight reduction became negligible. For pears, the drying trend was slower due to higher fructose content. On the first day, weights were reduced to 222 g (selective) and 280 g (non-selective). By the 20th day, the weights reached 116 and 150 g, respectively. The open drying method showed marginally higher final weight, indicating that higher temperatures are essential for efficient pear drying.

Figure 1: Experimental view of (**a**) the solar dome inner view with a selective and non-selective absorber-coated tray. All the trays are equipped with 600 g of carrots and 600 g of pears, separately. (**b**) 600 g of carrots and pears are placed for conventional sun/open drying.

Figure 2: Experimental results after 20 days for (**a**) a selective absorber-coated tray with carrots, (**b**) a non-selective absorber-coated tray with carrots, (**c**) a selective absorber-coated tray with pears and (**d**) a non-selective absorber-coated tray with pears.

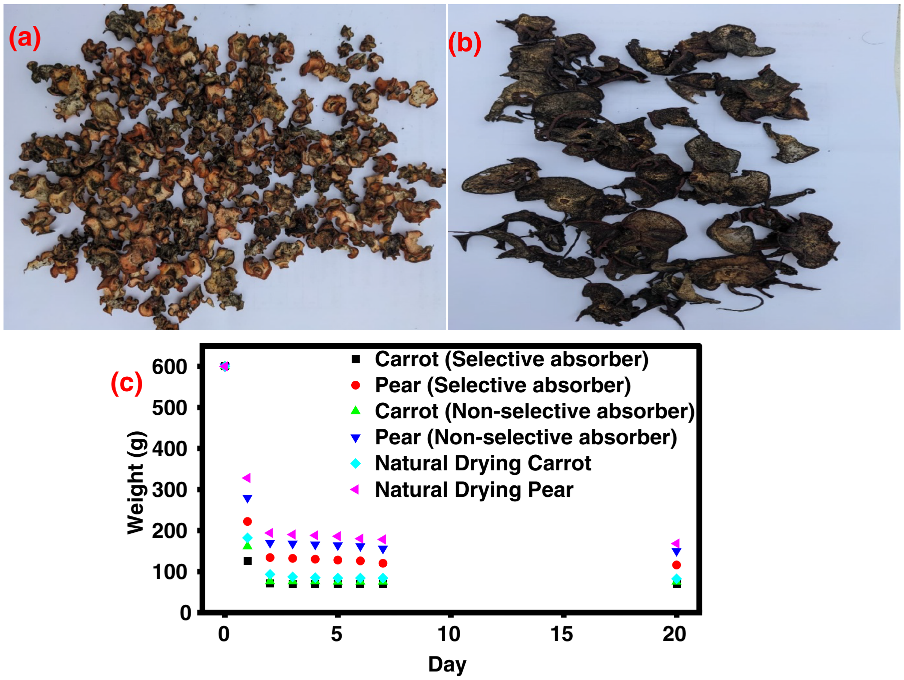

Figure 3: Experimental results after 20 days for (**a**) open sundried carrots and (**b**) open sundried pears. (**c**) Weight of the carrots and pears using both selective and non-selective absorber-coated trays. Carrot (selective absorber), pear (selective absorber), carrot (non-selective absorber), pear (non-selective absorber), natural drying carrot and natural drying pear represent the weight loss of carrot using a selective absorber-coated tray, pear using a selective absorber-coated tray, carrot using a non-selective absorber-coated tray, pear using a non-selective absorber-coated tray, open sundried carrot and open sun dried pear, respectively.

3.2 Operation of Solar Dome Dryer

The thermal performance analysis of a selective and non-selective absorber-coated tray is shown in Fig. 4a. The selected location was rich in solar potential, with peak and average values of 1155 and 354.78 W/m^2 on the first day of the experiment, respectively. Throughout the experimental day, higher oscillations in solar irradiance were observed due to seasonal rain; however, the selective absorber-coated tray temperature reached 80.91°C, whereas the non-selective absorber-coated tray temperature was 57.92°C. A peak inner-dome surface temperature was 54.74°C, indicating that the selective coating significantly enhanced thermal absorption capacity. Beneficially, the selective absorber-coated tray temperature reached a higher thermal energy. The higher temperature on a selectively absorber-coated tray was due to the high thermal absorptivity of the black paint. Secondly, the dome's inner surface temperature represents the point of interaction with the sun, similar to ambient and air temperature. Due to the polycarbonate sheet, the dome's inner surface temperature was sustained higher than the air temperature. Peak and average air temperatures on day 01 were 39.06°C and 31.03°C; however, the ambient temperatures were comparably lower, at 35.84°C and 30.46°C, respectively. For most of the experimental period, the inner dome surface temperature was higher than that of the non-selective absorber-coated tray, with an average difference of 0.83°C. With a non-selective absorber coating, drying performance was low; however, it was free of fungal growth compared with the conventional open-sun drying method.

