



Original Research Paper

Experimental Optimization, Drying Kinetics and Energy-Efficiency Assessment of a Developed Refractance Window Dryer for Palmyrah Palm Pulp Drying

¹Er. Azmirul Hoque, ²Dr. Ajita Tiwari

¹Research Scholar, ²Assistant Professor cum Supervisor

^{1,2}Affiliation Address: Department of Agricultural Engineering, Triguna Sen School of Technology, Assam University, Silchar (India)-788011

¹Email: hoquebtech95@gmail.com, ²Email: ajitatiwari@gmail.com

*Corresponding mail: hoquebtech95@gmail.com

Abstract

Refractance Window Drying (RWD) is a promising thin-layer drying technology for reducing drying time and energy consumption while preserving the quality of heat-sensitive food products. This study experimentally evaluated and optimized a developed RWD system for energy-efficient drying of palmyrah palm pulp. A three-factor, three-level Box–Behnken design (BBD) combined with Response Surface Methodology (RSM) was employed to investigate the effects of circulating water temperature, product-layer thickness, and belt speed on drying time, Specific Energy Consumption (SEC), rehydration ratio, and Total Colour Difference (ΔE). Multi-response desirability optimization was performed, followed by thin-layer kinetic modelling using six semi-empirical models and estimation of Effective Moisture Diffusivity (D_{eff}) and activation energy. The quadratic models showed excellent agreement with experimental data, with R^2 values of 0.9982–0.9994. The optimum condition was 75.5 °C, 2.15 mm thickness, and 0.50 m/min belt speed, giving a predicted drying time of 61.4 min, SEC of 12.22 MJ/kg water evaporated, rehydration ratio of 4.45, ΔE of 4.84, and desirability of 0.60. The Page model provided the best kinetic fit (R^2 up to 0.9996). D_{eff} increased from 5.69×10^{-10} to 2.26×10^{-9} m²/s, while activation energy was 71.5 kJ/mol.

Keywords: Refractance Window Drying; Palmyrah Palm Pulp; Response Surface Methodology; Thin-Layer Drying Kinetics; Effective Moisture Diffusivity.

*Corresponding Author:

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1. Introduction

Drying is one of the most common preservation methods employed in food and agricultural processing as it lowers the moisture content which helps inhibit the growth of microorganisms, slow enzymatic and chemical degradation and prolong product shelf life [1]. The traditional drying methods, however, usually involve a considerable amount of energy being invested, and can have a negative impact on the nutritional, physical and sensory characteristics of heat-sensitive products [2]. For example, hot-air drying usually involves high temperature and long drying time to cause excessive shrinkage, colour loss, nutrient loss and case hardening of food material, and affect the functional properties of the food [3]. Therefore, the development of drying technologies has become more and more important to remove moisture quickly without sacrificing product quality and with low energy consumption for sustainable food processing [4].

Refractance Window Drying (RWD) is a relatively new thin-layer drying technology with significant potential for energy-efficient processing of heat sensitive materials such as fruit pulps and vegetable purees [5]. In this technology the product is applied as a thin layer onto a hot water bath which is floated on or in contact with a transparent polymeric film [6]. The primary mechanism of heat transfer is conduction from hot water to the film and then to the wet product, and the radiation and convection heat transfer contribute to the overall heat transfer [7]. The drying product temperature can be maintained at relatively lower levels than the drying medium temperature, especially in the initial stage of drying, which can help preserve the value-added ingredients. RW drying is being considered for small- and medium-scale food-processing applications, because of the relatively simple configuration, efficient heat transfer and potential for reduced processing time [8,9]. The developed RWD is shown in figure 1 with product application, hot water circulation, conveyor movement, vapour removal and dried product collection.

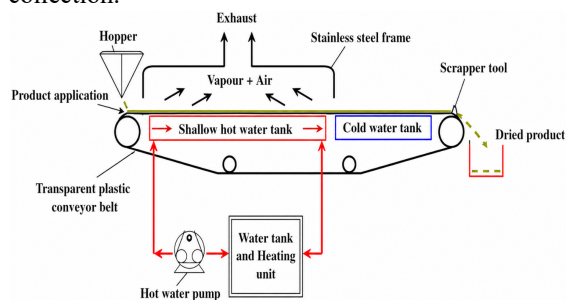


Figure 1. Schematic representation of the developed RWD system and its major components [10]

Nevertheless, the drying efficiency of a RWD is strongly dependent on operating and design conditions such as water-bath temperature, product-

layer thickness, initial moisture content, and drying time. If these parameters are not carefully selected, they can lead to higher energy consumption, longer drying times and the quality of the dried product can be affected [11]. Thus, there is a need for systematic experimental optimization to determine the optimal operating condition that gives the balance of the drying rate, energy efficiency and product quality [12]. It is also important to know the moisture transfer behaviour during drying because it can be used to predict drying times and to optimise industrial scale drying processes [13].

The drying kinetics gives a quantitative description of moisture removal with time and is usually characterized by Moisture Ratio (MR), drying rate, D_{eff} and the parameters of the kinetic model [14]. The experimental drying behaviour can be represented by mathematical models, which are "Lewis model, Page model, Henderson–Pabis model, logarithmic model, and Midilli–Kucuk model", and can be determined which mathematical model best describes moisture migration under various operating conditions [15,16]. Therefore, kinetic analysis can be helpful in determining the dominant drying mechanism and for scale-up and process control of RW drying systems [17].

The scope of the present study is to focus on the experimental optimization and drying kinetics of the developed RWD for standardized energy efficient drying. The dryer developed is experimentally tested for various operating parameters to find their effect on the drying time, moisture reduced, SEC and rehydration ratio along with colour change. A BBD is used with RSM to systematically investigate the effects of the selected operating variables and to determine the optimized operating condition. The optimized condition is then experimentally tested to check the reliability of the response models developed. Meanwhile, experimental drying data collected under varying water-bath temperatures are analyzed by several mathematical models to select the most suitable one for drying process as a kinetic model. The moisture-transfer behaviour and temperature dependence of the drying process is also estimated by the D_{eff} and activation energy.

