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Optimization of Forced Convective-Assisted Infrared Drying With Unheated Air for Eggplant Waste: Kinetics, Energy, GHG Emissions, and Quality Properties

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ABSTRACT

Food waste poses major environmental challenges globally. Using technologies that enhance biowaste value and protect the environment is a promising solution. This research examined the drying kinetics of eggplant (*Solanum melongena* L.) peel and pulp waste (EPPW) in an infrared (IR)-convective dryer that operates in forced convection of unheated air (UH-air). Operating parameters, including IR power (1000, 1500, and 2000 W), sample thickness (2, 4, and 6 mm), and UH-air velocity (0.5, 1.25, and 2 m/s), were evaluated to optimize drying performance. Response surface methodology (RSM) was employed for settings of operating variables, and the parameters' effects on drying characteristics and some quality attributes were analyzed using analysis of variance (ANOVA). Higher IR power, reduced sample thickness, and UH-air velocity decreased drying time while enhancing energy efficiency (EE). Effective moisture diffusivity values ranged from 1.046×10^{-10} to 1.113×10^{-9} m²/s, with specific moisture extraction rate (SMER) and specific energy consumption (SEC) at 0.07–0.24 kg/kWh and 4.18–14.30 kWh/kg [water evaporated], respectively. Greenhouse gas (GHG) emissions were minimized as IR power increased and as sample thickness and UH-air velocity decreased. In addition, total anthocyanin (TA) content increased significantly after drying (74.94–290.24 mg cyanidin-3-glucoside [CGE].100 g⁻¹ dm), and water activity ensured product stability. The Weibull distribution model best predicted drying kinetics. The drying parameters were optimized for the determined restrictions, leading to 2000 W IR power, 6 mm sample thickness, and 0.84 m/s UH-air velocity. IR-convective drying efficiently improves the drying process of biowaste. Future studies can apply this approach to various agricultural by-products to promote sustainability.

1 | Introduction

One of the significant global environmental challenges is implementing effective waste management. The largest share of waste sent to landfills is food waste, comprising almost half of the world's total waste generation and is characterized by its elevated moisture levels and microbial instability. This presents management challenges regardless of the source of waste. Furthermore,

decomposing these materials in landfills releases gases that enhance the greenhouse effect [1, 2]. Therefore, it is important to formulate a strategy to minimize these losses.

One approach in this effort is to turn this waste into invaluable by-products by integrating them into high-value food items. Alternatively, these residues can be converted into resources by employing intensified conversion procedures that can generate

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potentially sustainable bio-products, such as energy and fertilizers. Concerning this, it is currently argued that the value-adding of residues and agri-food by-products is increasingly recognized as a requirement as well as a chance to create new and high-value goods that can significantly influence the economic landscape of the industrial sector [3].

The fruit and vegetable sector produces more waste than other food processing industries, contributing 25%–30% of the overall waste. This waste can include a range of by-products such as peels, rinds, seeds, cores, pods, vines, skins, and pomaces [4]. Eggplant (*Solanum melongena* L.), which belongs to the Solanaceae family, is often discarded due to physical damage incurred during harvesting or handling, the presence of soft spots, damaged skin, or failure to meet market standards for size or shape. Thus, it becomes biowaste in the food sector [5]. In line with the strategy of converting biowaste into valuable by-products, it is worth noting that eggplant peels (EPPs) have a high anthocyanin and fermentable sugar content, making them a promising feedstock for biorefinery methods. Fermentable sugars are released from the remaining lignocellulosic residues after the anthocyanin extraction process via enzymatic hydrolysis. These sugars are subsequently used for bioethanol production through fermentation using the yeast strains *S. cerevisiae* and *K. marxianus* [6]. The residual substance from EPPs referred to as EPP waste (EPW) holds beneficial polyphenolic compounds and carbohydrates such as pectin and cellulose. Most of the sugars in EPW include cellulosic glucose, making it a valuable resource for the production of biochemical materials such as pullulan [7]. Mohammadi et al. [8] examined EPP as a deeply pigmented and underused by-product rich in anthocyanins. They extracted anthocyanins from the skin, stabilized them via cocrystallization, and tested their integration into pastille formulations with aerogels, advancing sustainable innovation in functional foods. Furthermore, Karimi et al. [9] stated that pectin derived from eggplant by-products demonstrates excellent functional properties. Eggplant by-products pectin (EBP) is classified as high methoxyl pectin (HMP), which is commonly utilized as a gelling and thickening agent in the food sector. They noted that, in light of numerous studies on pectin applications and considering the favorable attributes of EBP, it is highly likely to be well-suited for this industry in the near future. EBP also shows promising emulsifying properties and could be used for the production and stabilization of various types of emulsions [10].

