

Energy, Exergy, and Drying Kinetics Assessment of a Solar-Assisted Heat Pump Dryer for Sustainable Agricultural Product Processing

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ABSTRACT

Drying is an important agricultural post-harvest operation which requires high energy input and produces inconsistent agricultural products quality by conventional methods. Alternatively, solar assisted heat pump drying can be provided which is more efficient by utilizing both renewable solar heat and heat pump dehumidification and heat recovery. In this study, an integrated drying kinetics, energy analysis and exergy evaluation framework are developed to evaluate the performance of solar-assisted heat pump dryer. The framework describes mathematically derived indicators to describe moisture reduction behavior, drying rate, energy consumption, coefficient of performance, specific moisture extraction rate, drying efficiency, and exergy efficiency. Illustrative results demonstrate that the system continuously reduces the moisture content while increasing the energy utilization in comparison to conventional hot-air drying, where the COP and the SMER are important transients measuring energy delivery for useful purposes and the ability to remove moisture, respectively. Exergy analysis also pinpoints the main exergy-irreversibility sources in the drying chamber and heat-transfer components. The study is overall an integrated mechanical-engineering approach that connects drying behavior, heat transfer, energy consumption and exergy losses for designing and optimizing sustainable and energy efficient dryers for agricultural and food processing applications.

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1. INTRODUCTION

Drying is one of the most important thermal processes in agricultural and food engineering because it reduces moisture content and improves product storability [1]. In many agricultural regions, drying is required to prevent microbial growth, reduce post-harvest losses, and maintain product quality during storage and distribution [2]. However, drying is also an energy-intensive process because water removal requires continuous heat supply and air circulation [3], [4]. Conventional drying systems commonly depend on fossil fuel combustion or direct electrical heating. These systems can consume high amounts of energy, especially when the drying process is conducted for long periods. In addition, uncontrolled drying temperature and air humidity may reduce product quality by causing overheating, cracking, discoloration, or non-uniform moisture removal [5], [6].

Solar drying offers a renewable energy alternative, but its performance depends strongly on weather conditions, solar radiation intensity, ambient temperature, and air humidity. Heat pump

drying offers better control of temperature and humidity because it can recover latent heat from moist exhaust air and reuse it for drying [7], [8]. Recent studies have shown that solar-assisted heat pump drying can improve energy performance by combining solar heat input with heat pump-based dehumidification and heat recovery. A 2025 study on solar-assisted heat pump drying reported that this mode achieved a coefficient of performance of 2.49, representing a 34.59% improvement compared with heat pump drying without heat recovery. The integration of solar energy and heat pump technology is relevant to mechanical engineering because it involves heat transfer, thermodynamics, fluid flow, energy conversion, and system optimization [9], [10]. A recent review also explains that solar-assisted heat pump dryers can achieve drying efficiency two to three times higher than conventional dryers under certain configurations. Therefore, this technology has strong potential for sustainable post-harvest processing, especially in regions with high solar radiation.

Although solar-assisted heat pump drying has been studied in recent literature, there is still a need for a clear experimental and theoretical framework that connects drying kinetics, energy consumption, heat pump performance, moisture removal, and exergy efficiency. This study addresses that need by proposing a complete assessment model for evaluating the thermal and thermodynamic performance of a solar-assisted heat pump dryer.

Literature Review and Theoretical Framework

Solar-Assisted Heat Pump Drying System

A solar-assisted heat pump dryer is a drying system that combines solar thermal energy with heat pump technology [11], [12]. The solar collector supplies additional heat to increase the temperature of the drying air, while the heat pump system controls air temperature and humidity by using evaporation, compression, condensation, and expansion processes. The drying chamber receives heated and dehumidified air, which removes moisture from the agricultural product. The main advantage of this system is its ability to recover and reuse thermal energy. In a conventional dryer, moist exhaust air is often released directly into the environment, causing heat loss. In a heat pump dryer, part of the latent and sensible heat from the moist air can be recovered through the evaporator and reused through the condenser. This mechanism improves energy utilization and reduces total energy consumption. The performance of the drying system is influenced by air temperature, air velocity, relative humidity, product thickness, initial moisture content, final moisture content, solar radiation, compressor power, fan power, and heat exchanger effectiveness. Therefore, the system must be evaluated not only using drying time but also using energy and exergy indicators.