A comprehensive method for evaluating the performance of the proposed RW drier is provided by the combination of multi-factor optimisation and drying-kinetics analysis. The proposed approach relates quantitatively various drying parameters to the dryer performance and the energy consumption and product quality, facilitating reproducible characterization of the dryer under the specified experimental conditions. The optimized conditions and kinetic parameters obtained from such studies can provide a scientific basis to enhance the reproducibility, energy efficiency, and practicability of drying for small and medium scale food-

processing operation with the method of drying with RW. Here are the research objectives as shown on given below:

- To develop and evaluate a laboratory-scale RWD for drying palmyrah palm pulp under controlled operating conditions.
- To investigate the effects of circulating water temperature, product-layer thickness, and belt speed on drying time, specific energy consumption, rehydration ratio, and total colour difference.
- To optimize the drying process using RSM and a three-factor, three-level BBD to determine the optimum operating conditions.
- To determine which of many thin-layer drying models captures the experimental moisture-removal behaviour by characterising the drying kinetics of palmyrah palm pulp.
- To evaluate the energy-performance and possible commercial usability of the optimised RW drying process while determining the effective moisture diffusivity and activation energy at different drying temperatures.

This is the structure that the rest of the paper follows. Section 2 finds the missing component of research by reviewing the existing literature. Dryer design, experimental study, RSM optimisation, and drying kinetics analysis are all covered in Section 3, which also includes the materials and techniques. Section 4 discusses the experimental results, model fitting, optimization, kinetics, and energy performance. Section 5 summarizes the major findings and presents the conclusions and future scope.

2. Literature of Review

In recent studies of RWD, the main focus has been on process optimization, drying kinetics, moisture diffusion and preserving nutritional and physicochemical properties. Srivastava et al. (2021) [18] researched the drying of strawberry-puree with an in-house fabricated RWD system under the following conditions: water temperature of 75°C and a product thickness of 1.5 mm. The drying was found to proceed throughout the falling-rate stage and the various heat transfer components such as the evaporative capacity (5.28 kg m⁻² h⁻¹) were determined. The results indicated the feasibility of using RWD for the economical drying of products, with acceptable product quality. The RSM was used to optimize RWD temperature and drying time for passion-fruit powder by Asiimwe et al. (2022) [19] where “moisture, vitamin C, β -carotene, phenolic content, and antioxidant activity” were taken into consideration. The best results were obtained at 82.5 °C and 60 min, leading to good retention of nutritional and bioactive compounds. The study by Nansereko et al. (2022) [20] also used RSM to optimize the RWD water temperature and pulp thickness for jackfruit to get the optimum conditions of 93.4°C and 2.56 mm, respectively,

which showed the applicability of the statistical model for the prediction of water temperature and pulp thickness for drying. The RWD was compared with convective-air drying of pumpkin seeds by Ortiz-Jerez et al. (2022) [21] and indicated that Logarithmic model is the most suitable model for the RWD as it yielded an D_{eff} of 6.60×10^{-10} m²/s. Zalpouri et al. (2023) [22] also examined the puree of onion at varying thicknesses and reported that the drying time increased significantly with the increase in thickness and the Lewis model fitted the RWD well. The study also showed that the effective moisture diffusions were higher for RWD than convective drying and the physicochemical properties were better.

Recent studies have focused more and more on experimental design, multi-parameter optimisation, energy efficiency, and advanced RWD configurations, further supporting the development of standardised dryers. He et al. (2024) [23] used a D-optimal mixture design to study tomato-pulp drying and found that the Page model with modification could best estimate the moisture-ratio curve with an R^2 of 0.9960. The relationships between drying conditions and the kinetic model coefficients also obtained in the study supported the predictive process optimization. Largo-Avila et al. (2024) [24] investigated RWD of peach slices and peach pulp using maltodextrin and found that moisture was reduced rapidly, water activity showed good response-surface relationships and had favorable diffusion properties. Herrera et al. (2025) [25] investigated the effect of product thickness and temperature on RWD of milk and yogurt in an optimal design model, determining optimal operating conditions, and comparing energy consumption and physicochemical properties. Box- Behnken RSM was used to optimize the water temperature, slice thickness and KMS concentration for drying of mushroom by Kumar et al. (2025) [26] and the optimum conditions obtained were 90°C, 6 mm and 1.01% KMS. Drying time and energy efficiency were assessed by Gaviria-Lozano et al. (2025) [27] for RWD, RWD+IR and RWD+VA and RWD+FA, with drying time being decreased by up to 68.8% and energy efficiency increased by up to 41.9% when using RWD+IR. Ramirez et al. (2025) [28] showed that microwave drying could achieve up to 66% saving in drying time of apple without loss of bioactive compounds compared to conventional drying. Finally, Zomorodi et al. (2026) [29] combined RSM-CCD with kinetic, energy, thermodynamic and quality analyses for infrared-assisted RWD of thyme. In summary, these studies indicate that there is a lack of research for a standardized RWD system that is able to integrate experimental dryer development, drying kinetics, energy consumption, optimization of operating parameters and experimental validation of the

system, which forms the basis for the proposed research.

3. Materials and Methods

3.1 Raw Material and Sample Preparation

The model feed material used for the RWD experiments was fresh palmyrah palm pulp. The pulp was chosen as it has high moisture content and can be pumped, making it well suited for use as a thin continuous layer on the drying film. The initial moisture content of the new pulp was obtained experimentally and was found to be around 85% on a wet basis. The moisture content was determined by following the adopted standard procedure, where the sample is dried in an oven to constant moisture. The water content of the mixture was about 5.67 kg water per kg dry solids. Pulp was thoroughly homogenized and de-aerated prior to each experiment to reduce the amount of entrapped air and to ensure a uniform product layer was available during spreading. The pulp thus prepared was kept under controlled conditions until just prior to the drying experiments.