Though dryer operation mainly depends on solar irradiance, sudden fluctuations in it don't affect the drying process. For example, on day 01, the solar irradiance was 1012 W/m^2 at 12:24. Due to a passing cloud and moderate rain shower, the solar irradiance dropped to 370.3 W/m^2 within a minute and remained lower until 12:57. During this period, the selective absorber tray temperature gradually decreased from 50.08°C to 47.06°C, while the inner cover temperature decreased from 45.07°C to 40.78°C. Though a significant temperature difference was observed during dryer operation, it did not affect the carrots and pears drying process. However, open sun drying exposed the carrots and pears to rain, resulting in gradual fungal growth [15]. On the 20th day, the weights of pears and carrots were 82 and 168 g, respectively, which were higher than those in the selective absorber-coated tray.

A similar pattern was observed on day 02: the peak temperature of the selective absorber-coated tray was 81.55°C, whereas that of the non-selective absorber-coated tray was 54.66°C. Compared with the inner dome's surface temperature, it was lower, as shown in Fig. 4b. Furthermore, to assess the consistency of the experimental results, days 03–06 were included in Fig. 4c–f. All six days of experimental results show that the operation of the solar dome depended on solar irradiance, and an increase in solar irradiance greatly increased the temperature of the selective absorber-coated tray. Although the temperature was rising in the non-selective absorber-coated tray, it was less effective than in the selective absorber-coated tray. On day 04, lower solar irradiance occurred, with a peak of 808 W/m^2 and an average of 270.83 W/m^2. The selective absorber-coated tray temperature difference from the inner dome's surface was sustained at a peak of 19.74°C and an average of 8.44°C. In contrast, the non-selective absorber-coated tray temperature was 22.97°C and 8.43°C, respectively. Throughout the entire experimentation period, the selective absorber-coated tray temperature was higher, resulting in faster drying and moisture removal for carrots and pears compared with the non-selective absorber [16]. The faster drying is mainly due to the selective absorber, which has a higher absorption rate. The non-selective absorber tray experiences greater long-wave infrared radiation loss during the temperature rise, whereas the selective absorber-coated tray exhibits lower loss.