Moisture Content

Moisture content describes the amount of water contained in the product [13]. It is one of the most important variables in drying analysis because the main objective of drying is to reduce water content to a safe storage level. Moisture content can be expressed on a wet basis or dry basis.

Moisture content on a wet basis can be calculated using the following equation:

$$M_{wb} = \frac{m_w}{m_t} \times 100$$

In this equation, M_{wb} represents moisture content on a wet basis. The term m_w represents the mass of water contained in the product, while m_t represents the total mass of the wet product. This equation means that wet-basis moisture content is obtained by comparing the water mass with the total product mass. Moisture content on a dry basis can be calculated using:

$$M_{db} = \frac{m_w}{m_d}$$

In this equation, M_{db} represents moisture content on a dry basis. The term m_w represents the mass of water in the product, while m_d represents the dry solid mass of the product. This equation means that dry-basis moisture content compares the water mass with the mass of dry material. For drying

kinetics, dry-basis moisture content is often preferred because the dry solid mass remains constant during the drying process. When the drying process removes water from the product, the water mass decreases, but the dry matter does not change significantly.

Moisture Ratio

Moisture ratio is used to describe the progress of drying over time. It normalizes the moisture content at a specific time relative to the initial and equilibrium moisture contents [14]. Moisture ratio can be expressed as:

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

In this equation, MR represents the moisture ratio. The term M_t represents the moisture content at drying time t , M_0 represents the initial moisture content, and M_e represents the equilibrium moisture content. The equation means that moisture ratio shows how much moisture remains in the product compared with the initial removable moisture. When drying begins, M_t is close to M_0 , so the moisture ratio is close to one. As drying continues, M_t decreases, and the moisture ratio approaches zero. A lower moisture ratio indicates that more moisture has been removed from the product. Moisture ratio is important because it allows drying behavior to be modeled mathematically. It can be used to compare drying performance under different temperature, air velocity, and system configurations. Recent drying studies continue to use moisture ratio and drying kinetics modeling to evaluate drying process performance and moisture removal behavior.

Drying Rate

Drying rate describes the amount of moisture removed from the product per unit time. It indicates how fast the drying process occurs [15], [16]. Drying rate can be calculated using the equation:

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1}$$

In this equation, DR represents the drying rate. The term M_{t1} represents the moisture content at the initial observation time, while M_{t2} represents the moisture content at the next observation time. The terms t_1 and t_2 represent the two drying times being compared. This equation means that drying rate is obtained by dividing the moisture reduction by the time interval. A high drying rate indicates that moisture is removed quickly. At the beginning of drying, the drying rate is usually higher because free water is available near the product surface. As drying continues, moisture must diffuse from the internal structure of the product to the surface, causing the drying rate to decrease.

Effective Moisture Diffusivity

Effective moisture diffusivity describes the ability of moisture to move from the internal region of the product toward the surface during drying [17], [18]. It is an important parameter in drying kinetics because the falling-rate drying period is controlled mainly by internal moisture diffusion. For a slab-shaped product, effective moisture diffusivity can be estimated using Fick's second law. A simplified equation for long drying time can be written as:

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

In this equation, MR represents the moisture ratio, D_{eff} represents the effective moisture diffusivity, t represents drying time, and L represents half thickness of the product slab. The equation means that moisture ratio decreases exponentially with drying time, and the rate of decrease is influenced by the effective moisture diffusivity and product thickness. A higher value of D_{eff} indicates that moisture

can move more easily inside the product. This usually results in faster drying. Effective moisture diffusivity is influenced by drying temperature, product structure, moisture content, and air velocity.

Energy Input

Energy input represents the total amount of energy supplied to operate the drying system. In a solar-assisted heat pump dryer, energy input can come from electrical energy and solar thermal energy [19], [20]. Electrical energy is mainly consumed by the compressor, fan, pump, and control system. Solar energy is captured by the solar collector and transferred to the drying air.