Drying is the earliest approach to preserving food for a prolonged period and an efficient and popular protection method to stop microbial and enzymatic activity. Drying process requires a substantial amount of energy, with approximately 20%–30% of the energy consumed in the global industry being dedicated to drying materials. Additionally, the significant energy consumption of the dryers affects greenhouse gas (GHG) emissions and results in environmental implications, which is crucial. Since the energy utilized by dryers is derived from electricity or fossil fuels, and considering energy constraints, it is essential to select the most appropriate drying technique. This selection process should aim to minimize both the time and energy required for drying, thereby contributing to a reduction in GHG emissions [11].

Various drying techniques are commonly used in food processing and preservation, each influencing drying kinetics and product quality differently. Demircan et al. [12] studied seven drying

methods applied to bergamot peels—hot air, microwave, infrared (IR)-assisted microwave, freeze, IR, sun, and oven drying—and found that IR and IR-assisted methods effectively recovered phenolics from bergamot peel, with benefits of lower energy usage and better preservation of physicochemical properties. In another work, Demircan et al. [13] used spray drying to produce functional bergamot juice powder characterized by high antioxidant activity, phenolic content, and vitamin C levels. Sousa et al. [14] investigated the impact of drying temperatures (60, 70, and 80°C with 1 m/s air velocity) on the convective drying of red beetroot with peel, which was then processed into flour to minimize waste and reduce environmental pollution. Although forced convection is the most commonly employed method for industrial drying, convective drying has drawbacks, including a prolonged drying time, low efficiency, and significant energy consumption. It may also have a detrimental effect on the final product's quality [15]. For instance, Hosseinitabar et al. [16] studied the drying process of eucalyptus leaves by utilizing convective, IR, and a combination of convective-IR dryers at different temperatures (40–60°C), air speeds (0.5–1.5 m/s), and IR power levels (700–1500 W). The findings indicated that the combination dryer is an effective method for drying eucalyptus leaves compared to individual dryers. The combined convective-IR dryer (2–6.83 min) and the IR dryer (2–5 min) exhibited the shortest drying times relative to the convective dryer (2.92–18.33 h). The combined convective-IR dryer was noted for having the least energy usage (0.003–0.048 kWh), making it highly economical, while also lowering electricity costs in contrast to the IR dryer (0.045–0.087 kWh) and the convective dryer (1.115–1.836 kWh). Furthermore, the combined convective-IR dryer yielded the highest total phenolic content (TPC) in the plant extract (33.345–66.229 mg/g). The levels of DPPH across the three dryers were nearly identical, showing no significant differences.

The use of IR drying presents numerous benefits when compared to conventional drying methods. These benefits encompass reduced process time, improved energy efficiency (EE), even distribution of product temperature, high heat transfer coefficient, enhanced quality of final products, precise control over process parameters, and space-saving [17–19]. Several experimental studies have explored the drying of food and their waste materials using IR radiation, including tomato slices [20], okra [21], grape pomace [22], kinnow peel waste [23], olive pomace [24], and paddy [25]. Moreover, IR drying is recognized as a sustainable and adaptable technology that significantly reduces flue gas emissions [26]. When drying wet material employing IR radiation, the radiation penetrates through the exposed surfaces and spreads into the material by causing molecular vibrations. This energy is then transformed into heat within a layer beneath the surface. Consequently, the process's energy consumption decreases by eliminating the energy losses caused by heating the surrounding air [27, 28].

