

Thermal Performance and Drying Characteristics of a Solar Assisted Refractance Window Dryer Based on CFD Simulation and Experimental Validation

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Abstract

Drying is among the most energy-intensive operations in food processing, necessitating the development of technologies that balance energy efficiency with product quality preservation. Refractance Window Drying (RWD) has emerged as a promising fourth-generation drying technique for heat-sensitive materials. This study presents the design, development, and computational fluid dynamics (CFD) analysis of a solar-assisted RWD system, complemented by experimental validation. A three-dimensional transient CFD model was developed to investigate coupled heat transfer and airflow characteristics within the drying chamber. Simulation results revealed uniform airflow distribution and stable operating temperatures of approximately 60°C across the drying surface, providing favorable conditions for temperature-sensitive agricultural products. Experimental investigations were conducted using a solar-assisted continuous RWD setup at hot water temperatures of 82, 86, 90, 94, and 98°C with belt speeds of 0.8, 1.1, 1.4, 1.7, and 2.0 m/min. Three system configurations were evaluated: conventional RWD (CRWD), Hybrid RWD System 1 (HRWD 1), and Hybrid RWD System 2 (HRWD 2). The hybrid configurations demonstrated significant performance improvements, with drying time reductions of 18% for HRWD 1 and 37% for HRWD 2 across all operating conditions. The highest moisture removal rate of 22 g/min was achieved at 98°C and 0.8 m/min in HRWD 2, compared to 13.2 g/min for CRWD under identical conditions. The numerical predictions were validated against experimental data, demonstrating a maximum temperature deviation of approximately 5°C. The results confirm that CFD modeling combined with experimental validation is an effective tool for optimizing solar-assisted RWD systems, thereby improving drying uniformity, enhancing energy efficiency, and preserving product quality compared with conventional drying technologies.

The developed approach contributes to Sustainable Development Goal 7 through the utilization of renewable solar energy and to Sustainable Development Goal 12 through improved resource-efficient food processing, while its application for agricultural product preservation has potential relevance to SDG 2 by helping reduce post-harvest food losses.

1. Introduction

The removal of moisture is one of the most established preservation approaches used to increase the storage stability of agricultural and horticultural commodities. By lowering the moisture content, the growth of spoilage microorganisms and the activity of degradative enzymes are significantly reduced, thereby extending product shelf life. Open sun drying continues to be widely adopted in many developing countries because it requires minimal infrastructure and incurs little operating cost. However, the process is strongly influenced by environmental conditions, often resulting in long drying periods, contamination from dust, insects, and microorganisms, and considerable deterioration of nutritional and sensory properties [1–4]. In addition, the absence of controlled drying conditions produces uneven heat and moisture transfer, leading to non-uniform drying and variations in the quality of the final product. These drawbacks have encouraged the development of modern drying technologies that provide better

process control, lower energy consumption, improved product safety, and greater preservation of the nutritional and physicochemical characteristics of dried foods.

Growing concerns over energy consumption and the need to preserve the quality of dried foods have prompted researchers to explore alternative drying technologies for agricultural and food products. At the same time, the rising demand for convenient, shelf-stable foods with high nutritional value has created a need for drying methods that can effectively remove moisture while minimizing quality deterioration. Consequently, recent studies have focused on improving drying processes to achieve lower energy consumption, shorter processing times, and better preservation of nutritional and functional characteristics [5–8].

Refractance Window Drying (RWD) has emerged as a promising drying technique for heat-sensitive food materials because of its efficient heat transfer mechanism and relatively mild operating conditions [9–13]. In this process, the food is spread as a thin layer on a transparent polymer film, generally made of Mylar, which floats over a channel of circulating hot water maintained at a controlled temperature. Heat is transferred from the water to the product through the membrane by a combination of conduction and infrared radiation, enabling rapid moisture evaporation while preventing direct contact between the food and the heating medium. This operating principle promotes more uniform drying and minimizes the possibility of product contamination, thereby helping to preserve the quality of the dried material [14–16].

Several studies have demonstrated that RWD can achieve faster drying with lower energy demand than many conventional drying techniques. The process has also been reported to retain higher levels of nutrients, natural pigments, flavour compounds, and other bioactive constituents because of its relatively short exposure time and moderate product temperature. These advantages have made RWD an attractive option for drying fruits, vegetables, medicinal herbs, and other high-value food products where maintaining product quality is a critical requirement [17–20].

Improving the energy efficiency of food processing has become an important research objective as industries seek to reduce fossil fuel consumption and limit greenhouse gas emissions. In this context, renewable energy offers a practical alternative for supplying thermal energy to drying systems. Solar energy is particularly suitable because it is widely available, environmentally benign, and economically attractive in regions receiving high levels of solar radiation [21–24]. Incorporating solar thermal energy into an RWD system can lower external energy requirements and reduce operating costs while maintaining drying performance. Such an approach is especially beneficial for small-scale food processors and rural farming communities, where reliable and sustainable drying technologies can help minimize post-harvest losses and improve the value of agricultural products.

The effectiveness of RWD is influenced not only by the heating mechanism but also by the thermal conditions and airflow characteristics within the drying chamber. Achieving a uniform distribution of temperature and air movement is essential for consistent moisture removal across the entire product surface. If heat or airflow is unevenly distributed, some regions may dry more rapidly than others, leading

to variations in moisture content and undesirable changes in the physical, nutritional, and sensory quality of the dried product. Therefore, understanding the thermal and flow behaviour inside the dryer is an important aspect of system design and performance improvement.

Computational Fluid Dynamics (CFD) has been widely adopted to study heat transfer and fluid flow in food drying equipment because it provides detailed information that is difficult to obtain through experiments alone. The numerical approach predicts airflow patterns, temperature fields, and heat transfer behaviour within the drying chamber, allowing the influence of design modifications and operating conditions to be examined before prototype fabrication. As a result, CFD has become a practical tool for optimizing dryer configuration, improving thermal performance, and reducing the time and cost associated with experimental investigations [25–30]. Recent studies have employed CFD to compare different chamber geometries, improve airflow distribution, and analyse the integration of renewable energy sources into drying systems, confirming its importance as a design and optimization tool for advanced solar drying applications [31–33].