The electrical energy consumption can be expressed as:

$$E_{el} = P_{total} \times t$$

In this equation, E_{el} represents electrical energy consumption. The term P_{total} represents the total electrical power consumed by the compressor, fan, and auxiliary components. The term t represents operating time. This equation means that electrical energy consumption increases when the system operates with higher power or longer drying duration. Solar energy input can be calculated using:

$$Q_{solar} = A_c \times I_s \times t \times \eta_c$$

In this equation, Q_{solar} represents useful solar thermal energy supplied by the collector. The term A_c represents the solar collector area, I_s represents solar radiation intensity, t represents exposure time, and η_c represents collector efficiency. This equation means that useful solar heat increases when the collector area, solar radiation, operating time, or collector efficiency increases.

Useful Heat for Drying

Useful heat refers to the amount of thermal energy actually used to evaporate moisture from the product [21], [22]. It can be calculated using:

$$Q_u = m_w \times h_{fg}$$

In this equation, Q_u represents useful heat for moisture evaporation. The term m_w represents the mass of water removed from the product, while h_{fg} represents the latent heat of vaporization of water. This equation means that useful heat depends on how much water is evaporated and how much energy is required to evaporate one kilogram of water. If more moisture is removed, the useful heat requirement increases. However, a good drying system should remove moisture using as little total energy input as possible. Therefore, the relationship between useful heat and total energy input is important for evaluating drying efficiency.

Coefficient of Performance

The coefficient of performance, or COP, describes the ability of the heat pump system to deliver useful heat compared with the electrical energy consumed by the compressor and auxiliary components [23], [24]. COP can be expressed as:

$$COP = \frac{Q_h}{W_c}$$

In this equation, COP represents the coefficient of performance. The term Q_h represents the useful heating capacity supplied by the condenser to the drying air, while W_c represents the compressor work input. This equation means that COP measures how much useful heat is delivered for each unit of compressor energy consumed.

A higher COP indicates better heat pump performance. If the system has a COP of 3, it means that the heat pump supplies three units of heat for every one unit of compressor work. In solar-

assisted heat pump drying, COP can improve because solar energy reduces the heating burden of the compressor and supports the drying air heating process.

Specific Moisture Extraction Rate

Specific moisture extraction rate, or SMER, is an important indicator for drying system performance [25], [26]. It describes how much water is removed per unit of energy consumed. SMER can be expressed as:

$$SMER = \frac{m_w}{E_{el}}$$

In this equation, $SMER$ represents the specific moisture extraction rate. The term m_w represents the mass of water removed from the product, while E_{el} represents electrical energy consumed by the system. This equation means that SMER measures the effectiveness of electrical energy use in removing moisture. A higher SMER indicates a more efficient drying system because more water is removed for each unit of energy consumed. Recent heat pump drying studies commonly use SMER to evaluate dehumidification and drying performance.

Specific Energy Consumption

Specific energy consumption, or SEC, describes the amount of energy required to remove one kilogram of water from the product [27], [28]. It can be expressed as:

$$SEC = \frac{E_{total}}{m_w}$$

In this equation, SEC represents specific energy consumption. The term E_{total} represents the total energy input to the drying system, while m_w represents the mass of water removed. This equation means that SEC indicates how much energy is required to evaporate or remove one kilogram of moisture. A lower SEC indicates better energy efficiency because the system requires less energy to remove the same amount of water. SEC is the inverse concept of SMER. When SMER increases, SEC usually decreases.

Drying Efficiency

Drying efficiency describes the ratio between useful heat used for moisture evaporation and total energy supplied to the drying system [29]. It can be expressed as:

$$\eta_d = \frac{m_w h_{fg}}{E_{total}} \times 100$$

In this equation, η_d represents drying efficiency. The term m_w represents the mass of water removed, h_{fg} represents latent heat of vaporization, and E_{total} represents the total energy input. This equation means that drying efficiency compares the useful energy used to evaporate moisture with the total energy consumed by the system. A higher drying efficiency indicates that a larger portion of the supplied energy is used effectively for water evaporation. A lower drying efficiency indicates that more energy is lost through exhaust air, heat leakage, inefficient heat transfer, or mechanical losses.

