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Efficient Tomato Drying Using Refractance Window-UV Equipped With a Heat Pump: Performance Optimization and Kinetic Modeling

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ABSTRACT

This study investigates the efficiency of a combined Refractance Window-Ultraviolet drying system with a heat pump for tomato processing. Experiments were conducted at three different temperatures: 60, 70, and 80°C, with and without the heat pump. The objective of this research was to evaluate drying time, determine relative humidity, and develop a model under varying conditions. The results showed that at 80°C, with the use of the heat pump, drying time was reduced to 91 minutes, and the final moisture content ratio reached 0.13. The Midilli model was used to analyze moisture reduction, which described the moisture changes well, with a coefficient of determination (R^2) higher than 0.99. The highest R^2 was observed at 70°C without the pump ($R^2 = 0.99834$), and the lowest was at 80°C without the pump ($R^2 = 0.98832$). These results indicate that the use of a heat pump can optimize the drying process and reduce time. This study demonstrates that the combined Refractance Window-Ultraviolet system with a heat pump can be an efficient method for processing heat-sensitive products such as tomatoes.

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INTRODUCTION

Drying, as one of the key methods in agricultural product processing, plays a vital role in reducing microbial growth, increasing shelf life, and decreasing transportation and storage costs. By reducing the moisture content of the product, this method prevents spoilage and degradation of quality (Moses et al., 2014). Traditional drying methods, such as sun drying and air drying, are associated with limitations due to long drying times, high energy consumption, and negative impacts on product quality, including color changes and reduced vitamin content (Calín-Sánchez et al., 2020; Hosseini et al., 2023). To address these issues, modern drying methods have been introduced, which are designed to optimize the drying process and preserve high product quality. These methods include infrared drying, microwave drying, freeze-drying, and vacuum drying (Pragati & Preeti, 2014). Each of these techniques has its own advantages. For example, infrared drying is particularly suitable for heat-sensitive products due to its high heat transfer rate and reduced drying time.

One of the advanced techniques that has recently attracted a lot of attention is the refractance window drying technology. This system is particularly suitable for heat-sensitive products such as purees and juices. This method uses a transparent plastic film that floats on the surface of hot water and effectively transfers heat to the product. This method has been able to significantly preserve product quality, reduce energy consumption, and shorten drying time (Rezvani, et al., 2022). Heat transfer in this system is simultaneously carried out through conduction, convection, and radiation, which helps to preserve the sensory and nutritional properties of the product (Rezvani, Mortezapour, et al., 2022).

One of the main challenges in the drying process is the high energy consumption, which accounts for about 12 to 20 percent of the total energy demand in the production industry (Bernaert et al., 2019). This high energy consumption not only leads to increased costs but also has negative impacts on the environment. Therefore, the use of energy-efficient systems such as heat pumps can help optimize temperature and reduce energy costs. The heat pump is capable of transferring heat from cold environments to hot environments and preventing temperature changes that may damage product quality (Deymi-Dashtebayaz et al., 2024). This device, especially in combination with refractance window dryers, can improve system performance and help preserve the sensory and nutritional properties of dried products.

In addition to the heat pump, the use of ultraviolet (UV-C) radiation also helps improve the quality of the process. UV-C radiation with a wavelength of 190-280 nanometers is effective in reducing microbial activity and delaying the spoilage of products (Bintsis et al., 2000; Erkan et al., 2001). This method can be used as a complementary solution to improve the quality and increase the shelf life of dried products. Various studies have shown that the use of modern drying systems can significantly improve the quality and speed of drying. For example, a study on the refractance window dryer for drying spirulina showed that the use of infrared radiation and photovoltaic-thermal solar collector helps reduce energy consumption and preserve the nutritional quality of spirulina (Rezvani, et al., 2022). Also, the use of heat pumps and solar energy in combined dryers for drying radish chips has obtained positive results (Singh et al., 2022).

Another study examined the effect of drying conditions using a refractance window dryer on the physical and microbiological properties of kefir powder. The results of this study show that the refractance window dryer significantly improves the quality and speed of drying due to its effective use of conduction and radiation for heat transfer. Also, the survival of beneficial microorganisms in powders produced by this method was better than freeze-drying (Tontul et al., 2021).