3.2 Developed Refractance Window Dryer (RWD)

A laboratory-scale RWD was designed to give optimized and reproducible drying conditions for the experimental investigation. The dryer was a stainless-steel water trough with an electric immersion heater and a centrifugal pump for continual flow of the heating medium. A proportional–integral–derivative (PID) controller with an immersed thermocouple was used to control the circulating-water temperature, which was held within ± 1 °C of the set point. A biaxially oriented polyethylene terephthalate (PET) film (Mylar was used) was firmly placed over the water trough and was used as a drying surface. The pulp was prepared and evenly spread across the film with a feed hopper and adjustable gap spreader bar to achieve the desired thickness of product layer based on the experimental design.

To facilitate the removal of moisture from the product an axial fan was placed above the drying surface. All trials were conducted with the air velocity maintained at 0.8 m/s, thus it cannot be regarded as an experimental factor. Once dried, the dried material was separated from the film by a scraper blade, and then collected in a receiving tray. The system was instrumented with type-K thermocouples for measuring water-bath, film-surface, and exhaust-air temperatures and a capacitive temperature–relative humidity sensor for exhaust conditions. The power consumption in electrical energy of the heater and circulation pump was monitored with the help of a calibrated energy meter. Mass loss from the sample was continuously measured by a precision balance, and all the sensor outputs were acquired at 10-s interval using a data-acquisition system. The temperature, mass and energy-measurement systems were calibrated

before experiments were conducted to obtain reliable and reproducible measurements. The developed RWD with the drying chamber, supporting frame and the integrated temperature-control panel are shown in figure 2.



Figure 2. Photograph of the developed RWD showing the drying unit and integrated temperature-control panel.

3.3 Experimental Design for Process Optimization

RSM is a statistical tool for determining the optimal conditions by testing the individual and interaction effects of process factors. This study employed a three-level BBD to examine the performance of the RWD that was built. The factors that were considered were the influence of circulating water temperature (70°C), product-layer thickness (80°C), and belt speed (90°C). The investigated levels were 70, 80, and 90°C for water temperature; 2, 3, and 4 mm for product-layer thickness; and 0.5, 1.0, and 1.5 m/min for belt speed.

The ranges were chosen from the developed dryer considering its practical use and initial experiments. The temperature range provided for water-bath operation with an acceptable margin below boiling water. The thickness range indicated the actual spreading ability of the applicator and the belt speed range the stable operating range of the conveyor system.

Four responses were evaluated: drying time (Y_1), SEC (Y_2), rehydration ratio (Y_3), and total colour difference (Y_4). The SEC was measured in MJ/kg of water evaporated, whereas the drying time was the amount of time needed to achieve a 10% wet basis moisture content. The rehydration ratio was calculated by immersing the pulp in water for 5 minutes at 5°C, and the colour difference compared to the fresh pulp was denoted by ΔE . Twelve

factorial points and three duplicated centre points made up the fifteen experimental runs that made up the BBD.

The responses were fitted to a second-order polynomial model:

$$Y = b_0 + \sum_{i=1}^3 b_i X_i + \sum_{i=1}^3 b_{ii} X_i^2 + \sum_{i<j}^3 b_{ij} X_i X_j$$

where Y is the predicted response, b_0 is the intercept, and b_i , b_{ii} , and b_{ij} represent the linear, quadratic, and interaction coefficients, respectively. Model adequacy was evaluated using Analysis of Variance (ANOVA), R^2 , adjusted R^2 , and lack-of-fit testing at $p < 0.05$. The overall experimental workflow from sample preparation to drying-kinetics analysis is summarized in Figure 3.

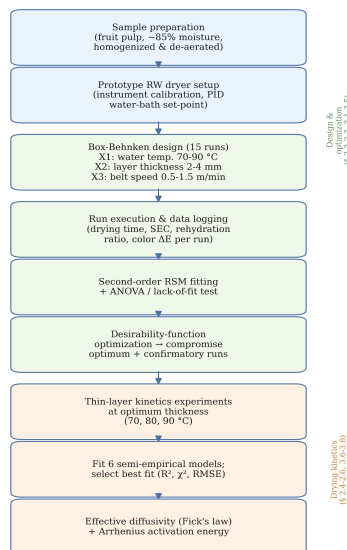


Figure 3. Overall experimental workflow of the developed RW drying process

The optimization was performed using a multi-response desirability-function approach. Drying time, SEC, and ΔE were minimized, whereas rehydration ratio was maximized. The predicted optimum was subsequently subjected to experimental validation using three independent confirmatory experiments.

3.4 Experimental Validation of the Optimized Condition

Experimental validation is an important part of RSM-based optimization to see if the optimum value predicted can be achieved in practice. After the optimization based on the desirability function, three independent drying runs were conducted to test the predicted water temperature, product-layer thickness and belt speed. Each run involved fresh pulp and fresh drying film to reduce variations due to pulp history and film reuse.

Optimized conditions from the response surface model were used directly. These drying properties were determined in the same way as in the BBD experiments, namely: drying time, SEC, rehydration ratio and ΔE . The mean experimental

results were compared to the model predicted results to evaluate the predictive ability of the models. The PE was determined by:

$$\text{Relative Error (\%)} = \frac{|\text{Experimental Value} - \text{Predicted Value}|}{\text{Predicted Value}} \times 100$$

The low relative error suggested that there was good agreement between the experimental and predicted responses. To assess the reproducibility of the optimized drying condition, the consistency of the three replicate runs was also taken into consideration. Therefore, the satisfactory validation of the optimum derived from the RSM was regarded as the close agreement between the experimental and predicted values, along with satisfactory experimental variation.

3.5 Drying Kinetics Experiments

The drying characteristics of the developed RWD were studied by drying 25 kgs of raw materials which were extracted from each of the two zones of the window pane, under various water temperatures and circulating-water rates. The moisture-removal behavior of the developed RWD was characterized using drying kinetics analysis of 25 kgs of raw materials taken from both window pane zones at different water temperature and circulating-water rates. The ideal product-layer thickness and belt speed were maintained constant throughout the trials, which were conducted at temperatures of 70, 80, and 90°C. Also, the air velocity was set at 0.8 m/s so that temperature could play a starring role in the drying process. Using the calibrated balance, we recorded the mass of each sample at regular intervals during each experiment. The moisture data measured were converted into moisture content on a dry basis with the following:

$$M_t = \frac{m_t - m_d}{m_d}$$

where M_t is the moisture content at time t (kg water/kg dry matter), m_t is the sample mass at time t , and m_d is the dry-solid mass.