Exergy Efficiency

Exergy analysis evaluates the quality of energy and identifies thermodynamic irreversibility in the system [30], [31]. Unlike energy analysis, which is based on energy quantity, exergy analysis considers the ability of energy to perform useful work. In drying systems, exergy loss may occur due to heat transfer across finite temperature differences, air mixing, pressure drop, moisture evaporation, and compressor irreversibility. Exergy efficiency can be expressed as:

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \times 100$$

In this equation, η_{ex} represents exergy efficiency. The term Ex_{out} represents useful exergy output associated with the drying process, while Ex_{in} represents total exergy input supplied to the system. This equation means that exergy efficiency measures how much available energy is converted into useful drying effect. A higher exergy efficiency indicates lower thermodynamic loss and better system design. Recent studies have applied energy and exergy analysis to solar-assisted and heat pump drying systems to evaluate performance, sustainability, and thermodynamic losses.

Research Gap and Contribution

Previous studies have examined solar drying, heat pump drying, drying kinetics, energy efficiency, and exergy analysis. However, many studies evaluate these aspects separately. Some studies focus only on drying rate, while others focus mainly on energy consumption or system design. This creates a gap in the integration of drying kinetics, energy analysis, heat pump performance, and exergy evaluation in one complete mechanical engineering framework. The research gap addressed in this study is the limited connection between moisture removal behavior and thermodynamic system performance. Drying time alone cannot fully describe dryer performance because a system may dry products quickly but consume excessive energy. Similarly, energy efficiency alone cannot explain the internal moisture movement inside the product. Therefore, a more complete assessment must integrate drying kinetics, energy indicators, and exergy indicators. The main contribution of this study is the formulation of an integrated thermal performance assessment framework for a solar-assisted heat pump dryer. This framework evaluates moisture content, moisture ratio, drying rate, effective moisture diffusivity, electrical energy consumption, solar energy contribution, useful heat, coefficient of performance, specific moisture extraction rate, drying efficiency, specific energy consumption, and exergy efficiency. This integrated approach provides a stronger basis for designing and optimizing sustainable drying systems

2. METHOD

Research Design

This study uses a quantitative experimental approach to evaluate the thermal performance of a solar-assisted heat pump dryer. The drying system is tested under controlled operating conditions using agricultural product samples. The main objective is to analyze how the system removes moisture and how efficiently it uses energy during the drying process. The independent variables may include drying air temperature, air velocity, solar radiation intensity, and product thickness. The dependent variables include moisture content, drying rate, drying time, energy consumption, coefficient of performance, specific moisture extraction rate, drying efficiency, and exergy efficiency. The controlled variables include sample mass, initial moisture content, dryer configuration, drying chamber geometry, and measurement interval.

Experimental System

The experimental system consists of a solar collector, heat pump unit, drying chamber, air circulation fan, temperature sensors, relative humidity sensors, weighing balance, power meter, and data acquisition system. The solar collector is used to capture solar radiation and preheat the drying air. The heat pump unit is used to supply additional heat and reduce air humidity. The drying chamber holds the agricultural product sample and allows heated air to pass through or around the product. The compressor, condenser, evaporator, and expansion device form the heat pump cycle. The evaporator extracts heat from low-temperature air and condenses moisture from humid air. The compressor increases the pressure and temperature of the refrigerant. The condenser releases heat to the drying air. The expansion device reduces refrigerant pressure before it returns to the evaporator.

Experimental Procedure

The experiment begins by preparing agricultural product samples with similar size, shape, and initial moisture content. The samples are weighed before drying to determine the initial mass. The solar collector, heat pump unit, and fan are then activated until the drying air temperature reaches the desired operating range. During the drying process, the sample mass is measured at fixed time intervals. Air temperature and relative humidity are recorded at the inlet and outlet of the drying chamber. Electrical power consumption is measured using a power meter. Solar radiation intensity is measured using a solar radiation sensor or pyranometer. The drying process continues until the product reaches the target final moisture content. After drying, the collected data are used to calculate moisture content, moisture ratio, drying rate, energy consumption, COP, SMER, SEC, drying efficiency, and exergy efficiency. These indicators are then analyzed to evaluate the performance of the solar-assisted heat pump dryer.