The main goal of this research is to evaluate the refractance window-ultraviolet dryer equipped with a heat pump for processing heat-sensitive products, focusing on tomatoes. In this study, the performance of the system was investigated through various experiments, and the Midilli model was used to describe the changes in moisture over time. The Midilli model, as a semi-empirical model, was able to accurately predict the behavior of moisture reduction. This research focuses on evaluating the performance of the system and the effect of the heat pump, and optimizing the drying process to increase efficiency and preserve the quality of the final product.

MATERIALS AND METHODS

Design of the System and Its Components

This research investigates the performance of a combined refractance window-ultraviolet dryer equipped with a heat pump. The main components of the system include a chassis, air passage channel, plastic conveyor belt resistant to heat, electric motor, water pump, hot water tank, blower, UV lamps, auxiliary tank with electric heater, compressor, condenser, evaporator, gas-containing tubes, and display and control systems. The system is equipped with sensors to measure temperature and humidity, and controllers to precisely adjust parameters. Additionally, a fuse is used as a protective element in electrical circuits, and an RCCB (25 amps, 30 milliamps) earth leakage protector is used for the safety of the entire system. A schematic of the proposed dryer is shown in Figure 1.

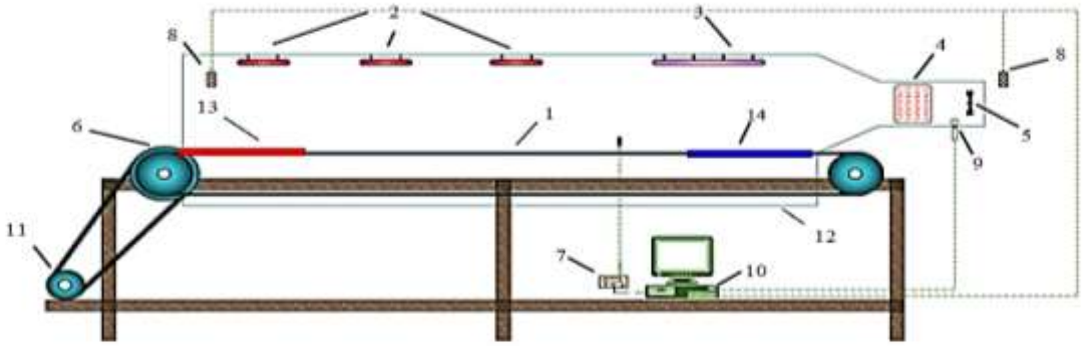

Figure 1. Schematic of the Reflexence Window-UV dryer equipped with a heat pump,1- Polyester conveyor belt, 3- UV lamp, 4- Heater, 5- Blower, 6- Belt and pulley, 7- Temperature controller, 8- Temperature and relative humidity sensor, 9- Anemometer, 10- Wattmeter, 11- Electric motor, 12- Hot water tank, 13- Evaporator unit, 14- Condenser unit.

Experimental Method

Experiments were conducted at three different temperatures of 60, 70, and 80 degrees Celsius, and in two modes with and without a heat pump. The goal of selecting these temperatures was to investigate the effects of different temperatures on drying time and final product quality. These temperatures are commonly used in drying processes for heat-sensitive products and help investigate the system's behavior under various conditions.

Sampling and Preparation

Fresh tomatoes were purchased from the local market in Kerman, Iran, and stored in the refrigerator (at a temperature of 4 ± 1 degree Celsius) until testing. About two hours before each experiment, 2 kilograms of tomatoes were transferred to room temperature and then cut transversely to a thickness of 3 ± 1 millimeters. This cutting method was used to provide uniform samples for more accurate evaluation.

Drying Process

Sliced tomatoes were placed on a plastic conveyor belt. The belt moves over the hot water tank using an electric motor, and the product dries along the path by receiving heat from the hot water tank and passing through a flow of hot air. A belt and pulley mechanism is used to transfer movement to the belt. UV lamps are installed in the ceiling of the channel for disinfection. The evaporator unit is installed at the end of the dryer to cool the product and return heat to the system.