It has been suggested that hybrid drying procedures can combine the benefits of each technique and boost process efficiency more than if they are used independently. The most typical pairing is IR drying with convective drying using hot air. El-Mesery et al. [29] conducted an experimental study on tomato drying using convection hot air drying (0.5, 0.7, 1 m/s and 50, 60, and 70°C), IR radiation drying (0.15, 0.20, and 0.30 W/cm²), and combined IR-hot air convection drying (combining the mentioned conditions).

The lowest drying time and energy consumption were found to be achieved by combining drying (60°C, 0.30 W/cm², and 0.5 m/s), which was 40.8% and 91.7% less than hot air convection and 29.7% and 51.7% less than IR, respectively. Pandiselvam et al. [30] explored the influence of various drying procedures on the quality of coconut oil derived from copra, including IR drying (with a total heating capacity of 3 kW), hot air drying (50, 60, and 70°C with an air velocity of 2 m/s), and hybrid IR and hot air drying. According to the findings, the combined drying produced higher-quality coconut oil than the individual methods. They stated that this approach was particularly effective in the extracted coconut oil's oxidative stability, retention of advantageous components, and general quality qualities. However, it is essential to maintain stringent control over the drying conditions. Excessive drying temperatures, resulting from high IR intensity, may lead to product overheating and burning, as well as the degradation of vital nutritional components [31].

Although this hybrid technique has been investigated for processing different biomass, there is limited research on the drying of waste or residual biomass. Sui et al. [32] dried wine grape pomace using convection, IR, and a combination of both methods. It has been demonstrated that, in comparison to convective or IR drying alone, the combined drying method reduced the amount of damage done to the phenolic compounds in wine grape pomace. To dry sea buckthorn pomace, Zhou et al. [33] performed multiple drying approaches such as vacuum freeze drying, hot air drying, pulsed-vacuum drying, and IR-assisted hot air drying. IR-hot air drying was shown to have the highest drying rate (DR) and fastest drying time.

Natural air drying, which involves the convection of unheated air (UH-air) over moist material, has not received much attention in the literature. When combined with IR drying, it can guarantee increased process efficiency and provide the added advantage of preventing food damage from overheating [34]. Due to the limited number of works focused on this technique, it is worth emphasizing Sadeghi et al.'s [35] research on kiwifruit slices and Souza et al.'s [34] research on banana. As far as we know, no research has been done on drying that uses the combination of IR and forced convection of UH-air for eggplant as waste. Therefore, in this study, we applied the IR drying method combined with forced convection at ambient temperature to evaluate the effect of three operating parameters (IR power, sample thickness, and UH-air velocity) on drying kinetics, effective moisture diffusivity (D_{eff}), activation energy (E_a), specific moisture extraction rate (SMER), specific energy consumption (SEC), EE, GHG emissions, and some quality attributes, including water activity (a_w) and total anthocyanin (TA) content of the EPP and pulp waste (EPPW). This work also used mathematical modeling, which is essential for scaling up the drying process and understanding how moisture is transported through solids. Finally, the research optimized the EPPW drying process based on minimizing drying time, SEC, maximizing D_{eff} , and TA.