The MR, which stands for the normalised behaviour of moisture loss during drying, was determined by:

$$\text{MR} = \frac{M_t - M_e}{M_0 - M_e}$$

where M_0 is the initial moisture content, M_t is the moisture content at drying time t , and M_e is the equilibrium moisture content. When M_e was sufficiently small relative to M_0 , the commonly used simplified expression was applied:

$$\text{MR} = \frac{M_t}{M_0}$$

The resulting MR–drying-time data were subsequently used for comparative fitting of the selected thin-layer drying models.

3.6 Thin-Layer Drying Model Fitting

For the purpose of predicting drying behaviour under different operating circumstances, mathematical models of moisture removal as a

function of drying time are commonly employed. These models are known as thin layer drying models. In this study, the experimental moisture-ratio data at circulating water temperatures were 70, 80 and 90°C were compared with six widely used semi-empirical models namely, “Newton (Lewis), Page, Modified Page, Henderson–Pabis, Logarithmic and Wang and Singh”. The selected models are used to make comparative assessment of the drying behaviour of the developed RWD. The model parameters were calculated at each explored temperature, via nonlinear least-squares regression, by the Levenberg–Marquardt algorithm. The Newton (Lewis) model was expressed as:

$$MR = \exp(-kt)$$

where k is the drying constant and t is drying time.

The Page model was represented by:

$$MR = \exp(-kt^n)$$

where k and n are empirical constants.

The Modified Page model was expressed as:

$$MR = \exp[-(kt)^n]$$

The Henderson–Pabis model was given by:

$$MR = a \exp(-kt)$$

where a is an empirical constant.

The Logarithmic model was represented as:

$$MR = a \exp(-kt) + c$$

where a , k , and c are model parameters.

The Wang and Singh model was expressed as:

$$MR = 1 + at + bt^2$$

where a and b are empirical coefficients.

These models were assessed by the “Coefficient of Determination (R^2), the Root-Mean-Square Error (RMSE) and the Reduced chi-square (χ^2)”. The RMSE quantified the difference between experimental and predicted moisture-ratio values and χ^2 was an additional measure of model residual error. The values of R^2 and RMSE and χ^2 showed better agreement between model and experimental results, as they were getting smaller. The model with the highest R^2 and the lowest RMSE and χ^2 values were chosen as the model that gave the best fit for each drying temperature. This model was then selected to explain the moisture removal characteristics of the designed RW dryer and subsequently the estimation of D_{eff} and activation energy.

3.7 Effective Moisture Diffusivity and Activation Energy

D_{eff} is an important parameter used to characterize the internal moisture-transfer behaviour of food materials during drying. It represents the combined effect of liquid diffusion, vapour diffusion, capillary movement, and other moisture-transport mechanisms occurring within the product. In the present study, D_{eff} was estimated from the falling-rate drying period at 70, 80, and 90°C using the analytical solution of Fick’s second law for one-dimensional moisture diffusion through a slab. The first term of the series solution was considered as:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{\text{eff}} t}{4L^2}\right)$$

where D_{eff} is the (m^2/s), t is drying time (s), and L is the characteristic half-thickness of the product layer (m). The effective moisture diffusivity was determined from the slope of the linear relationship between $\ln(MR)$ and drying time during the falling-rate period. Higher D_{eff} values indicate faster internal moisture migration within the product.

The temperature dependence of moisture diffusivity was evaluated using the Arrhenius relationship:

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right)$$

where D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy (J/mol), R is the universal gas constant ($8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$), and T is the absolute temperature (K). The activation energy was obtained from the slope of the linear regression between $\ln(D_{\text{eff}})$ and $1/T$, while the intercept provided the pre-exponential factor.

3.8 Energy Analysis Assessment

Energy-efficiency assessment was conducted to evaluate the electrical energy requirement and energy performance of the developed RWD. During each drying experiment, the electrical energy consumed by the heating and water-circulation systems was recorded using a calibrated energy meter. The total energy consumption was determined from the cumulative electrical energy used during the drying period. SEC was calculated as the energy required to evaporate a unit mass of water:

$$SEC = \frac{E_{\text{total}}}{m_{\text{water, evap}}}$$

where SEC is SEC (MJ/kg water evaporated), E_{total} is total electrical energy consumed (MJ), and $m_{\text{water, evap}}$ is the mass of water evaporated (kg). The evaporated water mass was determined from the difference in sample water content before and after drying. SEC was included as a response variable in the RSM optimization, with lower values indicating better energy performance. The SEC obtained at the optimized condition was compared with other experimental conditions to assess the energy efficiency of the developed RW dryer.

3.9 Statistical Analysis

All the experimental data was processed, regression analysis was performed, drying-kinetics model fitting was carried out, ANOVA, and optimization calculations were done using numerical and statistical tools based on Python. The numerical calculations and data manipulation were done using NumPy, and the nonlinear regression and parameter estimation were performed using SciPy. The statistical approach used was a statistical modelling and ANOVA, using the Statsmodels package. To ensure computational reproducibility, the following

packages were used: Python, NumPy, SciPy, and Statsmodels. The significance of model terms and experimental effects was tested at $p < 0.05$. The R^2 , adjusted R^2 , ANOVA, and lack-of-fit statistics were used to evaluate the adequacy of the response-surface models.

The parameters of the different mathematical models selected were estimated by nonlinear least-squares regression for drying-kinetics analysis. These models were tested for their performance with R^2 , RMSE and χ^2 . The experimental measurements were mean values of independent replicate experiments, with the appropriate variability reported if indicated. The uncertainty of fitted regression parameters was expressed as standard errors.