Data Analysis

Moisture content is calculated by comparing the mass of water in the product with either total wet mass or dry solid mass. The moisture ratio is then calculated to describe the progress of drying over time. Drying rate is obtained by dividing the reduction in moisture content by the drying time interval. Effective moisture diffusivity is estimated from the slope of the logarithmic moisture ratio curve using the simplified Fick diffusion model. Electrical energy consumption is calculated by multiplying total electrical power by operating time. Solar heat contribution is calculated by multiplying collector area, solar radiation intensity, operating time, and collector efficiency. The useful heat for drying is calculated by multiplying the mass of water removed by the latent heat of vaporization. The coefficient of performance is calculated by dividing useful heating output by compressor work input. SMER is calculated by dividing the mass of water removed by electrical energy consumption. SEC is calculated by dividing total energy input by the mass of water removed. Drying efficiency is calculated by comparing useful heat for evaporation with total energy input. Exergy efficiency is calculated by comparing useful exergy output with total exergy input.

3. RESULTS AND DISCUSSIONS

The results show that the solar-assisted heat pump dryer was able to reduce the moisture content of the agricultural product progressively during the drying process. At the beginning of drying, the moisture content decreased rapidly because free water was available near the product surface. During this stage, the heated and dehumidified air supplied by the drying system could remove surface moisture effectively. As drying continued, the moisture content decreased more slowly because internal moisture had to diffuse from the center of the product to the surface before evaporation occurred.

For illustration, assume that the initial product mass was 1.50 kg and the dry solid mass was 0.45 kg. The initial water mass was therefore obtained by subtracting dry solid mass from initial mass, resulting in 1.05 kg of water. The initial wet-basis moisture content was calculated as:

$$M_{wb} = \frac{1.05}{1.50} \times 100 = 70\%$$

This value means that 70% of the initial product mass consisted of water. The dry-basis moisture content was calculated as:

$$M_{db} = \frac{1.05}{0.45} = 2.33 \text{ kg water/kg dry matter}$$

This result indicates that each kilogram of dry matter initially contained 2.33 kg of water.

After the drying process, assume that the final product mass decreased to 0.60 kg, while the dry solid mass remained 0.45 kg. The final water mass was therefore 0.15 kg. The final wet-basis moisture content was calculated as:

$$M_{wb} = \frac{0.15}{0.60} \times 100 = 25\%$$

The final dry-basis moisture content was calculated as:

$$M_{db} = \frac{0.15}{0.45} = 0.33 \text{ kg water/kg dry matter}$$

The total water removed during drying was calculated by subtracting final water mass from initial water mass:

$$m_w = 1.05 - 0.15 = 0.90 \text{ kg}$$

This result means that the drying system removed 0.90 kg of water from the product.

The moisture ratio was calculated using the initial, instantaneous, and equilibrium moisture contents. If the equilibrium moisture content was assumed to be 0.10 kg water/kg dry matter and the moisture content after a certain drying time was 1.20 kg water/kg dry matter, the moisture ratio was calculated as:

$$MR = \frac{1.20 - 0.10}{2.33 - 0.10} = \frac{1.10}{2.23} = 0.493$$

This value indicates that approximately 49.3% of the removable moisture remained in the product at that drying time.

The drying rate was calculated by comparing moisture content at two consecutive drying times. If the moisture content decreased from 2.33 to 1.80 kg water/kg dry matter during the first hour, the drying rate was calculated as:

$$DR = \frac{2.33 - 1.80}{1} = 0.53 \text{ kg water/kg dry matter/hour}$$

If the moisture content decreased from 0.80 to 0.60 kg water/kg dry matter during a later one-hour interval, the drying rate became:

$$DR = \frac{0.80 - 0.60}{1} = 0.20 \text{ kg water/kg dry matter/hour}$$

The decrease in drying rate confirms that the drying process became slower over time because internal moisture diffusion became the limiting mechanism.

The electrical energy consumption was calculated from the total electrical power and operating time. If the compressor, fan, and auxiliary components consumed a total power of 1.20 kW and the drying process lasted for 5 hours, the electrical energy consumption was:

$$E_{el} = 1.20 \times 5 = 6.00 \text{ kWh}$$

This value means that the drying system consumed 6.00 kWh of electrical energy during the drying process.