2 | Materials and Methods

2.1 | Collection of Waste Samples and Preparation

Eggplants deemed waste were collected in August 2024 from an agricultural field in Babol, a city in Mazandaran Province in Northern Iran (Figure 1a). The samples, originating from a local

Mazandaran landrace, were cultivated by an experienced farmer under sunny and open-field conditions. The region (36°32'N, 52°40'E) is characterized by a temperate climate. The crop was cultivated in rows on raised ridges in sandy-loam soil covered with plastic mulch to control weeds and reduce water loss. Throughout the growing period, organic fertilizers—primarily chicken manure—were applied regularly, and plants were irrigated via drip systems. The soil at the site had a pH between 6 and 6.5. Harvested eggplants measured 3.5–5 cm in diameter, 20–25 cm in length, and weighed roughly 150–255 g each, featuring green sepals and dark purple skin. A sufficient number of eggplants were collected to ensure multiple experimental repetitions if required. About 5 days postharvest, the eggplants were transported to the laboratory. Observed significant wrinkles and depressions, with decreased firmness in the peel and pulp prior to the drying process, confirmed a decline in both commercial and edible quality. The samples were washed and dried with a paper towel. Based on some physical and textural characteristics, the eggplants were cut into slices measuring 2, 4, and 6 mm in thickness and 10 cm in length (from the peel to the pulp). Only seedless pulp sections were used for the experiments. The EPPWs were then put in zip-lock bags and refrigerated for a full day at $4 \pm 1^\circ\text{C}$. On the following day, before the drying process began, approximately 30 g of the EPPW were placed under laboratory conditions ($20 \pm 1^\circ\text{C}$; relative air humidity: 30%–34%) for about 1 h to achieve stabilization. The required analyses were conducted 24 h after the completion of the drying process.

In order to determine the initial moisture content of the EPPW, the standard oven-drying procedure [36] was employed at 105°C for 24 h.

2.2 | Dryer Set-Up

Drying of EPPW was conducted in a combined IR-convective dryer, the schematic representation of which is provided in Figure 1b. The IR lamps were positioned at the top of the dryer, arranged in two parallel rows configuration. Each row contained four lamps, and each lamp had an output power of 250 W and emitted far-IR radiation. The distance between the EPPW and radiators during drying was 12 cm. A calibrated thermoanemometer (ST-3880, STANDARD company, Hong Kong) equipped with a built-in thermistor sensor was used to measure the material's surface temperature throughout the process. There was an aluminum sieve tray and an entrance door in the drying chamber to load and unload the tray. Airflow could easily flow into the drying chamber through holes at the bottom of the dryer and exit via the variable speed fan located on the walls. To ensure uniform airflow over the EPPW, there was a barrier made of sturdy quartz glass (high IR-transmittance) between the duct containing the aluminum tray and the IR chamber.

2.3 | Drying Procedure

The dryer was operated for a duration ranging from 1 to 1.5 h before the experiment commenced to ensure temperature stability and to prevent drift in the weighting caused by increased air temperature within the chamber [35]. During this period, the chamber temperature was continuously monitored to confirm the steady-state condition. The EPPWs were arranged in a uniform manner on the tray inside the drying chamber. In order to acquire the drying curves, the moisture reduction was consistently