3.10 Assumptions and Limitations

The experimental method was founded upon a number of explicit assumptions. First of all, the air velocity above the product surface was always kept at 0.8 m/s during the experiments and was not made an independent variable. Hence, the effect of the three factors studied was not accounted for by the developed models. This was intentional to keep the experimental framework small and the experimental design three factor. Second, a single type of palmyrah palm pulp, wherein the initial moisture content was kept constant at about 85% wet basis, was used for feeding. The reported response-surface coefficients and drying-kinetics parameters, therefore, should not be taken as representative of the product and should not be directly extrapolated to products having significantly different soluble-solids content, viscosity, moisture content, or structural properties. Third, BBD uses second-order polynomial models to approximate the actual responses surfaces in the experimental ranges studied. To test this assumption, they used ANOVA and lack-of-fit tests but did not consider the model to be valid beyond the experimental domain if it fit well in the experimental domain. Fourth, both the thin-layer kinetic models make the assumption that there is relatively uniform, one-dimensional moisture transport normal to the drying film, but they do not specifically consider edge effects or local variations in product-layer thickness. These sources of variability were minimized by visual assessment of the uniformity of layers, but were not quantified. The assumptions in these models outline the applicability of the developed models and are thus considered when interpreting the results and evaluating the potential scale-up of the developed RWD system.

4. Results and Discussion

4.1. Formation and Stability of Dryer Performance

Preliminary tests showed that the selected temperature value set-point could be stabilised within $\pm 1^\circ\text{C}$ by the PID-controlled water bath, and

that the film-surface temperature reached the equilibrium value within about 3-4 min after a change in set-point temperature. The BBD was replicated with three centre point runs (Runs 13-15) to evaluate the repeatability of the developed dryer. Low variability was observed for the runs, as the coefficient of variation for drying time, SEC, rehydration ratio and ΔE were below 1.0% and below 1.5% respectively. The responses from the centre points show little variation, which represents high repeatability of the developed dryer and measurement procedure for the same operating conditions. The results validate the reliability of the experimental data and serve as a suitable basis for further response-surface modelling and optimization

4.2. Box–Behnken Design (BBD) Matrix and Experimental Responses

The BBD was used and the data obtained from the 15 runs are tabulated in Table 1. The drying times ranged between 52.64 and 86.76 min, with the minimum drying time found under Run 6 (90°C , 3 mm layer thickness, 0.5 m/min belt speed) and maximum drying time under Run 3 (70°C , 4 mm thickness, 1.0 m/min belt speed). The range of SEC was from 10.906 MJ/kg of water evaporated to 14.931 MJ/kg, with lower SEC typically recorded in moderate to low-temperature and in thicker layers. Rehydration ratio varied from 3.489 to 4.442, whereas ΔE ranged from 4.611 to 8.570. The overall increase in water temperature significantly increased the drying rates but was also accompanied by an increase in SEC and colour change. The thicker layers tended to keep drying longer and their SEC was affected by the operating temperature. This response variation emphasises the need of multi-response optimisation and suggests a trade-off between drying pace, energy consumption, and product quality.

Table 1. BBD matrix and experimental responses

R u n	X 1	X 2	X 3	T e m p ($^\circ\text{C}$)	T h i c k (mm)	S p e e d (m/min)	Y 1 T i m e (min)	Y 2 S E C (MJ/kg)	Y 3 R e h y d. r a t i o	Y 4 ΔE
1	-1	-1	0	70	2	1	68.6	12.586	4.442	4.611
2	1	-1	0	90	2	1	5	14.931	3.489	7.954

		1		0			3.79	931	652	334
3	-1	1	0	70	4	1	86.76	10.976	3.825	5.636
4	1	1	0	90	4	1	63.69	12.038	3.489	8.57
5	-1	0	-1	70	3	0.5	74.09	11.045	4.273	4.71
6	1	0	-1	90	3	0.5	52.64	12.872	3.732	7.627
7	-1	0	1	70	3	1.5	79.44	12.278	4.054	5.346
8	1	0	1	90	3	1.5	62.26	14.114	3.524	8.052
9	0	-1	-1	80	2	0.5	56.32	12.903	4.332	5.319
10	0	1	-1	80	4	0.5	71.17	10.906	3.882	6.489
11	0	-1	1	80	2	1.5	63.33	14.208	4.063	5.908
12	0	1	1	80	4	1.5	78.4	11.814	3.726	7.01

							2			2
13	0	0	0	80	3	1	64.42	12.04	4.123	6.08
14	0	0	0	80	3	1	65.07	11.869	4.094	6.268
15	0	0	0	80	3	1	64.94	11.88	4.143	6.132

4.3. Response Surface Model Fitting and ANOVA

The ANOVA results of the four second-order response surface models fitted are shown in Table 2. The drying time, SEC, rehydration ratio and ΔE of all models were highly significant with F values of 869.7, 308.2, 417.8 and 496.7, respectively, and p values of <0.001. The models had high R^2 ranging from 0.9982 to 0.9994, and adjusted R^2 ranging from 0.9950 to 0.9982, indicating good correlation between the model predicted and experimental responses. The best model fit was achieved for drying time and the lowest model fit was obtained for SEC with an R^2 of 0.998, but relatively. The results again indicate that the quadratic models developed were good representations of the experimental responses in the design space and appropriate for the response surface analysis and optimization.