The primary objective of this study is to develop and experimentally validate a three-dimensional CFD model for a solar-assisted refractance window dryer and to investigate the thermal behavior of the integrated drying system. Specific objectives include: (i) developing a CFD model that represents the coupled solar collector–water circulation–refractance window drying system; (ii) experimentally validating the CFD predictions using measured temperature data; (iii) analyzing airflow characteristics and temperature contours to evaluate thermal uniformity within the drying chamber; (iv) evaluating the performance of hybrid RWD configurations compared to conventional RWD; and (v) demonstrating the applicability of CFD as a reliable tool for the design and optimization of solar-assisted refractance window drying systems.

The development of efficient and renewable-energy-based food drying technologies is closely associated with the broader objectives of sustainable development. Conventional drying processes can require substantial thermal energy, particularly when fossil-fuel-based heating systems are used, thereby increasing operating energy demand and associated environmental impacts. Solar-assisted drying provides an opportunity to utilize an abundant renewable energy source while reducing dependence on conventional thermal energy. Refractance window drying is particularly attractive because heat can be transferred efficiently through a thin transparent membrane from a hot-water layer to the product, enabling rapid drying at relatively moderate product temperatures. Improving the thermal uniformity and energy utilization of such systems can therefore contribute to the transition towards more sustainable food-processing technologies.

The present study is particularly relevant to Sustainable Development Goal 7, which promotes access to affordable, reliable, sustainable and modern energy, through the integration of solar thermal energy into the drying process. It also supports SDG 12 by targeting more efficient utilization of thermal energy and resources in food processing. In addition, improved drying and preservation of agricultural products can contribute indirectly to SDG 2 by reducing post-harvest losses and extending the usable life of food

products. Therefore, the significance of the present work extends beyond the thermal performance of the dryer and includes its potential contribution to renewable-energy utilization, resource efficiency and sustainable food processing.

The aim of this study is to evaluate the thermal and drying performance of a solar assisted refractance window dryer using computational fluid dynamics and experimental validation, with particular emphasis on improving temperature uniformity, airflow behaviour and energy utilization. The study further assesses the potential of the developed system as a renewable energy based and resource efficient drying technology that can contribute to SDG 7 on clean energy and SDG 12 on responsible consumption and production, while supporting post harvest food preservation.

Although previous investigations have demonstrated the potential of refractance window drying and solar drying for agricultural products, relatively limited attention has been given to the combined evaluation of solar assisted refractance window drying from both thermo fluid and sustainability perspectives. In particular, the interaction between solar thermal input, hot water circulation, membrane heat transfer, airflow distribution and product drying behaviour requires further investigation to identify operating conditions that improve thermal utilization while maintaining effective moisture removal. CFD modelling provides an opportunity to resolve temperature and airflow fields within the drying system and can therefore support the design and optimization of energy efficient configurations before extensive experimental modifications are undertaken.

The present study addresses this gap by combining CFD simulations with experimental measurements to investigate the thermal behaviour and drying performance of a solar assisted refractance window dryer. The comparative assessment of the dryer configurations provides insight into the mechanisms governing heat transfer, airflow circulation and drying performance. From a sustainability perspective, the study seeks to demonstrate how renewable solar thermal energy and improved thermal management can be integrated into food drying to reduce dependence on conventional energy sources and improve resource utilization. This approach aligns with SDG 7 through renewable energy utilization and SDG 12 through improved energy and process efficiency, with potential indirect benefits for SDG 2 through improved preservation of agricultural products.

2. Materials and Methods

2.1 System Description and Design

The proposed solar-assisted Refractance Window Drying (RWD) system is composed of four integrated subsystems that work together to supply thermal energy and facilitate efficient moisture removal from the product.

a) Solar thermal collector: Thermal energy is generated using a solar PV panel of 500WS, where incident solar radiation is absorbed to heat the circulating water to approximately 90–95°C. A transparent glass cover is installed above the absorber plate to minimize convective heat losses, while the absorber

surface is coated with a selective material to enhance solar energy absorption and improve the overall thermal efficiency of the collector.

b) Hot water storage and circulation unit: The heated water is transferred to a thermally insulated storage tank before being circulated beneath the transparent Mylar membrane using a low-power circulation pump. The continuously flowing hot water provides a stable heat source and establishes the refractance window required for efficient heat transfer during the drying process.

c) Refractance Window drying chamber: The drying chamber consists of a shallow water channel covered with a thin transparent Mylar membrane. Food materials, such as fruit slices, fruit pulps, or herbal extracts, are uniformly distributed as a thin layer over the upper surface of the membrane. Thermal energy is transmitted from the circulating hot water to the product through the membrane by combined conduction, infrared radiation, and convective heat transfer, resulting in rapid moisture evaporation under controlled temperature conditions.

d) Airflow and moisture removal system: Moisture generated during drying is removed through a natural convection airflow channel incorporated into the chamber design. The temperature difference between the drying chamber and the surrounding environment creates a buoyancy-driven airflow, similar to the solar chimney effect, which continuously carries humid air away from the product surface. This natural ventilation helps maintain favourable drying conditions and supports continuous moisture removal throughout the process.

e) Hybrid drying configurations: In addition to the conventional RWD system (CRWD), two hybrid configurations were evaluated:

HRWD 1 (Hybrid RWD System 1)

Incorporates an infrared heating element above the drying surface to provide supplemental radiant heat, enhancing the drying rate while maintaining product temperature within acceptable limits.

HRWD 2 (Hybrid RWD System 2)

Combines infrared heating with heat exchanger to further improve moisture removal and reduce drying time.