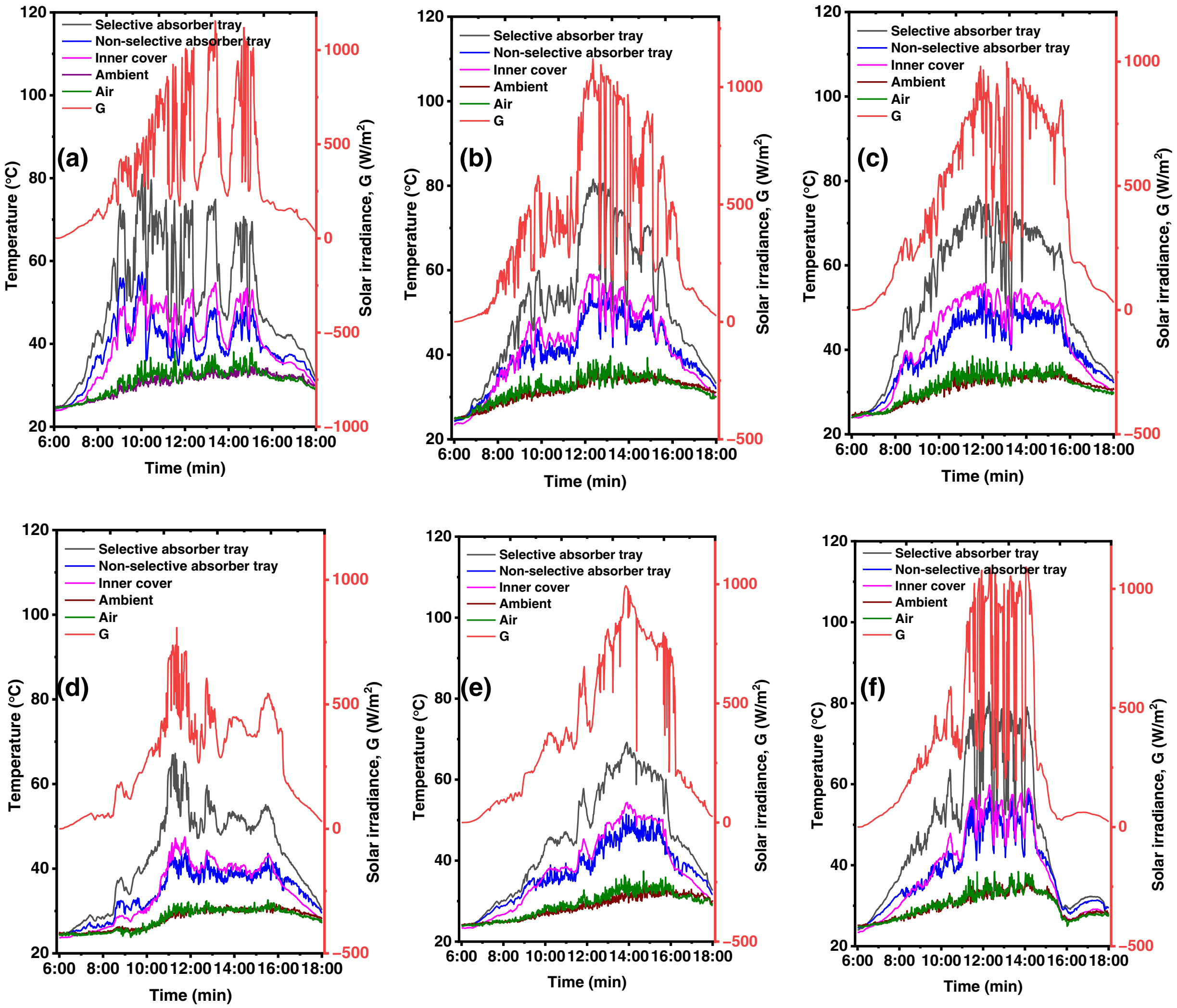

Figure 4: Temperature and meteorological data of solar dome dryer for a selective (**a**) day 01, (**b**) day 02, (**c**) day 03, (**d**) day 04, (**e**) day 05 and (**f**) day 06 experiment. In Fig. 4, the graph legends selective absorber tray, non-selective absorber tray, inner cover, ambient, air and G represent the selective absorber coated tray temperature, non-selective absorber coated tray temperature, solar dome inner cover (polycarbonate) temperature, ambient temperature, air temperature and solar irradiance, respectively.

3.3 Two-Way ANOVA Statistical Analysis

Furthermore, to assess the consistency of the experimental results, a two-way ANOVA was performed on the above-mentioned fruits and methods. The sum of squares (SS) was calculated for both fruits and methods to find the deviations. The moisture removal rates for carrots and pears varied widely. Notably, an SS of 0.242963 indicates that carrots and pears differ in their moisture patterns and require different amounts of thermal energy to remove moisture, as listed in Table 1. Secondly, the weight loss in pears was lower than in carrots. Due to this difference in weight loss, higher SS was attained for the fruit category. Further, SS for the method indicates that the selective absorber-coated tray plays a dominant role in drying carrots and pears compared to other methods, resulting in a lower SS of 0.038 for the fruit category, which validates the claim. Notably, the residual SS was 0.168, indicating that experimental errors or measurement uncertainty were negligible and that the observed weight loss was significant for the solar dome dryers' operation. Following that, the Degree of Freedom (DF) is 1.0 and 2.0 for fruits and methods, respectively, due to two fruits and three methods involved in this study. However, residual DF was 44.0 because the total weight loss measurement was 48 and the fruit, method and intercept were together 4; in total, 44 is the residual DF. The signal-to-noise of the experiment was analysed using F-statistics. Though a higher range of 63.566 was obtained for fruits, it was mainly linked to the drying speed of carrots and pears, which suggests that the biological structure of fruits differs, mainly due to the sucrose and fructose content of carrots and pears, respectively. However, the methods explain the relationship with drying speed; for example, the F-statistic for the method is 5.099 indicating that the solar dome dryer plays a significant role in drying the fruits, particularly the selective absorber-coated tray, which plays a dominant role in drying. Overall, the F-statistic of 63.566 for fruit explains two different biological patterns of the fruits selected for the experiment and a 5.09 for methods explains that the examined solar dryer with a selective absorber coated tray exhibits a higher thermal energy to remove the moisture at a higher rate. indicating statistically significant variation between the applied drying techniques. $F > 1$ is considered a lower noise level in the data; in this case, 5.099 strongly indicates the consistency of the experimental data, which was in good agreement. The p-value was statistically significant and the methods attained 0.0101, which satisfies the condition of $p < 0.05$ [17]. It is concluded that the selective absorber-coated tray temperature is significantly higher and favours the removal of moisture at a higher rate.