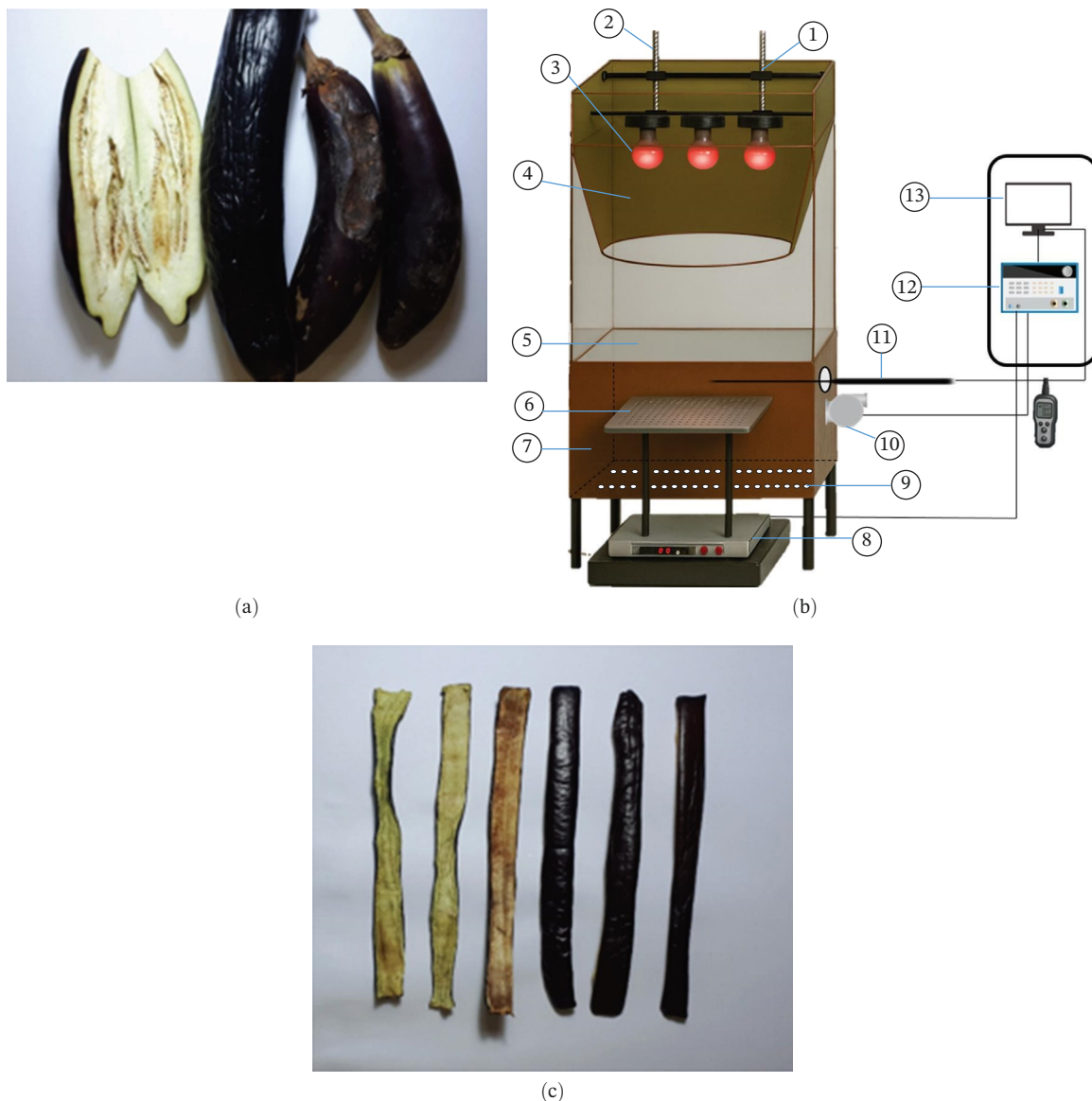


FIGURE 1 | (a) Eggplant peel and pulp waste (EPPW), (b) schematic diagram of the laboratory infrared-convective dryer—(1) distance adjustment screws, (2) threaded bar, (3) infrared lamps, (4) trapezoid cover, (5) quartz glass, (6) aluminum tray, (7) drying chamber, (8) balance, (9) holes, (10) fan, (11) thermo-anemometer, (12) control unit, and (13) computer—(c) dried EPPW.

monitored by a digital electronic balance (EK-6000i, A&D company, Japan) with an accuracy of ± 0.1 g. The PC was connected to the digital electronic balance to record the weight reduction of the EPPW at specific time periods (every second). The EPPWs underwent drying in the dryer until their final moisture content were reached to approximately 6% wet basis (Figure 1c) [37].