Table 2. ANOVA results for the fitted response-surface models

Response	R^2	Adjusted R^2	F-value	p-value
Y1 - Drying time (min)	0.9994	0.9982	869.7	< 0.001
Y2 - SEC (MJ/kg)	0.9982	0.9950	308.2	< 0.001
Y3 - Rehydration ratio	0.9987	0.9963	417.8	< 0.001
Y4 - Total color	0.9989	0.9969	496.7	< 0.001

difference				
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The fitted second-order polynomial equations in terms of coded variables were obtained for drying time (Y_1), SEC (Y_2), rehydration ratio (Y_3), and total colour difference (Y_4) as follows:

Y_1 (Drying time): $Y_1 = 64.81 - 9.56X_1 + 7.25X_2 + 3.65X_3 - 2.07X_1X_2 + 1.07X_1X_3 + 0.07X_2X_3 + 1.60X_1^2 + 1.80X_2^2 + 0.70X_3^2$

Y_2 (SEC): $Y_2 = 11.93 + 0.88X_1 - 1.11X_2 + 0.59X_3 - 0.32X_1X_2 + 0.00X_1X_3 - 0.10X_2X_3 + 0.41X_1^2 + 0.29X_2^2 + 0.24X_3^2$

Y_3 (Rehydration ratio): $Y_3 = 4.12 - 0.27X_1 - 0.20X_2 - 0.11X_3 + 0.11X_1X_2 + 0.00X_1X_3 + 0.03X_2X_3 - 0.19X_1^2 - 0.08X_2^2 - 0.04X_3^2$

Y_4 (Total colour difference): $Y_4 = 6.16 + 1.40X_1 + 0.57X_2 + 0.26X_3 + 0.05X_1X_2 - 0.04X_1X_3 - 0.02X_2X_3 + 0.32X_1^2 + 0.06X_2^2 - 0.03X_3^2$

where X_1 is the coded value of water temperature, X_2 is the coded value of product-layer thickness, and X_3 is the coded value of belt speed. Water temperature had the largest effect with a coefficient of -9.56 , followed by layer thickness ($+7.25$) and belt speed ($+3.65$) among the linear terms. The water temperature was the most significant positive linear effect ($+0.88$) while thickness of layers was the greatest negative linear effect (-1.11) for SEC. As both the water temperature and the thickness of the layer rose, the rehydration ratio decreased, although ΔE mostly increased with the water temperature. The drying time had a negative X_1X_2 interaction (-2.07), suggesting a drying time that was somewhat diminished at higher water temperatures when the layer thickness was increased. All of the fitted equations provide a quantitative description of the relationship between the four responses in the design space that were explored and the operational factors.

The drying time, SEC, rehydration ratio, and ΔE were compared between the predicted and actual values as shown in figure 4. The plotted values were also very close to the experimental values, with most values being close to the 1:1 reference line. The R^2 for the drying time, rehydration ratio and ΔE were about 0.999 for both models, and an R^2 of 0.998 was observed for SEC. The predicted drying times were about 53–87 min which was very close to the actual measurements for drying time. Likewise, the predictions for the rehydration ratio were close to actual values from around 3.5 to 4.5 and the ΔE values were fairly well predicted over approximately 4.6–8.6. Overall, the distribution of data points is tight, which indicates a high predictive ability of the models developed using the RSM.

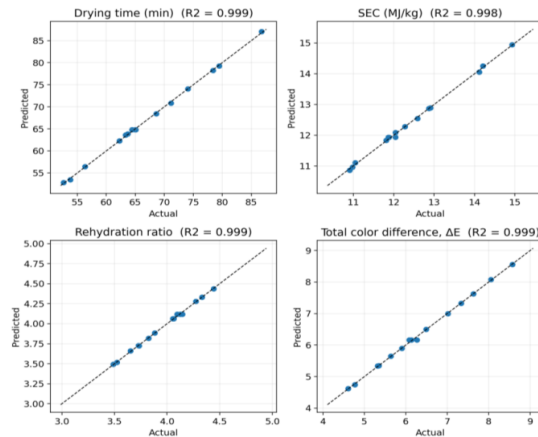


Figure 4. Effect of Process Variables: Response Surfaces

4.4. Effect of Process Variables: Response Surfaces

As shown in Figure 5, the drying time was significantly reduced by increasing water temperature and reducing the thickness of the product layer, when operating at a constant belt speed of 1.0 m/min. It was found that the moisture removal time was significantly affected by the layer thickness and the drying temperature, as the moisture removal time was reduced from about 86–88 min at 70 °C and 4 mm thickness to about 52–54 min at 90 °C and 2 mm thickness. The opposite was observed for SEC which varied between about 10.8 and 15.0 MJ/kg of water evaporated. There was a lower SEC where the temperature was lower and the thickness of the layer was thicker, while the higher temperature and the thinner thickness of the layer were higher. The opposite trends are consistent with the trade-off between the drying rate and the energy consumption, and emphasize the importance of multi-response optimization.

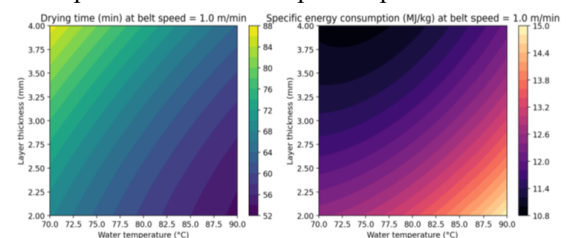


Figure 5. Response surface contours of (a) drying time and (b) SEC as functions of water temperature and layer thickness at 1.0 m/min belt speed

4.5. Multi-Response Optimization

The optimum operating condition of 75.5 °C water temperature, 2.15 mm product-layer thickness and 0.50 m/min belt speed was found by the desirability-function analysis with a value of 0.60 (Table 3). In such conditions, the prediction for the drying time was 61.4 min and the SEC of 12.22 MJ/kg water evaporated. The predicted rehydration ratio was 4.45, good rehydration properties, and the predicted ΔE was 4.84, relatively low colour change. The optimum is a compromise between the conflicting needs of minimizing drying time, SEC,

colour change and maximizing rehydration ratio. The results indicate that multi-response desirability optimization can help to obtain a balanced operating condition instead of optimizing a single parameter of the drying performance independently.