Table 1: A two-way ANOVA approach for different fruit types and methods.

	Sum of Squares (SS)	Degrees of Freedom (DF)	F-Statistic	PR (>F)
Fruit	0.242	1.0	63.566	$4.413029e^{-10}$
Method	0.038	2.0	5.099	$1.019267e^{-2}$
Residual	0.168	44.0	–	–

3.4 Random Forest Regression Analysis

Following thermal and statistical analyses, a machine-learning approach was applied to a selectively absorber-coated tray using a random forest regression model. Fig. 5a shows the relationship and accuracy of the random forest prediction for the selective absorber-coated tray temperature. The experimental temperature was highly consistent with the prediction, with an R^2 of 0.975. The importance rates of solar irradiance, ambient air, inner cover, and the selective absorber-coated tray temperature are shown in Fig. 5b. The inner cover temperature was highly significant and the most influential parameter in raising the selective absorber-coated-tray temperature, with an importance rate of 0.958. The primary input feature, solar irradiance, increased by 0.027, which was lower than the dome inner cover temperature. Similarly, ambient and air temperature had importance values of 0.008 and 0.006, respectively. Although the solar irradiance is a source of drying for carrots and pears, it was lower than the inner cover temperature. Because the inner cover maintains the temperature within the drying chamber, it is called the thermal state. The inner cover temperature was directly proportional to the selective absorber-coated tray temperature, but the solar irradiance was less proportional. Therefore, a sudden fluctuation in solar irradiance does not immediately affect the temperature inside the drying chamber. Fig. 5c shows the residuals between the actual and predicted selective absorber-coated-tray temperature; notably, the residual density decreases after ±3. It indicates RF captured the non-linear thermal dynamics behaviour and the predicted selective absorber-coated tray temperature was highly reliable. Secondly, the bell curve was symmetrical and centred at zero, indicating that the RF model was not overfitting and that the actual error was expected to be zero or close to zero. The symmetry of the bell curve indicates that the model's error was randomly distributed to attain a best fit; therefore, the system was reliable and highly predictable.