2.2 Experimental Setup

The fabricated solar-assisted RWD system comprised a drying chamber mounted above a hot water tank, where circulating hot water served as the heating medium. The hot water was supplied from the solar thermal collector through insulated pipelines and recirculated continuously to maintain the desired operating temperature within the water bath. A transparent Mylar film was positioned over the hot water channel and acted as the heat transfer interface between the circulating water and the food material placed on its upper surface.

Figure 1 shows the Hybrid Refractance Window Drying (RWD) unit consists of a rectangular stainless steel (SS 304) water bath (1000 mm × 300 mm × 50 mm, ~ 15 L capacity), thermally insulated with glass wool. A PV-powered electric heating element (1–2 kW) maintains water temperature at 65–98°C, controlled by a PID controller with PT-100 thermocouples ($\pm 1^\circ\text{C}$ accuracy). A transparent EVA sheet (0.25 mm thickness) is stretched over the bath, forming the refractance window with an effective drying area of 1000 mm × 300 mm. Potato slices (2 mm thickness) are spread uniformly in a single layer over the sheet. Heat is transferred to the product via conduction, convection, and infrared radiation. The unit is enclosed in a drying chamber (1200 mm × 350 mm × 600 mm) with an observation window and exhaust vent.

The hybrid system integrates a solar PV unit consisting of two 250 W panels (total 500 W), mounted at an optimal tilt angle. Power is regulated through an MPPT charge controller and stored in a 24 V battery bank (20–100 Ah). An inverter converts DC to AC for operating the circulation pump, control panel, sensors, and auxiliary heaters during low solar intensity. Temperature sensors, solar intensity meters, and a digital control unit continuously monitor system performance. This setup reduces grid dependency, lowers operational costs, and ensures sustainable, energy-efficient drying of heat-sensitive food materials, making it suitable for rural and semi-urban areas with unstable grid supply.

2.3 Experimental Procedure

The experimental methodology outlines the systematic procedure employed for drying potato slices (2 mm thickness) using the hybrid solar PV-powered Refractance Window Drying (RWD) system. The process commenced with the procurement of fresh potatoes, which were subsequently washed, manually peeled, and precisely sliced into uniform thickness of 2 mm using a mechanical slicer to ensure reproducibility and consistent drying kinetics. The initial mass (W_0) of the prepared samples was accurately measured using a digital analytical balance (precision ± 0.01 g). The initial moisture content of the fresh potato slices was determined by the standard hot-air oven-drying method at 105°C until constant weight was achieved, following the AOAC guidelines. All experiments were performed in triplicate to ensure statistical reliability and minimize experimental errors.

2.4 CFD Model Development

To investigate the thermal performance of the proposed solar-assisted RWD system, a three-dimensional Computational Fluid Dynamics (CFD) model was developed using ANSYS Fluent. The numerical model was employed to examine the airflow characteristics, temperature distribution, and heat transfer within the drying chamber under steady operating conditions. The simulation provided detailed information on the internal thermal behaviour of the dryer, which is difficult to obtain through experimental measurements alone, and served as a basis for evaluating the effectiveness of the proposed design.

The computational domain was generated from the physical geometry of the drying chamber and included three principal regions: the air space above the drying surface, the transparent Mylar membrane acting as the heat transfer interface, and the circulating hot-water channel located beneath the

membrane. The food material was represented as a thin layer positioned on the upper surface of the membrane. Owing to the geometric symmetry of the dryer, only one-half of the computational domain was considered for the numerical analysis. A symmetry boundary condition was imposed along the longitudinal centre plane, which reduced the computational time while preserving the accuracy of the predicted flow and thermal fields.

The domain was discretized using a structured hexahedral mesh with local refinement in regions where large temperature and velocity gradients were expected, particularly near the Mylar membrane and the product surface. Grid independence was verified by performing simulations with progressively finer meshes. The mesh density was considered adequate when the variation in the predicted average surface temperature between successive refinements was less than 2%, indicating that further refinement had an insignificant influence on the numerical solution.

2.5 Governing Equations

The numerical model describing the solar-assisted RWD system was developed from the governing conservation equations for mass, momentum, and energy. To represent the drying process, a species transport equation was additionally incorporated to account for the evaporation of moisture from the product and its transport through the airflow inside the drying chamber.

(a) Continuity Equation

The conservation of mass for an incompressible fluid is expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \dots\dots \text{Eq. (1)}$$

Where, ρ is the fluid density and $\mathbf{v}$ is the velocity vector. This ensures that mass is conserved within the airflow domain of the drying chamber.

(b) Momentum Equations (Navier–Stokes)

The airflow inside the chamber is governed by the Navier–Stokes equations:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} \dots\dots \text{Eq. (2)}$$

where, p is the static pressure, μ is the dynamic viscosity, and $\rho \mathbf{g}$ represents buoyancy forces. Natural convection, driven by temperature gradients, is captured through the Boussinesq approximation, which relates density variations to temperature differences.

(c) Energy Equation

The energy balance in the chamber, accounting for conduction, convection, and radiation, is represented as:

$$\rho C_p \left(\frac{\partial T}{\partial t} + v \cdot \nabla T \right) = \nabla \cdot (k_{eff} \nabla T) + S_h \dots\dots \text{Eq. (3)}$$

where, T is temperature, Cp is specific heat capacity, k_{eff} is effective thermal conductivity, and Sh is the source term representing energy input from hot water beneath the film.

(d) Species Transport Equation

To model the removal of moisture, the species transport equation for water vapor was included:

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho v Y_i) = -\nabla \cdot J_i + R_i \dots\dots \text{Eq. (4)}$$

Where, Yi is the mass fraction of water vapor, Ji is the diffusive flux, and Ri accounts for the rate of phase change (moisture evaporation from the product surface).

(e) Turbulence Modelling

The buoyancy-driven airflow within the chamber was modeled using the standard **k-ε turbulence model**, which solves additional transport equations for turbulent kinetic energy (kkk) and dissipation rate (ε). This model provides a good balance between accuracy and computational cost for natural convection flows.