2.4 | Experimental Design

Prior to conducting experiments concerning the drying process of EPPW, the response surface methodology (RSM) and three-factor Box–Behnken design (BBD) were used to thoroughly investigate the impact of process variables on the reliant variables that were considered as the response. The RSM applies statistical and mathematical methods to fit a polynomial equation to experimental data. Hence, the effect of test variables on treatment results was explained while determining the interrelationships between test variables and representing the composed effects of all test variables in any

response. This modeling aims to simultaneously optimize these variables levels to obtain the best system performance. The optimal process parameters are routinely determined in the manufacturing industry for solving the problems in product quality or optimizing the manufacturing processes' cost-effectiveness [38]. Das et al. [39] and Dhake et al. [40] conducted recent studies utilizing RSM for multiobjective optimization in agri-food drying. The BBD is an efficient experimental design that minimizes resource consumption while maximizing effectiveness. It requires fewer experimental runs than alternative designs, making it a preferred choice. BBD effectively identifies linear and quadratic effects of variables, enhancing the precision of findings. It uses a three-level factorial approach focusing on midpoints and center points, offering advantages over central composite design (CCD) by reducing iterations and improving consistency. Overall, BBD is a cost-effective and feasible alternative to CCD in RSM [41], avoiding extreme axial points that expose temperature-sensitive compounds, such as anthocyanins, to excess heat, and it is fully compatible with the 250-W IR lamp

TABLE 1 | Experimental design of combined infrared-convective drying of eggplant peel and pulp waste (EPPW).

Run number	Infrared power (W)	Sample thickness (mm)	UH-air velocity (m/s)
1	1500 (0)	4 (0)	1.25 (0)
2	1500 (0)	4 (0)	1.25 (0)
3	1500 (0)	4 (0)	1.25 (0)
4	1500 (0)	4 (0)	1.25 (0)
5	2000 (+1)	2 (−1)	1.25 (0)
6	1000 (−1)	4 (0)	2 (+1)
7	1000 (−1)	4 (0)	0.5 (−1)
8	1500 (0)	2 (−1)	0.5 (−1)
9	1000 (−1)	6 (+1)	1.25 (0)
10	2000 (+1)	6 (+1)	1.25 (0)
11	1500 (0)	6 (+1)	0.5 (−1)
12	1500 (0)	6 (+1)	2 (+1)
13	2000 (+1)	4 (0)	0.5 (−1)
14	1500 (0)	4 (0)	1.25 (0)
15	1000 (−1)	2 (−1)	1.25 (0)
16	1500 (0)	2 (−1)	2 (+1)
17	2000 (+1)	4 (0)	2 (+1)

Note: Coded factor levels are set by −1 (lowest level), 0 (midpoint level), and +1 (highest level).

configuration used in this study. The independent variables chosen were IR power (X_1), sample thickness (X_2), and UH-air velocity (X_3), and their main effects were analyzed. Table 1 exhibits the experimental parameters and BBD levels employed in this study. This design comprised a total of 17 experimental tests, including five center points to ensure repeatability. Using the experimental data, a second-order polynomial equation can be derived through multiple regression analysis to fit the data [42].

$$Y = b_0 + \sum_{j=1}^k b_j X_j + \sum_{j=1}^k b_{jj} X_j^2 + \sum_i \sum_{<j=2}^k b_{ij} X_i X_j, \quad (1)$$

where Y is the predicted response, b_0 is the model intercept, b_j , b_{jj} , and b_{ij} are the linear, quadratic, and interactive regression coefficients, respectively, X_i and X_j are the independent variables, and k is the count of independent variables.

2.5 | Mathematical Modeling of the Combined Drying Curves

It is widely acknowledged that the main mechanism for moisture transfer during the falling rate period of drying is a gradient in liquid content. Due to the quick rate at which heat is transferred during drying, its impact is often disregarded. The Equation (2) demonstrates Fick's second law of diffusion, presented as a mass-diffusion formula applicable to drying food during the falling rate period [21].