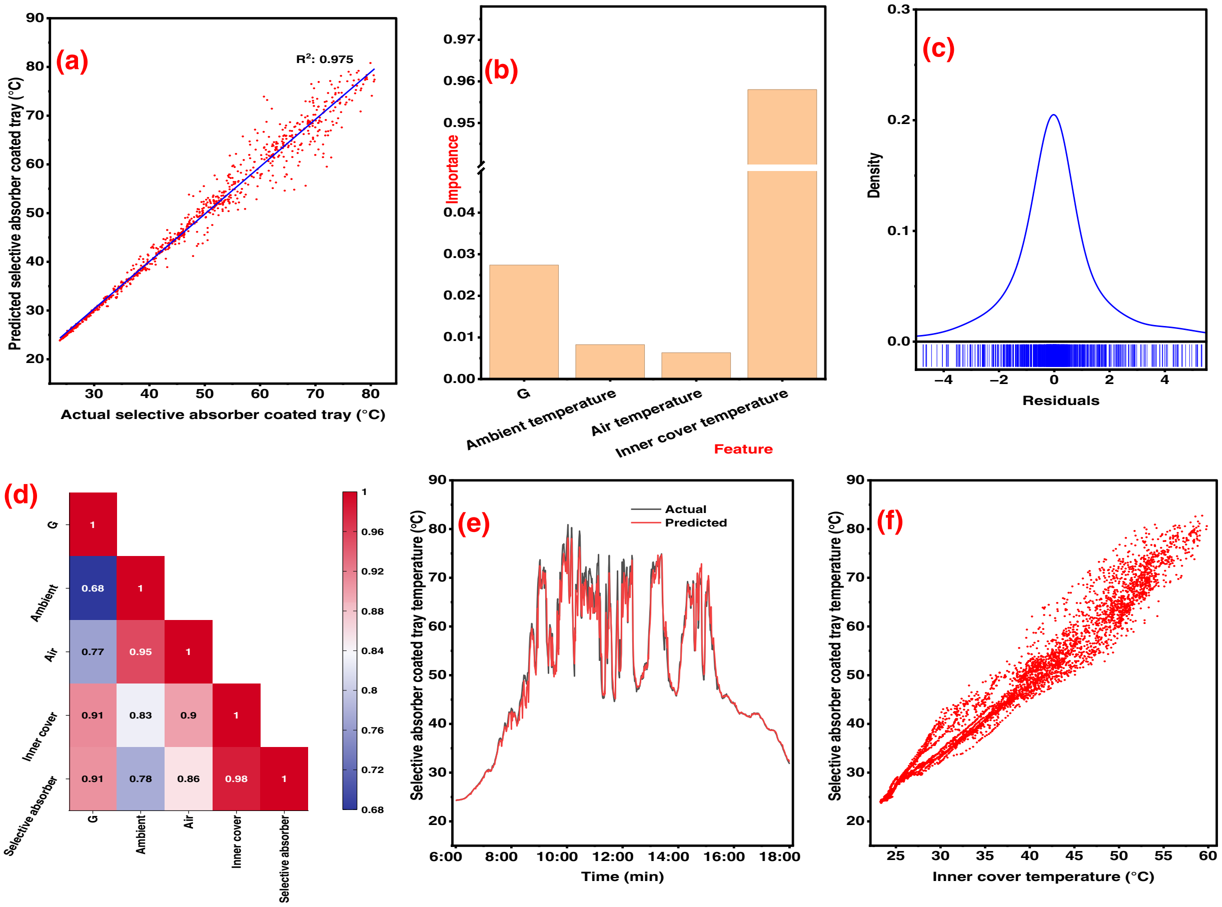

Figure 5: Machine learning analysis for the selective absorber coated tray (**a**) temperature prediction using Random Forest Regression model, (**b**) parameters influence, (**c**) residual and density, (**d**) correlation plot, (**e**) selective day prediction validation with experimental data and (**f**) relationship with inner cover.

Furthermore, to assess the linear relationship between the variables, Pearson correlation analysis was performed, as shown in Fig. 5d. In Fig. 5b, solar irradiance had a minor influence on the selective absorber-coated-tray temperature, but in Pearson correlation, it shows a strong positive linear relationship (r = 0.91). Because the Pearson correlation estimation was based on the two variables in total isolation. If the solar irradiance and selective absorber-coated tray temperature rise, it correlates positively and depending on the intensity, it gains a strong positive correlation. The RF importance factor was estimated using all features from experimental data. Sudden fluctuation in solar irradiance doesn't affect the drying chamber temperature; therefore, RF behaves differently from Pearson correlation. Notably, the highest correlation, 0.98, was observed with the inner cover temperature. Similarly, air and ambient temperatures increased by 0.86 and 0.78, respectively. To gain insight into accuracy in random forest prediction, the day 01 actual and predicted selective absorber-coated-tray temperature is shown in Fig. 5e. A maximum difference of 4.68°C was observed; however, the average difference was −0.35°C, which makes the random forest prediction model more reliable for solar drying applications. The relationship between the inner cover and the selective absorber-coated-tray temperature indicates a thermal connection and a stronger influence on temperature, with an R^2 of 0.961. Overall, the selective absorber-coated-tray performance was excellent, and its drying capabilities were better than those of the other two methods.

3.5 Comparative Analysis with Existing Solar Dryers

Table 2 shows a recent solar dryer performance over different drying methods and crops. It has been found that solar dryers are an efficient method for drying crops and fruits compared to conventional fuel-based drying methods. The cabinet-based indirect dryer significantly dried the pepper weight from 0.2 to 0.04 kg after three weeks [18]. Similarly, within five days, an 80 to 37 g weight loss is observed [19]. Comparatively, the present study shows a significant improvement with a selective absorber-coated tray, where the carrots and pears attained weight losses of 474 and 378 g within one day of drying, respectively. Extending the drying process by 20 days results in significant weight loss compared to existing methods, with 530 g for carrots and 484 g for pears. Overall, it is concluded that the selective absorber-coated tray enhanced the performance of the solar dryer and is recommended for a large-scale system.

Table 2: Comparative analysis of the proposed solar dryer with an existing solar dryer.