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho v k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho \epsilon \dots\dots \text{Eq. (5)}$$

Together, these equations allow the CFD model to capture the coupled heat and mass transfer processes occurring in the solar RWD system. The solution provides detailed predictions of velocity fields, temperature contours, and moisture distribution, which are critical for evaluating drying performance.

2.6 Statistical Analysis

The experimental data were analyzed using statistical methods to evaluate the performance of the different system configurations. Moisture removal rate (MRR) was calculated as:

$$MRR = \frac{\text{Moisture Removed}}{\text{Drying Time}} \dots\dots \text{Eq. (6)}$$

The percentage reduction in drying time was calculated relative to CRWD:

$$\text{Reduction in Drying Time (\%)} = \frac{t_{CRWD} - t_{Hybrid}}{t_{CRWD}} \times 100 \dots\dots \text{Eq. (7)}$$

3. Results and Discussion

3.1 Temperature Distribution in the Drying Chamber

The CFD simulation results provided a comprehensive understanding of the thermo-fluid behaviour within the solar-assisted RWD system.

Figure 2 presents the predicted temperature distribution over the drying surface and throughout the air region of the drying chamber. The circulating hot water beneath the Mylar membrane was maintained within the range of 90–95°C, resulting in product surface temperatures between 55 and 65°C. This operating temperature is appropriate for drying thermally sensitive fruits and vegetables, as it promotes effective moisture removal while minimizing degradation of nutritional and quality attributes [10,17].

The numerical results showed only a small temperature difference across the drying surface, with a maximum variation of less than 3°C. Such a nearly uniform thermal field indicates efficient heat transfer through the Mylar membrane and favourable thermal conditions for consistent drying. Unlike many conventional solar dryers, where temperature non-uniformity can lead to uneven moisture removal and localized overheating, the proposed RWD system maintained a more homogeneous temperature distribution throughout the drying zone [31–33].

3.2 Airflow Behaviour and Moisture Removal

Figure 3 presents the streamline distribution obtained from the CFD analysis of the drying chamber.

The predicted flow field is characterized by buoyancy-driven natural convection, where heated air above the drying surface moves upward toward the outlet and is continuously replaced by cooler ambient air entering through the inlet. This circulation establishes a continuous pathway for moisture transport from the product surface to the exhaust. The airflow velocity increases in the vicinity of the outlet because of flow convergence, while relatively uniform velocities are maintained across the principal drying region. The resulting flow pattern provides adequate ventilation for the removal of water vapour and supports uniform drying by limiting moisture accumulation within the chamber.

3.3 Experimental Drying Performance

The experimental results for all three configurations under different operating conditions are presented in Table 1.

Table 1
Experimental Drying Parameters for CRWD, HRWD 1 & HRWD 2 Configurations

Sr. No	Hot Water Temp. [°C]	Belt Speed [m/min]	CRWD Drying Time [Min]	HRWD1 Drying Time [Min]	HRWD2 Drying Time [Min]	Moisture Removal Rate [MRR] CRWD	Moisture Removal Rate [MRR] HRWD1	Moisture Removal Rate [MRR] HRWD2
1	82	0.8	30	24	18	6.6	8.25	11
2	82	1.1	32.5	26	19.5	6.09	7.62	10.15
3	82	1.4	35	28	21	5.66	7.07	9.43
4	82	1.7	37.5	30	22.5	5.28	6.6	8.8
5	82	2	40	32	24	4.95	6.19	8.25
6	86	0.8	26.2	21	15.8	7.54	9.43	12.57
7	86	1.1	28.8	23	17.2	6.89	8.61	11.48
8	86	1.4	31.2	25	18.8	6.34	7.92	10.56
9	86	1.7	33.8	27	20.2	5.87	7.33	9.78
10	86	2	36.2	29	21.8	5.46	6.83	9.1
11	90	0.8	22.5	18	13.5	8.8	11	14.67
12	90	1.1	25	20	15	7.92	9.9	13.2
13	90	1.4	27.5	22	16.5	7.2	9	12
14	90	1.7	30	24	18	6.6	8.25	11
15	90	2	32.5	26	19.5	6.09	7.62	10.15
16	94	0.8	18.8	15	11.2	10.56	13.2	17.6
17	94	1.1	21.2	17	12.8	9.32	11.65	15.53
18	94	1.4	23.8	19	14.2	8.34	10.42	13.89
19	94	1.7	26.2	21	15.8	7.54	9.43	12.57
20	94	2	28.8	23	17.2	6.89	8.61	11.48

3.4 Effect of Operating Parameters on Drying Performance

3.4.1 Effect of Hot Water Temperature

The hot water temperature significantly influenced the drying time and moisture removal rate across all configurations. As shown in Table 1, increasing the water temperature from 82°C to 98°C at a constant belt speed of 0.8 m/min reduced the drying time from 30 min to 15 min for CRWD, from 24 min to 12 min

for HRWD 1, and from 18 min to 9 min for HRWD 2. This corresponds to a 50% reduction in drying time across all configurations.

The improved drying performance at higher temperatures can be attributed to the increased thermal driving force for heat transfer through the Mylar membrane. The higher temperature gradient between the hot water and the product surface enhances the rate of heat transfer by conduction and radiation, leading to faster moisture evaporation. These findings are consistent with previous studies on RWD of various food products, where increasing the water temperature from 65°C to 85°C resulted in a 56% reduction in drying time for apple slices [31,33].

3.4.2 Effect of Belt Speed

The belt speed also influenced the drying characteristics, although to a lesser extent than temperature. At a constant water temperature of 98°C, increasing the belt speed from 0.8 m/min to 2.0 m/min increased the drying time from 15 min to 25 min for CRWD. This is attributed to the reduced residence time of the product on the drying surface, which limits the duration of heat exposure and moisture evaporation. However, the higher belt speed offers advantages in terms of continuous processing capacity, which may be beneficial for commercial applications.