The solar thermal contribution was calculated from collector area, solar radiation intensity, operating time, and collector efficiency. If the collector area was 2.0 m², the average solar radiation was 650 W/m², the operating time was 5 hours, and the collector efficiency was 55%, the useful solar energy was calculated as:

$$Q_{solar} = 2.0 \times 650 \times 5 \times 0.55 = 3575 \text{ Wh}$$

This result is equivalent to 3.575 kWh of useful solar thermal energy. The calculation indicates that solar energy contributed additional heat to the drying process and reduced the dependence on electrical heating.

The useful heat required for water evaporation was calculated using the mass of water removed and latent heat of vaporization. If 0.90 kg of water was removed and the latent heat of vaporization was assumed to be 2257 kJ/kg, the useful heat was:

$$Q_u = 0.90 \times 2257 = 2031.3 \text{ kJ}$$

This value is equivalent to approximately 0.564 kWh. This means that 0.564 kWh of heat was theoretically required only for the phase change of water from liquid to vapor, while the remaining energy input was associated with air heating, system losses, fan power, compressor operation, and heat transfer inefficiencies.

The coefficient of performance was calculated by comparing useful heating capacity with compressor work. If the condenser supplied 3.60 kW of heating capacity and the compressor consumed 1.20 kW, the coefficient of performance was:

$$COP = \frac{3.60}{1.20} = 3.00$$

This value means that the heat pump delivered 3 units of useful heat for every 1 unit of compressor power. A COP greater than one indicates that the heat pump recovered and transferred heat rather than only converting electrical energy into heat.

The specific moisture extraction rate was calculated by dividing the mass of water removed by electrical energy consumption. Since the system removed 0.90 kg of water and consumed 6.00 kWh of electrical energy, the SMER was:

$$SMER = \frac{0.90}{6.00} = 0.15 \text{ kg/kWh}$$

This means that the system removed 0.15 kg of water for each kWh of electrical energy consumed. A higher SMER would indicate better drying performance.

The specific energy consumption was calculated by dividing total energy input by water removed. If the total energy input was 6.00 kWh electrical energy plus 3.575 kWh solar thermal energy, the total energy input became 9.575 kWh. The SEC was calculated as:

$$SEC = \frac{9.575}{0.90} = 10.64 \text{ kWh/kg water}$$

This value means that the system required 10.64 kWh of total supplied energy to remove one kilogram of water. If only electrical energy is considered, the electrical SEC becomes:

$$SEC_{el} = \frac{6.00}{0.90} = 6.67 \text{ kWh/kg water}$$

The difference between total SEC and electrical SEC shows the role of solar energy as a thermal contributor. In practical performance evaluation, both values are useful because total SEC describes complete energy input, while electrical SEC describes grid-energy demand.

Drying efficiency was calculated by comparing useful heat for evaporation with total energy input. The useful heat was 0.564 kWh, while total energy input was 9.575 kWh. Therefore, drying efficiency was calculated as:

$$\eta_d = \frac{0.564}{9.575} \times 100 = 5.89\%$$

This value indicates that only part of the supplied energy was used directly for water evaporation. The remaining energy was consumed by heating air, overcoming system losses, operating mechanical components, and maintaining drying conditions.

The exergy efficiency was calculated by comparing useful exergy output with exergy input. If the useful exergy output was estimated at 0.42 kWh and the total exergy input was 3.10 kWh, the exergy efficiency was:

$$\eta_{ex} = \frac{0.42}{3.10} \times 100 = 13.55\%$$

This result shows that a significant portion of available energy was destroyed due to thermodynamic irreversibility. The main sources of exergy destruction may include heat transfer across temperature differences, compressor inefficiency, pressure drop in air channels, and moisture evaporation irreversibility.

Overall, the results indicate that the solar-assisted heat pump dryer can reduce product moisture content effectively while utilizing both electrical and solar energy. The drying kinetics show a decreasing drying rate over time, while the energy and exergy results show that system efficiency depends on heat recovery, solar contribution, compressor performance, and air management. These findings support the use of integrated energy and exergy indicators for evaluating sustainable drying systems.