Drying Item	Dryer Type	Benefit	Reference
Pepper	Cabinet-type indirect solar dryer	Over three weeks of drying, weight loss was observed from 0.2 to 0.04 kg.	[18]
Pork meat	Solar cabinet dryer	A raw pork weight loss was observed for two days, from 2 to 0.9 kg.	[20]
Fresh herbs	Hybrid smart solar dryer	Weight loss was observed from 1 to 0.24 kg.	[21]
Banana	Indirect-type solar dryer	A 3.1% moisture content was achieved.	[22]
Pepper	Customised solar dryer	Pepper weight loss was observed, from 80 to 37 g, over five days.	[19]
Carrot/Pear	Solar dome dryer with a selective absorber-coated tray	For both the carrot and the pear, the initial weight was 600 g. At the end of the first day, the weight was reduced to 126 and 222 g, respectively. After an additional 20 days of drying, the weights reached 70 and 116 g, respectively.	Present study

3.6 Economic Analysis

A standardized and simplified economic analysis is performed for the drying of carrots and pears using a selective absorber-coated tray. The total investment cost of the solar dryer was 12,000 THB and the life expectancy of the dryer was 10 years. The annual maintenance, interest rate and inflation rates were assumed to be 1.5%, 2.5% and 1.5%, respectively. Table 3 shows an annualized investment cost, drying cost, annual savings and payback period. The full loading capacity of 2.4 kg for carrots and pears was used in the economic analysis. Carrots take 2 days to reach a lower moisture content, whereas pears take 7 days. The payback period for carrots was 0.51 years. Although the cost of dried pears was higher than that of carrots, due to the 7-day time required to complete a single drying batch, the payback period was longer for dried pears.

Further, the addition of AI and IoT-based automation can enhance the efficiency of the dryer, and predictive maintenance will reduce the annual operational and maintenance costs [23]. Real-time drying monitoring can maintain the nutrients and excess drying can be avoided, which could economically benefit the system. Moreover, automation will enrich the agricultural sector with a minimal workforce and increase the revenue for farmers [24].

Table 3: Pears and carrots economic analysis using a selective absorber-coated tray.

Parameter	Carrot	Pears
Annual investment cost		
Capital recovery factor	0.1142	0.1142
Capital cost per year (THB)	1370	1370
Operation and Maintenance cost (THB)	180	180
Overall annual investment cost (THB)	1550.40	1550.40
Drying cost		
Fresh fruit per kg (THB)	25	35
Initial weight (g)	2400	2400
Final weight (g)	284	480
Time taken to dry	2	7
Total sunshine per year (nos)	300	300
Expected total drying batch per year (nos)	150	42
Annual dryer yield (kg)	42.6	20.16
Dryer overhead (THB)	36.39	76.90
Drying cost per kg (THB)	247.64	251.90
Annual savings		
Dried fruits market price per kg (THB)	800	1000
Our dryer savings per kg (THB)	552.36	748.10
Annual savings from our dryer (THB)	23,530.54	15,081.70
Payback period (year)	0.51	0.81

4 Conclusion

The selective absorber-coated tray demonstrated superior thermal absorption capability, resulting in more effective drying of both carrots and pears. Within 2 days, the weight of carrots decreased from 600 to 71 g when using the selective absorber-coated tray. In contrast, pears required a longer duration of approximately 7 days to reach a final weight of 120 g, owing to their higher fructose content and associated thermal requirements. The non-selective absorber-coated tray resulted in final weights of 75 and 150 g for carrots and pears, respectively, indicating comparatively lower drying efficiency. Although the open sun drying method achieved noticeable weight reduction, it exposed the samples to uncontrolled environmental conditions, leading to fungal growth due to seasonal rainfall. To evaluate the consistency and effectiveness of the drying process, a two-way ANOVA was conducted. The F-statistic value of 63.566 for fruit type confirms that carrots and pears exhibit distinct biological and moisture removal characteristics. Similarly, the F-statistic value of 5.099 for drying methods indicates a significant difference between selective and non-selective absorber-coated trays. Furthermore, the p-value (PR > F) of 0.0101 satisfies the condition $p < 0.05$, confirming the statistical significance of the results. These findings indicate that the selective absorber-coated tray enhances thermal energy transfer and accelerates moisture removal. Following the statistical analysis, a Random Forest regression model was developed for the selective absorber-coated tray. The model achieved an R^2 value of 0.975, demonstrating high prediction accuracy and strong agreement with experimental data. Feature importance analysis revealed that the dome inner cover temperature had the strongest influence (0.958), indicating a strong thermal relationship with the tray temperature. Overall, the results confirm that the selective absorber-coated tray provides enhanced drying performance and improved system efficiency. It is recommended that future systems incorporate smart monitoring and IoT-based integration with machine learning models to further optimize drying performance. Such advancements can enable real-time monitoring, improve product quality, and reduce operational and maintenance costs while supporting sustainable agricultural practices.

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