3.4.3 Effect of Hybrid Configurations

The hybrid configurations demonstrated significant improvements over the conventional RWD system. HRWD 1 consistently achieved 18% reduction in drying time across all operating conditions, while HRWD 2 achieved a 37SS% reduction. The enhanced performance of HRWD 1 can be attributed to the supplemental infrared heating, which provides additional thermal energy directly to the product surface, increasing the rate of moisture evaporation. The further improvement in HRWD 2 results from the combined effects of infrared heating and forced convection, which enhances moisture removal from the product surface and reduces the boundary layer resistance to mass transfer.

The moisture removal rates followed the same trend, with HRWD 2 achieving the highest rates across all conditions. At 98°C and 0.8 m/min, the MRR values were 13.2 g/min for CRWD, 16.5 g/min for HRWD 1, and 22 g/min for HRWD 2. These results demonstrate that the hybrid configurations can substantially improve the productivity of the RWD system without compromising product quality.

3.5 Drying Kinetics

The drying behaviour of the proposed solar-assisted RWD system was evaluated by combining the predicted temperature field with the moisture diffusion model. The simulated drying kinetics (Fig. 4) indicated that the solar-assisted RWD system substantially reduced the drying duration compared with conventional hot-air drying. For typical fruit pulps, complete drying was achieved within approximately 15–40 min, depending on the operating conditions, corresponding to a significant reduction in drying time compared to conventional methods.

The experimental drying profile consisted of a short constant-rate period followed by a prolonged falling-rate period, which is characteristic of moisture removal from biological materials. This behaviour agrees well with experimental observations reported for dragon fruit and aloe vera dried using the Refractance Window technique [10,13]. The relatively low product temperature maintained throughout the process promoted rapid moisture removal while limiting thermal damage, thereby reducing the possibility of case hardening and preserving the nutritional quality of the dried material.

3.6 Model Validation

To validate the CFD model, the predicted temperatures were compared with experimental measurements obtained from the thermocouples installed at key locations. The comparison showed good agreement between the simulated and experimental results, with a maximum deviation of approximately 5°C. The temperature predictions for the product surface (T5) showed the closest agreement, with a mean absolute error of 2.3°C. The slightly larger deviations observed for the air temperature measurements (T6) can be attributed to the inherent fluctuations in natural convection flows and the limitations of the steady-state assumption in the CFD model.

The validation results confirm that the developed CFD model provides a reliable representation of the thermal behaviour of the solar-assisted RWD system. The model can therefore be used as a predictive tool for evaluating design modifications and optimizing operating conditions without the need for extensive experimental testing.

3.7 Energy Efficiency

The thermal efficiency of the proposed solar-assisted RWD system was evaluated using the CFD predictions and compared with values reported in previous experimental studies. The numerical analysis indicated an average thermal efficiency in the range of 35–40%, which exceeds the efficiencies commonly reported for open sun drying (10–15%) and conventional solar cabinet dryers (20–25%) under similar operating conditions [6,27].

The improved thermal performance is primarily associated with the efficient transfer of heat from the circulating hot water to the product through the Mylar membrane. In addition, the insulated drying chamber reduces thermal losses to the surroundings, while the relatively uniform temperature distribution enhances moisture removal over the entire drying surface. These combined effects contribute to higher energy utilization and demonstrate the potential of the solar-assisted RWD system as an efficient and environmentally sustainable drying technology.

3.8 Product Quality Implications

The quality of the dried product is an important criterion for assessing the performance of any drying system. Previous studies have shown that products processed using RWD retain greater amounts of phenolic compounds, antioxidant activity, and natural pigments than those dried by conventional hot-air or freeze-drying techniques [10,17,20]. These improvements are generally associated with the relatively

low operating temperature and uniform heat transfer characteristics of the RWD process, both of which help limit thermal degradation of heat-sensitive constituents.

For example, Dadhaneeya et al. [10] reported that dragon fruit puree dried by RWD preserved more than 80% of its antioxidant activity, whereas hot-air-dried samples retained less than 60%. Similar trends have been observed for aloe vera and goldenberry, where higher retention of bioactive compounds and improved colour characteristics were obtained using the RWD technique [11,13]. The CFD analysis performed in the present study predicts a nearly uniform temperature field within the drying chamber, providing a numerical explanation for the enhanced quality retention reported in these experimental investigations.

The results demonstrate the potential of solar-assisted refractance window drying as a sustainable alternative for agricultural product dehydration. Solar thermal energy provides a renewable heat source, while improved thermal and airflow uniformity enhances drying performance and resource utilization. The study primarily supports SDG 7 (Affordable and Clean Energy) through renewable solar energy use and SDG 12 (Responsible Consumption and Production) through improved drying efficiency. It also has potential relevance to SDG 2 (Zero Hunger) by supporting food preservation and reducing post-harvest losses. However, these sustainability benefits are considered potential contributions, as a detailed life cycle assessment and direct energy and emission measurements were beyond the scope of this study.

4. Conclusion

A solar-assisted Refractance Window Drying (RWD) system was designed, fabricated, and experimentally evaluated to assess its thermal behaviour and drying performance for food processing applications. The integration of solar thermal energy with the RWD process provides an alternative to conventional drying technologies by improving heat utilization and creating more uniform drying conditions. The proposed configuration addresses several limitations associated with traditional drying methods, including uneven temperature distribution, prolonged drying periods, excessive energy consumption, and deterioration of heat-sensitive food components.

The three-dimensional CFD model successfully predicted the temperature field, airflow characteristics, and moisture transport within the drying chamber. The simulation results indicated that the product surface temperature remained within 55–65°C, providing favourable conditions for drying fruits, vegetables, and other temperature-sensitive materials. The predicted airflow pattern was governed by buoyancy-driven natural convection, which continuously removed moisture from the drying chamber and promoted stable drying conditions.

Experimental investigations demonstrated that the hybrid RWD configurations significantly improved drying performance compared to the conventional system. HRWD 1 achieved a 20% reduction in drying time, while HRWD 2 achieved a 40% reduction across all operating conditions. The highest moisture removal rate of 22 g/min was obtained with HRWD 2 at 98°C and 0.8 m/min belt speed. The drying time

decreased with increasing hot water temperature and decreased with increasing belt speed, with temperature having a more pronounced effect.