Table 3. Predicted optimum operating conditions and responses from desirability-function optimization

Optimized variable/response	Value
Water temperature	75.5 °C
Product-layer thickness	2.15 mm
Belt speed	0.50 m/min
Predicted drying time	61.4 min
Predicted SEC	12.22 MJ/kg water evaporated
Predicted rehydration ratio	4.45
Predicted ΔE	4.84
Composite desirability (D)	0.60

4.6. Thin-Layer Drying Kinetics

The Page model was determined to have the best overall match, as seen in Table 4, which compares the models over all three temperatures. The root-mean-squared error (RMSE) went down from 0.0098 to 0.0065, but the R^2 went up from 0.9989 at 70 °C to 0.9993 at 80 °C and 0.9996 at 90 °C. The agreement between the measured and model moisture-ratios improved when χ^2 decreased from 1.05×10^{-4} to 5.7×10^{-5} . The Page model's drying constant increased from 0.0224 to 0.0577 as the drying temperature rose, and the exponent increased from 1.103 to 1.217, both of which are positive values. Compared to the Page model, the Modified Page model is easier to represent while maintaining the same level of statistical fit. Both the Newton and Wang-Singh models have very low R^2 values, with the Wang-Singh model having the lowest R^2 value (0.9839-0.9909).

Table 4. Statistical comparison of six thin-layer drying models fitted to moisture-ratio data at each water temperature

Temp	Model	Fitted paramet	R^2	χ^2	RMSE
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(°C)		ers			
70	Newton	k = 0.0325	0.9961	3.38E-4	0.0180
70	Page	k = 0.0224, n = 1.103	0.9989	1.05E-4	0.0098
70	Modified Page	k = 0.0319, n = 1.103	0.9989	1.05E-4	0.0098
70	Henders on-Pabis	a = 1.032, k = 0.0335	0.9972	2.52E-4	0.0152
70	Logarithmic	a = 1.045, k = 0.0314, c = -0.023	0.9981	1.82E-4	0.0126
70	Wang and Singh	a = -0.0229, b = 1.32E-4	0.9839	1.48E-3	0.0367
80	Newton	k = 0.0595	0.9939	6.41E-4	0.0242
80	Page	k = 0.0368, n = 1.159	0.9993	8.4E-5	0.0084
80	Modified Page	k = 0.0579, n = 1.159	0.9993	8.4E-5	0.0084
80	Henders on-Pabis	a = 1.031, k = 0.0612	0.9951	5.67E-4	0.0217
80	Logarithmic	a = 1.068, k = 0.0535,	0.9981	2.42E-4	0.0135

		c = - 0.052			
80	Wang and Singh	a = - 0.0427, b = 4.65E-4	0.99 34	7.69 E-4	0.02 53
90	Newton	k = 0.0994	0.99 28	9.14 E-4	0.02 83
90	Page	k = 0.0577, n = 1.217	0.99 96	5.7E -5	0.00 65
90	Modified Page	k = 0.0959, n = 1.217	0.99 96	5.7E -5	0.00 65
90	Henderson-Pabis	a = 1.026, k = 0.1017	0.99 37	9.32 E-4	0.02 64
90	Logarithmic	a = 1.066, k = 0.0894, c = - 0.051	0.99 69	5.61 E-4	0.01 87
90	Wang and Singh	a = - 0.0693, b = 1.20E-3	0.99 09	1.36 E-3	0.03 19

As can be seen in figure 6, MR decreased at all three water temperatures as the drying operation was continued. The drying rate was significantly higher when drying at high temperatures. The MR decreased gradually with time at 70 °C and reached about 0.02 after approximately 105 min, while at 80 °C, the same level of MR was achieved after approximately 55–60 min and at 90 °C, MR reached approximately 0.01–0.02 after about 35–40 min. A constant-rate drying period was not found, suggesting that most of the drying was taking place under falling-rate conditions. The fitted Page-model curves were similar to the experimental observations, especially at 70 °C and 90 °C, which is an indication of the applicability of the Page model to moisture removal. Generally, the temperature of water had a significant effect on drying rates.

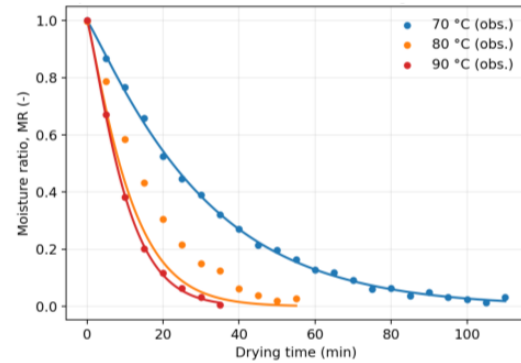


Figure 6. Experimental MR (points) and fitted Page-model curves (lines) at 70, 80 and 90 °C water temperature.

4.7. Drying Rate Curves

At 70, 80, and 90 °C, Figure 7 shows how the drying rate varies with moisture content. Temperature has a significant impact on the rate of moisture removal, as the drying rate was consistently greater at higher water temperatures. At 70, 80, and 90 °C, the drying rates were around 0.15, 0.24, and 0.37 kg water kg⁻¹ dry solid min⁻¹, respectively, at increasing moisture levels. As drying progressed and moisture content decreased, the drying rate generally declined, particularly at 80 and 90 °C, indicating predominantly falling-rate behaviour. The 90 °C condition maintained the highest drying rate throughout most of the investigated moisture range, followed by 80 and 70 °C. The fluctuations observed at 70 °C at lower moisture contents indicate greater variability during the final drying stage.

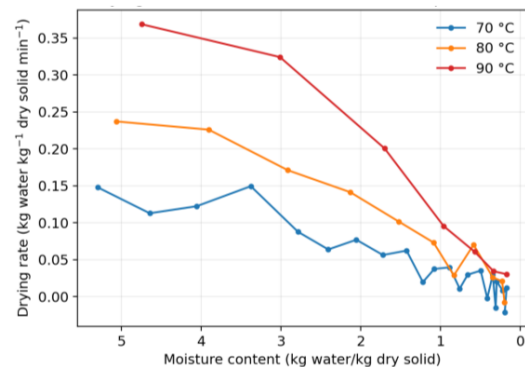


Figure 7. Drying rate versus moisture content at 70, 80 and 90 °C water temperature

4.8. Effective Moisture Diffusivity and Activation Energy

Table 5 shows that D_{eff} increased substantially with increasing water temperature. The D_{eff} increased from 5.69×10^{-10} m²/s at 70 °C to 1.15×10^{-9} m²/s at 80 °C, reaching 2.26×10^{-9} m²/s at 90 °C. This approximately four-fold increase indicates enhanced internal moisture migration at higher drying temperatures. The corresponding R^2 values of 0.974, 0.975, and 0.945 demonstrate a strong linear connection between $\ln(\text{MR})$ and drying time for the three temperatures. The lower R^2 at 90 °C may reflect greater deviation from ideal one-

dimensional diffusion behaviour during the later drying stage. Overall, higher temperature substantially promoted moisture diffusion.