Figure 2 shows the initial design of the Zeffctens Window dryer using Catia software.

Figure 2. Initial design of the Zeffctens Window dryer using Catia software

Measuring Instruments

To recording moisture changes during the drying process, relative humidity (RH) and temperature sensors were used, installed at various points of the dryer, including the inlet and outlet of the air passage channel and near the product, to accurately record moisture and temperature changes. These sensors continuously measured the relative humidity in the dryer environment and temperature, transmitting data to display and control systems. This study only examined changes in relative humidity (MR) over time with and without a heat pump. The Midilli model and its coefficients were also determined using MATLAB R2023b software. The well-known relationship for determining relative humidity is given below:

$$\text{Moisture ratio(MR)} = \frac{W_t - W_d}{W_0 - W_d} \qquad (1)$$

Modeling and Data Analysis

To describe moisture changes over time, the Midilli model was used. The Midilli model is one of the semi-empirical models used to describe the drying behavior of various materials, especially agricultural products. By combining exponential and linear characteristics, this model can accurately simulate the behavior of moisture reduction over time. The general formula of the Midilli model is as follows (Midilli et al., 2002):

$$MR = ae^{-kt^n} + bt \qquad (2)$$

k and n are model constants that must be obtained through experimental data. a and b are constants determined by the specific characteristics of the product and drying conditions. The Midilli model was analyzed using MATLAB R2023b software, and the model coefficients were accurately determined. This model was chosen due to its high accuracy and flexibility in describing various drying processes.

RESULTS AND DISCUSSION

Effect of Temperature and Heat Pump on Moisture Ratio

Figure 3 shows the changes in moisture ratio over time for tomatoes under two conditions: with and without a heat pump. The lowest drying time observed was at 80°C with a heat pump. Data show that, in this case, the moisture ratio decreases faster. The minimum recorded drying time under these conditions was 91 minutes, at which the moisture ratio reached 0.13.

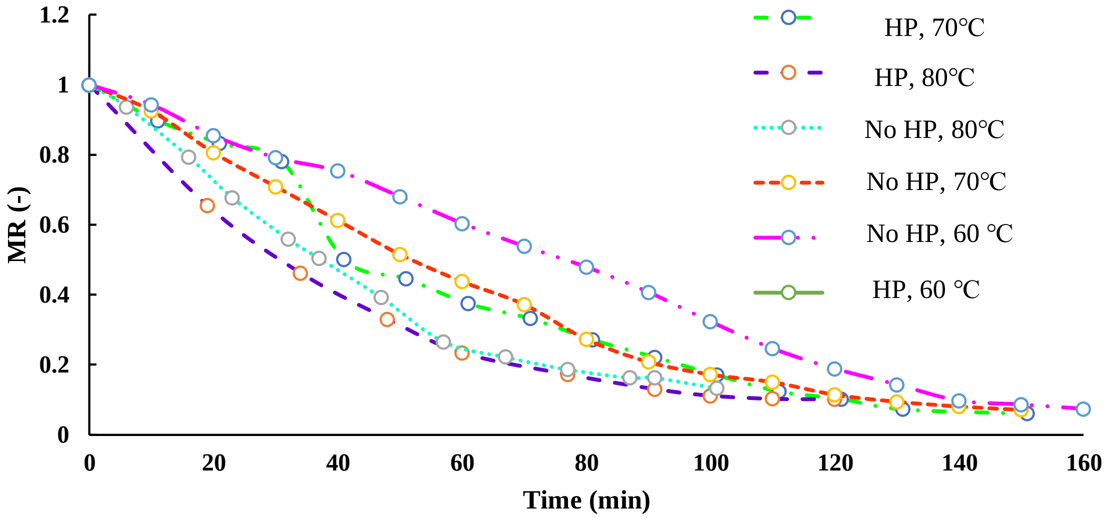

Figure 1. Change in tomato moisture over time at a thickness of 3 mm.