The numerical evaluation showed that the thermal efficiency of the proposed system ranged between 35 and 40%, exceeding the values commonly reported for conventional solar cabinet dryers. The moderate operating temperature and nearly uniform heat distribution are expected to improve the retention of antioxidants, phenolic compounds, natural pigments, and other quality attributes that are susceptible to thermal degradation. Comparison of the numerical predictions with experimental data showed a maximum deviation of less than 5%, demonstrating that the developed CFD model provides a reliable representation of the thermal behaviour of the solar-assisted RWD system.

The results of this study indicate that the combination of solar thermal energy and Refractance Window Drying can improve drying efficiency while maintaining favourable product quality. The validated numerical model also provides a useful tool for analysing heat transfer and airflow characteristics, enabling the evaluation of design modifications before prototype development. These features make the proposed system a promising option for sustainable food drying, particularly in regions with high solar radiation where decentralized agricultural processing is required.

Further investigation should focus on scaling the system to pilot and industrial capacities and evaluating its performance under actual climatic conditions. The incorporation of thermal energy storage, such as phase change materials (PCMs), may improve operational stability during periods of fluctuating solar radiation. Future studies may also integrate optimization techniques with CFD simulations to refine system geometry, operating parameters, and energy utilization, thereby supporting the development of high-performance solar-assisted drying systems for commercial food processing.

From a sustainable development perspective, the developed solar-assisted refractance window dryer contributes primarily to SDG 7 through renewable solar thermal energy utilization and SDG 12 through improved thermal and resource efficiency, while efficient drying has potential relevance to SDG 2 through improved post-harvest preservation and reduction of food losses.

Declarations

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Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

Declaration Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contribution

Gayatri S. Patil: Conceptualization, methodology, investigation, experimental work, development of the solar-assisted Refractance Window Drying system, CFD modelling and simulation, data collection, data analysis, visualization, and writing—original draft. Dr. K. R. Patil: Supervision, conceptualization, methodology, interpretation of results, critical review and editing of the manuscript, and project guidance.