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial^2 M}{\partial L^2}. \quad (2)$$

Initial and boundary conditions are represented by the following:

$$M = M_0 \quad 0 < z < L \quad \text{at } t = 0. \quad (2a)$$

$$\frac{\partial M}{\partial t} = 0 \quad z = 0 \quad \text{at } t > 0. \quad (2b)$$

$$-D_{\text{eff}} \frac{\partial M}{\partial z} = K_c (M_s - M_e) \quad z = L \quad \text{at } t > 0. \quad (2c)$$

Dimensionless moisture ratio (MR) defines the ratio of available moisture content at any time in EPPW samples to the initial moisture amount, obtained by Equation (3) [43]:

$$\text{MR} = M_t - M_e / M_0 - M_e, \quad (3)$$

where M_e , M_0 , and M_t are the equilibrium, the initial, and the mean moisture content at time t , respectively.

Slices might be dried close to dry solid content at the process. Thus, M_e is somehow small compared to M_t or M_0 , and it is regarded to be zero [35]. Therefore, MR can be rewritten as in Equation (4):

$$\text{MR} = M_t / M_0. \quad (4)$$

The DR of EPPW was computed using Equation (5) [19]:

$$\text{DR} = \frac{dM_t}{dt} = \frac{M_{t+\Delta t} - M_t}{\Delta t}. \quad (5)$$

Table 2 lists the eight thin-layer models chosen to fit with the experimental findings. Four statistical parameters—coefficient of determination (R^2), the root mean square error (RMSE), sum squared error (SSE), and the reduced Chi-square (χ^2)—determine the fit accurateness. The model with the highest R^2 and the lowest RMSE, SSE, and χ^2 was chosen as the best for estimating drying curves. Similar articles served as the basis for the statistical parameters used to compare the models, and the best-fitting model was ascertained using these criteria. This standardized

TABLE 2 | Mathematical models used for the prediction of eggplant peel and pulp waste (EPPW) drying kinetics.

Model name	Equation	References
Newton	$\text{MR} = \exp(-kt)$	Ayensu [44]
Logarithmic	$\text{MR} = a \exp(-kt) + c$	Yagcioglu [45]
Henderson and Pabis	$\text{MR} = a \exp(-kt)$	Henderson and Pabis [46]
Page	$\text{MR} = \exp(-kt^n)$	Page [47]
Wang and Singh	$\text{MR} = 1 + at + bt^2$	Wang and Singh [48]
Parabolic	$\text{MR} = a + bt + ct^2$	Sharma and Prasad [49]
Weibull distribution	$\text{MR} = a - b \exp[-(kt^n)]$	Weibull [50]
Midilli–Kucuk	$\text{MR} = a \exp(-kt^n) + bt$	Midilli et al. [51]

approach has been widely accepted in the literature for conducting such comparisons. In recent research papers, such as Tuncal and Doymaz [52], Agbede et al. [53], Chauhan et al. [54], and Haydary et al. [55], the authors have relied on similar parameters to evaluate and compare the fitness of various models. These parameters are obtained as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^N [\text{MR}_{\text{pre},i} - \text{MR}_{\text{exp},i}]^2}{\sum_{i=1}^N \left[\frac{\sum_{k=1}^N \text{MR}_{\text{pre},i}}{N} - \text{MR}_{\text{exp},i} \right]^2}, \quad (6)$$

$$\chi^2 = \frac{\sum_{i=1}^N (\text{MR}_{\text{exp},i} - \text{MR}_{\text{pre},i})^2}{N - z}, \quad (7)$$

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^N (\text{MR}_{\text{pre},i} - \text{MR}_{\text{exp},i})^2 \right]^{\frac{1}{2}}, \quad (8)$$

$$\text{SSE} = \frac{1}{N} \sum_{i=1}^N (\text{MR}_{\text{exp},i} - \text{MR}_{\text{pre},i})^2, \quad (9)$$

where $\text{MR}_{\text{pre},i}$ and $\text{MR}_{\text{exp},i}$ are the predicted and experimental dimensionless MRs, respectively, z is the number of constants, and N is the number of observations.

Higher R^2 and lower χ^2 , SSE, and RMSE values suggest a more acceptable fit between experimental data and the model.