Table 5. D_{eff} estimated from the slope method (Fick's second law, slab geometry, first term of the series solution).

Water temperature (°C)	D_{eff} (m ² /s)	R ² of ln(MR) vs. t regression
70	5.69E-10	0.974
80	1.15E-09	0.975
90	2.26E-09	0.945

The Arrhenius equation for the reciprocal absolute temperature ($1/T$) and the natural logarithm of D_{eff} is shown in Figure 8. The calculated diffusivity values show a clear linear decrease in $\ln D_{\text{eff}}$ with increasing $1/T$, confirming the strong temperature dependence of moisture diffusion. The three experimental points corresponding to 70, 80, and 90 °C lie closely along the fitted Arrhenius line, indicating good linearity of the relationship. A pre-exponential factor (D_0) of 42.9 m²/s and an activation energy of 71.5 kJ/mol were both determined by the regression. The strong linearity of the Arrhenius fit indicates that the Arrhenius equation may be used to describe the temperature dependence of moisture diffusivity in the range that was studied. Overall, increasing temperature substantially enhanced internal moisture migration during RW drying.

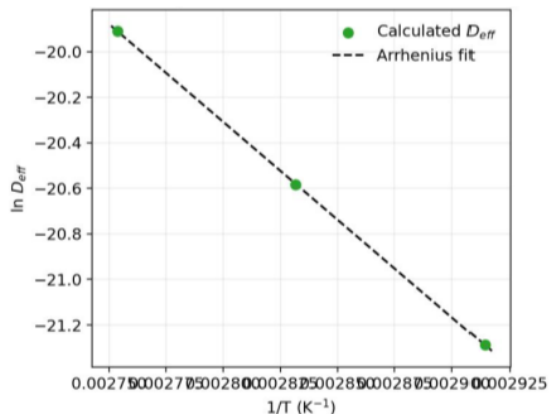


Figure 8. Arrhenius plot of the natural logarithm of D_{eff} against reciprocal absolute temperature

4.9. Energy Efficiency and Implications for Standardization

The optimum condition of the machine was found as 75.5 °C, 0.50 m/min belt speed and 2.15 mm layer thickness with a SEC of 12.22 MJ/kg water evaporated. This value represents a favourable energy performance of the developed RW dryer and shows the potential of optimized RW drying of

efficient processing of high moisture fruit pulps. The results also indicated that water temperature as well as product-layer thickness had significant effects on the drying performance, which highlighted the need for proper water temperature control and thin-layer uniform application during the dryer operation. The activation energy (71.5 kJ/mol) is also relatively high, which further suggests strong temperature dependence of moisture diffusion. The important operating parameters such as water/film temperature, layer thickness and air velocity should be reported regularly for standardization of future studies on drying of RW. Furthermore, providing a suitable thin-layer kinetic model, valid moisture diffusivity and activation energy would make it possible to compare different products and different configurations of the RW dryer.

4.10. Industrial Applicability, Scalability and Economic Considerations

The developed RW drying protocol has potential for processing high value and heat sensitive fruit pulps and purees where the benefits of using the RW drying technology is the ability to improve drying efficiency and product quality. Optimized condition of 75.5 °C, 2.15 mm layer thickness and 0.50 m/min belt speed with the predicted SEC of 12.22 MJ/kg water evaporated is used as a reference for pilot scale operation. Adopting these conditions directly to continuous industrial RW dryers, however, would necessitate additional optimization since there are differences in the residence time, throughput and belt length between the laboratory and industrial setups.

The uniform layer thickness, control of water-bath temperature and recovery, and reduction of heat losses from the drying system may affect scale-up. At larger scale these factors can impact drying uniformity and SEC. The results of the present work are used for a preliminary energy assessment, but a detailed techno-economic analysis has not been carried out. Thus, equipment cost, energy costs, maintenance, depreciation and production capacity should be taken into account prior to commercialization. Optimum conditions are also recommended to be validated by pilot-scale trials to assess the robustness of the optimized conditions for different feed properties.

5. Conclusion and Future Scope

It has been observed from the present study that the developed RWD has the potential to dry palmyrah palm pulp efficiently and in a standardized manner. Three-factor BBD and RSM successfully quantified the effects of the drying parameters (circulating water temperature, product-layer thickness and belt speed) on drying time, SEC, rehydration ratio and total colour difference. The developed quadratic models have been shown to be excellent predictors with R² values ranging from 0.9982–0.9994 and the highly significant ANOVA

results ($p < 0.001$). A water temperature of 75.5 °C, a layer thickness of 2.15 mm, a belt speed of 0.50 m/min, a drying duration of 61.4 min, a SEC of 12.22 MJ/kg water evaporated, a rehydration ratio of 4.45, a ΔE of 4.84, and a composite desirability of 0.60 were those ideal circumstances. The process was best described by the Page model, a kinetic model that achieved a R^2 of up to 0.9996. As the temperature grew from 70 to 90 °C, the activation energy was determined to be 71.5 kJ/mol and the D_{eff} increased from 5.69×10^{-10} to 2.26×10^{-9} m²/s. In general, the optimized RWD has proven to be a potentially energy-efficient method for processing high-moisture fruit-pulses. Future studies should include pilot scale validation, techno-economic assessment and testing of the optimized RWD under different feed properties to demonstrate industrial scalability and robustness.

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