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Figures

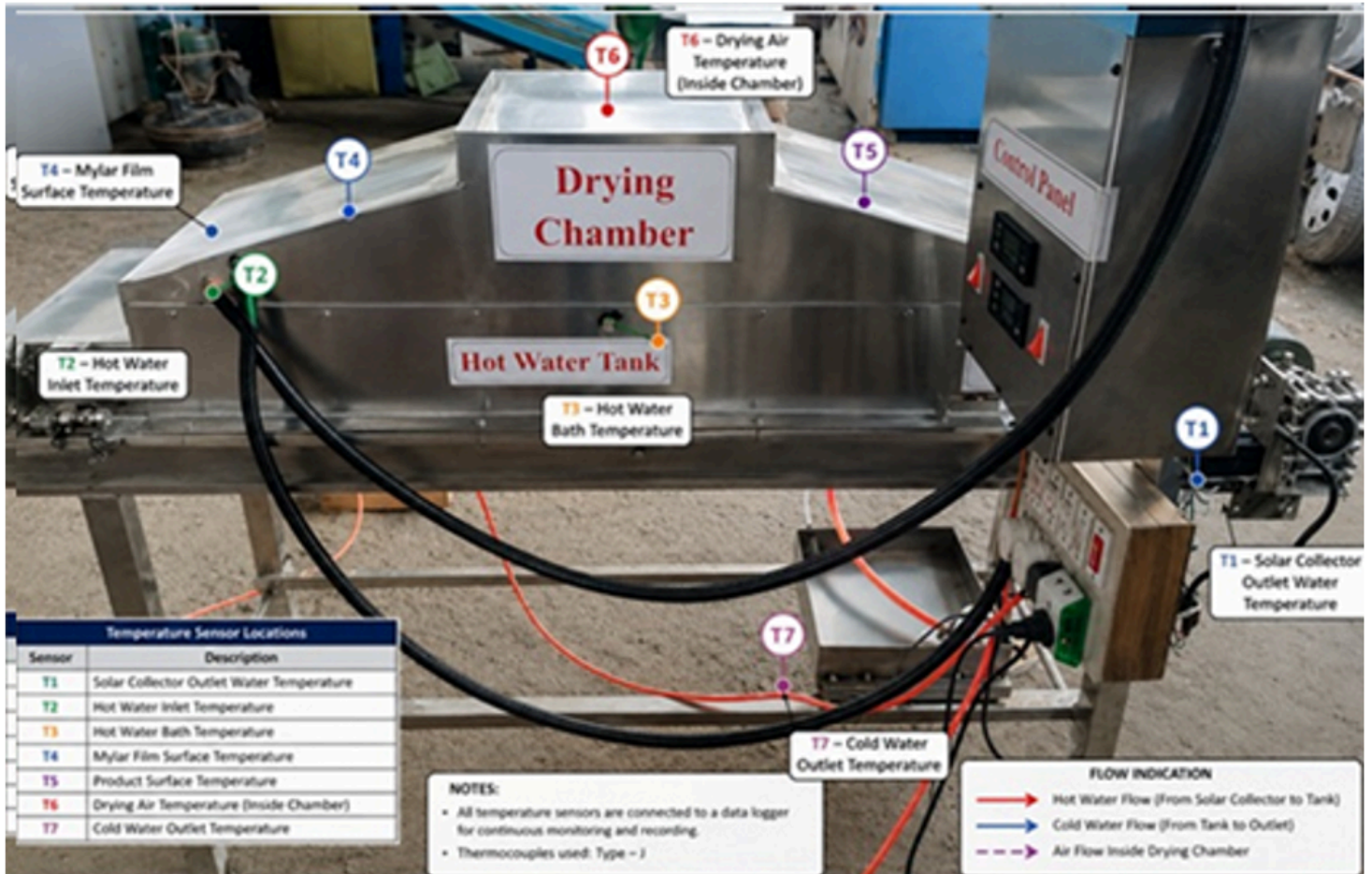


Figure 1

Experimental setup of the developed hybrid solar PV assisted RWD system

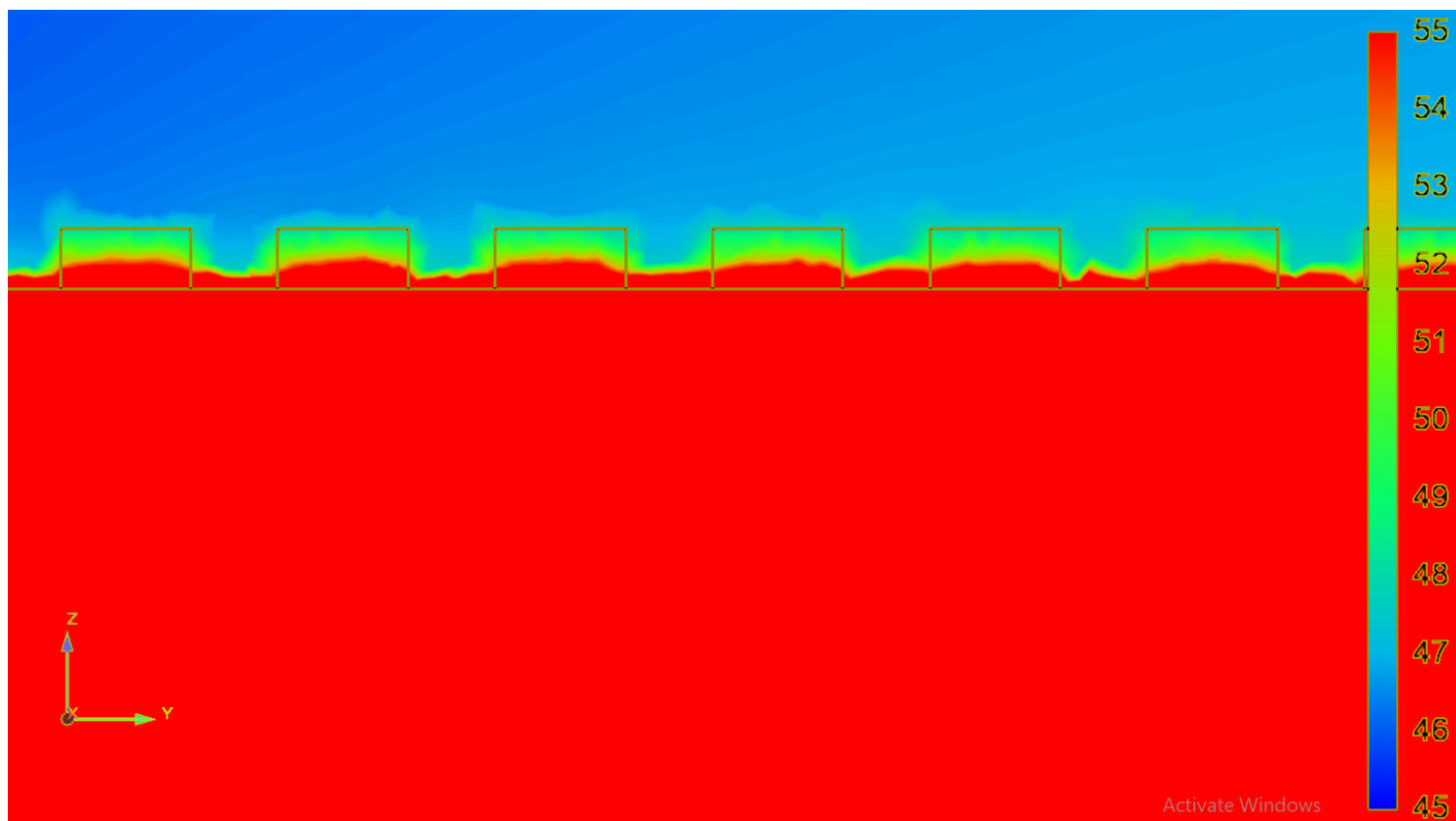


Figure 2