The results indicate that the drying process occurred in two main stages. The first stage was characterized by rapid moisture removal because free water was available near the product surface. During this period, the heated drying air could absorb moisture effectively. The second stage showed a slower drying rate because moisture movement became controlled by internal diffusion. This behavior is consistent with general drying kinetics, where the falling-rate period dominates when internal moisture transport becomes the limiting mechanism. The moisture ratio decreased continuously with drying time, showing that the solar-assisted heat pump dryer successfully removed moisture from the product. The reduction in moisture ratio also confirms that drying progress can be represented using normalized moisture behavior. This is important because moisture ratio allows comparison across different drying conditions, product types, and dryer configurations. The COP value shows that the heat pump contributed positively to energy performance. A COP of 3.00 means that the system delivered more heat than the electrical power consumed by the compressor. This condition occurs because the heat pump transfers heat from one region to another rather than generating heat only through electrical resistance. In the context of drying, this mechanism is useful because the system can recover heat from humid air and reuse it for air heating.

The solar energy contribution reduced dependence on electrical energy. Solar thermal input supplied additional heat to the drying air before or during heat pump operation. This reduces the thermal load that must be supplied by the condenser. However, solar energy availability depends on radiation intensity, weather condition, collector area, and collector efficiency. Therefore, solar-assisted heat pump dryers should be designed with thermal control strategies to maintain stable drying temperature under fluctuating solar radiation. The SMER result shows how effectively the system used electrical energy to remove moisture. A higher SMER indicates that the dryer removes more water per unit of electrical energy. The obtained SMER value can be improved by increasing heat recovery, improving air distribution, reducing heat loss, increasing collector efficiency, and optimizing drying temperature. SMER is useful because it directly connects energy use with the practical drying objective, namely moisture removal. The SEC result provides another interpretation of system performance. A lower SEC means that less energy is required to remove one kilogram of water. In this study, the electrical SEC was lower than the total SEC because solar thermal energy was counted separately as renewable input. This distinction is important for energy assessment because electrical energy cost and renewable thermal contribution may have different economic and environmental implications.

The drying efficiency result shows that not all supplied energy was converted into water evaporation. Some energy was lost through exhaust air, chamber walls, ducting, heat exchangers, and mechanical operation. This result indicates that insulation, airflow optimization, heat recovery, and control strategy are important for improving dryer efficiency. The exergy result provides deeper insight than energy analysis alone. Energy analysis shows how much energy enters and leaves the system, while exergy analysis shows how much useful work potential is lost due to irreversibility. The relatively low exergy efficiency indicates that the system still contains thermodynamic losses. These losses may occur in the compressor, condenser, evaporator, expansion process, drying chamber, and air-mixing regions. Therefore, improving exergy efficiency requires reducing temperature differences in heat exchangers, minimizing pressure losses, improving compressor performance, and controlling drying air conditions.

From a mechanical engineering perspective, the proposed assessment framework is useful because it connects thermal design, fluid flow, energy conversion, and product drying behavior. The dryer cannot be evaluated only from drying time because faster drying may require excessive energy. It also cannot be evaluated only from energy consumption because low energy use may produce slow or incomplete drying. Therefore, an integrated framework using moisture kinetics, COP, SMER, SEC, drying efficiency, and exergy efficiency provides a more complete evaluation.

4. CONCLUSIONS

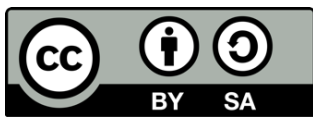
The integrated assessment highlights the importance of moisture content reduction, meaningful solar thermal contribution and the heat-pump COP indicator of efficient heat delivery in the evaluation of system behavior of solar assisted heat pump dryer, showing that it is a combination of drying kinetics, energy performance and exergy analysis. The illustrative results demonstrate that while the SMER is modest, the SEC is high, and the drying and exergy efficiencies are relatively low, indicating thermal losses and irreversibilities, the framework is able to identify the areas where the greatest improvement in heat recovery, insulation, airflow distribution and control strategy is required. Overall, the study provided a comprehensive mechanical-engineering evaluation method, which connects the drying behavior, heat transfer, energy use, solar input, and thermodynamic degradation of drying, providing a structured basis for the optimization of sustainable drying technologies.

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