At higher temperatures (80°C), the reduction in moisture ratio was significantly faster than at lower temperatures (60°C). These changes clearly indicate the effect of temperature on evaporation rate and heat transfer in the drying process. At this temperature, using a heat pump helps accelerate the drying process by improving heat transfer and increasing the evaporation rate of moisture from the product surface. This improvement in drying speed is due to increased energy efficiency and improved thermal process efficiency, which allows moisture to be quickly removed from the product surface, improving the rate of moisture ratio reduction.

At lower temperatures, such as 60°C, the effect of the heat pump on the rate of moisture ratio reduction is less noticeable. This is due to the decrease in evaporation rate at lower temperatures and the reduced efficiency of the heat pump at these temperatures. In other words, at lower temperatures, more time is required to reduce the moisture ratio, and the heat pump has a lesser impact on improving the drying rate. This result emphasizes that for optimizing the drying process, selecting a higher temperature and effectively using the heat pump can lead to better efficiency, especially when faster moisture reduction is needed.

The Midilli model

Table 1 shows the parameters of the Midilli model and R^2 values for different conditions. The Midilli model is also fitted to the data in Figure 4.

Table 1. Midili model parameters and R^2 values.

Temp (°C)	Condition	R^2	n	k	a	b
80	HP	0.99323	0.37889	0.53742	3.471	-0.00038427
80	No HP	0.98832	0.15718	0.63203	2.299	-0.0066861
70	HP	0.9575	0.20278	0.3636	1.8094	-0.0062189
70	No Hp	0.99834	0.28574	0.18652	1.4132	-0.0054987
60	Hp	0.99393	0.1967	0.098012	1.2161	-0.0075372
60	No HP	0.99714	-0.062561	0.16346	1.1547	-0.006886