CFD-simulated temperature distribution in the solar RWD drying chamber

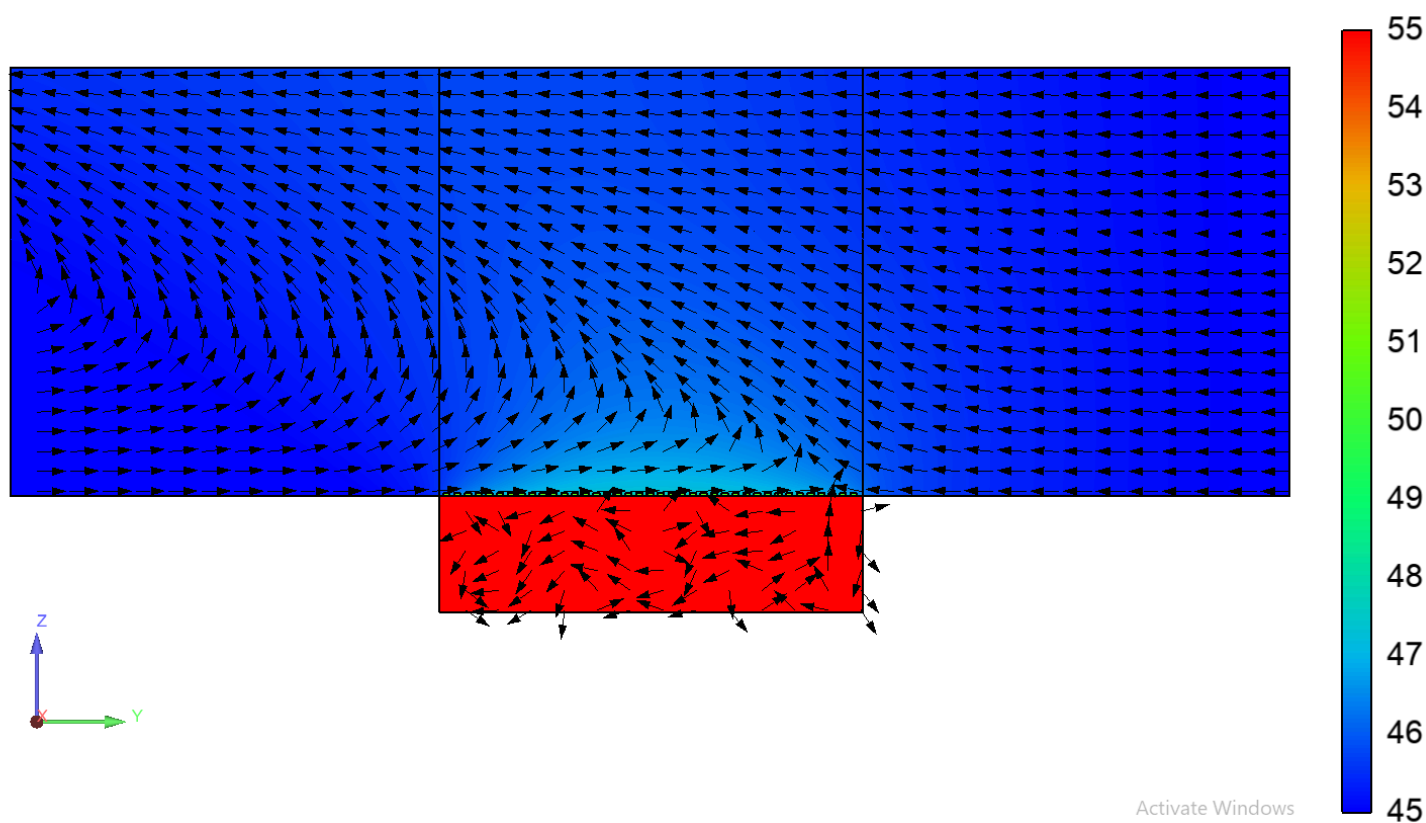


Figure 3

CFD-simulated airflow contours inside the solar RWD chamber

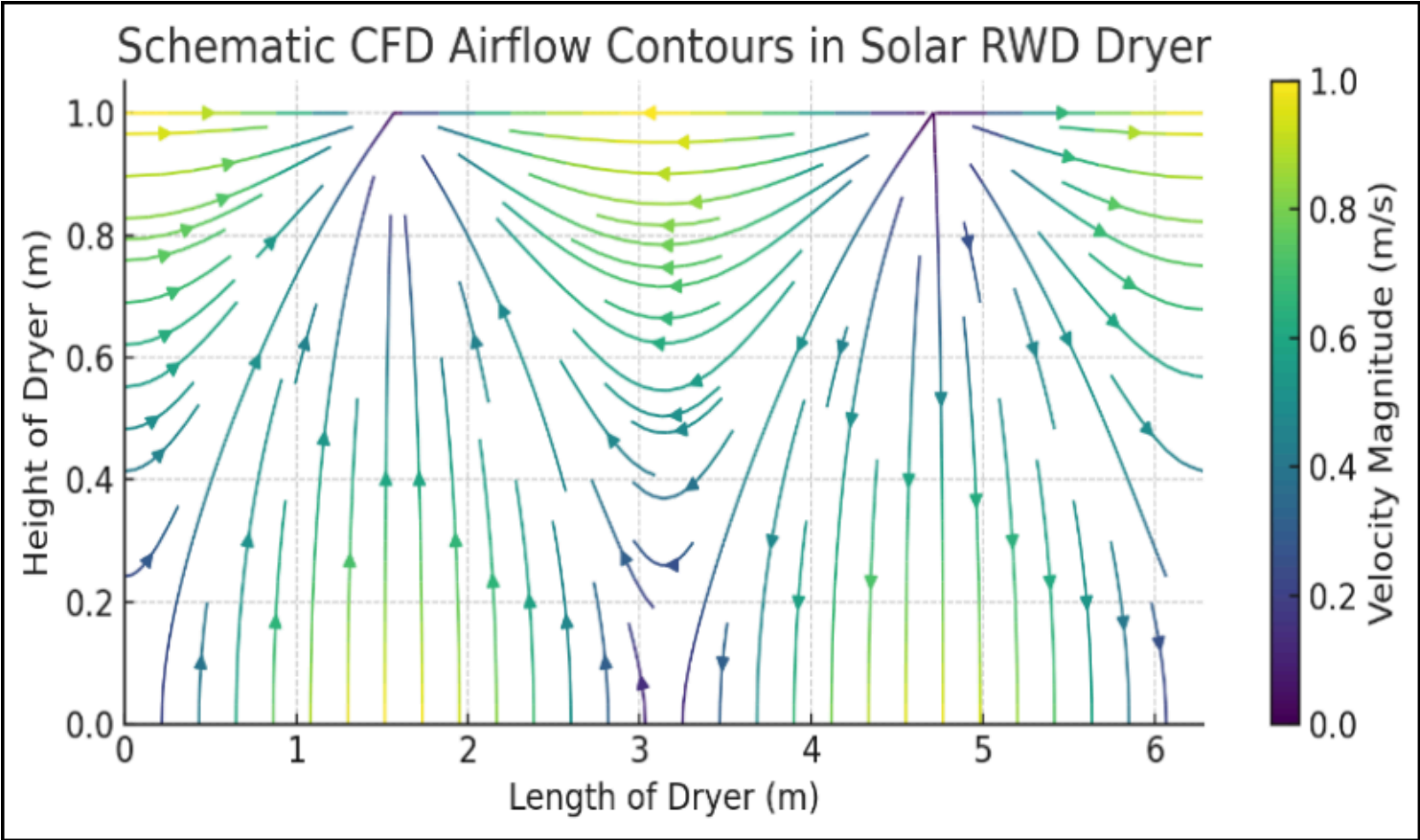


Figure 4

Simulated drying kinetics of fruit puree in the solar RWD system