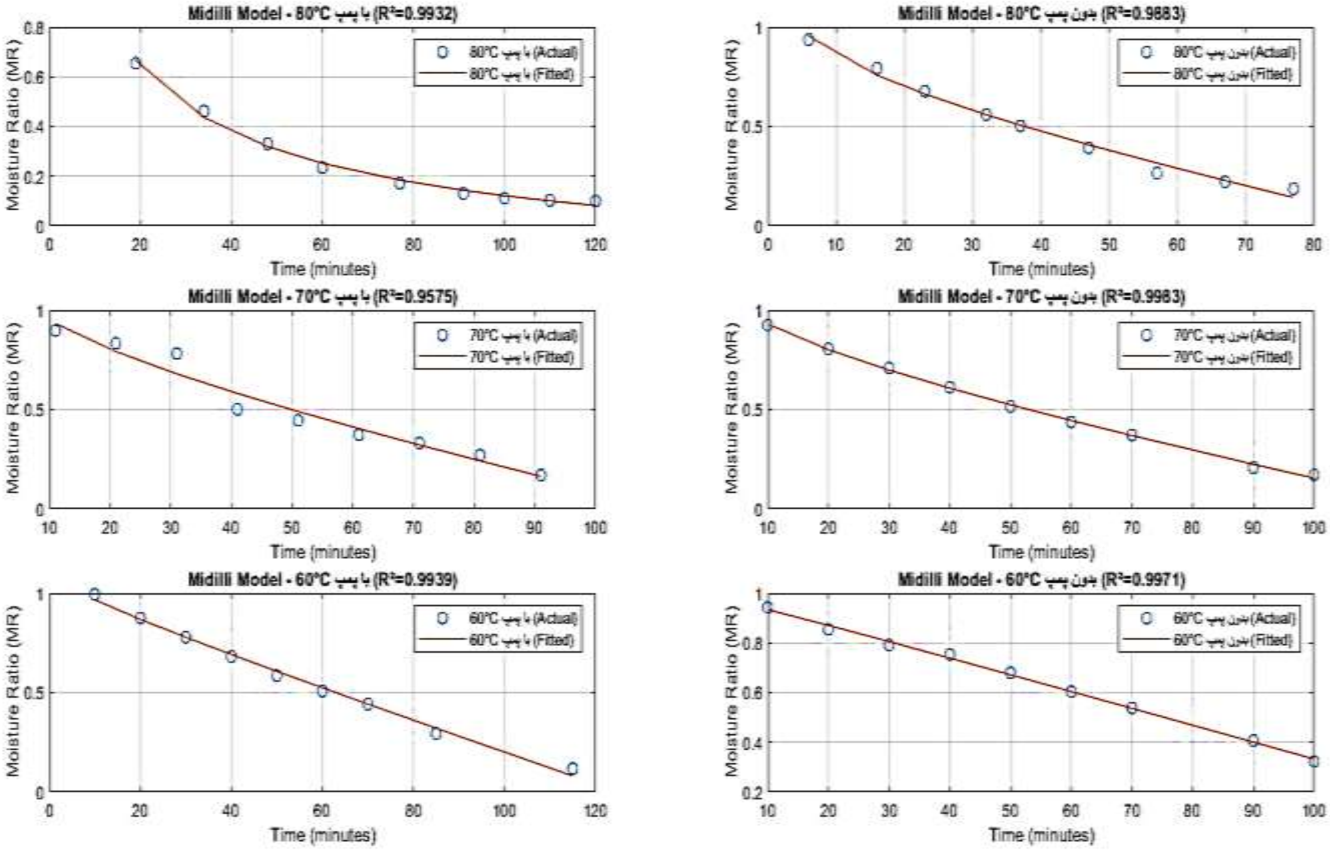

Figure 4. Midili model fitting.

In this section, the values of the Midilli model parameters for drying tomatoes under various conditions are examined. The parameter a, which represents the initial rate of moisture reduction, is higher in conditions with a heat pump than without, indicating a higher rate of moisture reduction with the heat pump. For 80°C with pump, the value of a is 3.471, and for 80°C without pump, the value of a decreases to 2.299. Generally, using a heat pump has a positive effect on the drying rate.

The parameter b, which specifies the effect of the time coefficient on the moisture reduction trend, shows negative values at high temperatures (80°C and 70°C), indicating an increase in the rate of moisture reduction over time. The value of b reaches -0.006861 in 80°C without pump, which indicates a more intense reduction in moisture compared to other conditions. At lower temperatures (60°C), the value of b is less negative, meaning a decrease in the rate of moisture reduction.

The parameter k, which represents the moisture variation coefficient, has higher values in conditions with a heat pump than without, indicating a greater reduction in moisture under these conditions. The parameter n, which represents the shape of the moisture reduction curve, has higher values in conditions with a heat pump than without, indicating a positive effect of the heat pump on the moisture curve changes.

The R^2 value, which indicates the model's fit to the actual data, is high in most conditions (above 0.8), indicating good accuracy of the Midilli model in predicting the moisture reduction trend. The highest R^2 value corresponds to 70°C without pump (0.99834

The highest R^2 value corresponds to 70°C without pump (0.99834), and the lowest R^2 value corresponds to 80°C without pump (0.98832). These results indicate a good fit between the model and the actual data under all conditions. The Midili model accurately predicts the moisture reduction trend, and the use of a heat pump significantly improves the efficiency of the drying process.

CONCLUSIONS

This study investigated and optimized the drying process of tomatoes using a heat pump system and UV lamp. The heat pump system effectively reduced the drying time and improved the uniformity of drying of the tomatoes. Analysis of the data obtained from the Midili model showed that the parameters a, b, k, and n significantly change under different conditions. Specifically, parameter a, which represents the initial rate of moisture reduction, is higher in conditions with a heat pump than in conditions without a pump, indicating a higher rate of moisture reduction. Parameter b, which specifies the effect of the time coefficient, is more negative at higher temperatures, indicating an increase in the rate of moisture reduction under these conditions. Also, parameters k and n indicate the positive effect of the heat pump on moisture reduction and changes in the moisture curve. The R^2 values also indicate a good fit between the model and the actual data under all conditions. According to the obtained results, it is suggested that further research be conducted on optimizing the parameters of the heat pump system and UV lamp. Also, examining the effect of these technologies on other agricultural products and large-scale economic evaluation can help develop practical applications of this system. Finally, this study showed that the integration of heat pump and UV lamp can significantly improve the performance of drying processes.

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