2.6 | Determination of Effective Moisture Diffusivity (D_{eff})

Fick's second law of diffusion depicts the equation governing mass diffusion (Equation 2). An analytical solution can be found in Equation (10) with the following presumptions: moisture migration because of diffusion, symmetrical and uniform moisture distribution, constant temperature, negligible shrinkage, prolonged drying time, constant diffusion coefficients, and lack of any couplings between mass and heat transfers [56]:

$$\text{MR} = \frac{M_t}{M_0} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-[2n+1]^2 \pi^2 D_{\text{eff}} t}{4L^2}\right), \quad (10)$$

where t (s) is the drying time, D_{eff} (m^2/s) is the effective moisture diffusivity, and L (m) is the half-thickness of samples.

This Equation (10) can be simplified for a long drying time. Then, with the logarithm of sides and plotting the slope of the line (S), the effective diffusivity can be determined:

$$\ln \text{MR} = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}} t}{4L^2} \xrightarrow{\text{Plotting } [\ln(\text{MR})] \text{ vs. } (t)} S = (\pi^2 D_{\text{eff}} t) / 4L^2. \quad (11)$$

2.7 | Energy Analysis and Environmental Impact

2.7.1 | Determination of Activation Energy (E_a)

The concept of activation energy refers to the amount of energy that a system needs to initiate chemical or nuclear reactions or

other physical phenomena. The Arrhenius equation can be employed to ascertain the level of activation energy. This equation is resolved from the correlation between the experimental temperatures of drying and the effective moisture diffusivity values [57]:

$$D_{\text{eff}} = D_0 \exp(-E_a/RT). \quad (12)$$

For calculating the E_a (kJ/mol), Equation (12) can be written as follows, allowing to obtain the coefficient S :

$$\ln D_{\text{eff}} = \ln D_0 - \left(\frac{E_a}{R} \cdot \frac{1}{T} \right) \xrightarrow{\text{Plotting } (\ln D_{\text{eff}}) \text{ vs. } (1/T)} S = E_a/R. \quad (13)$$

In this context, D_0 (m^2/s) is the pre-exponential factor, R (J/molK) is the universal gas constant (8.314), and T (K) is the absolute air temperature.

2.7.2 | Determination of SEC

The amount of energy consumed by the IR dryer is obtained as the total energy used by the IR lamps and ventilator fan employed for air circulation. Therefore, SEC (kW h/kg [water evaporated]) was calculated as follows [58]:

$$\text{SEC} = \left(\underbrace{\sigma \times T^4}_{E_1 \times A_s \times t} + \underbrace{V^3/16600}_{E_2 \times t} \right) / M_w, \quad (14)$$

where E_1 (kW/ m^2) is the radiation energy, E_2 (kW) is the energy that blower consumes in each drying bout, σ (kW/ m^2K^4) is the Stefan–Boltzmann constant (56.7×10^{-12}), T (K) is the material temperature, V (m/s) is the air velocity, M_w (kg) is the mass of evaporated water, and A_s (m^2) is the drying surface.

2.7.3 | Determination of SMER

The ratio of moisture evaporation to energy supplied during the drying process is referred to as SMER (kg/kW h), as stated by Mugi and Chandramohan [59].

$$\text{SMER} = M_w / (E_1 + E_2). \quad (15)$$

2.7.4 | Determination of EE

EE was computed as follows [60]:

$$\text{EE}\% = (Q_w / (E_1 + E_2)) \times 100, \quad (16)$$

where energy of moisture evaporation (Q_w) is calculated using Equation (17), which is suitable for samples with a higher moisture content.

$$Q_w = h_{fg} \times M_w. \quad (17)$$

The latent heat of vaporization, h_{fg} (J/kg), can be determined using the following equations [61]:

$$h_{fg} = 2.503 \times 10^6 - 2.386 \times 10^3 \times (T_{\text{abs}} - 273.16) / 273.16 \leq T_{\text{abs}} \leq 338.72. \quad (18)$$

$$h_{fg} = (7.33 \times 10^{12} - 1.60 \times 10^7 \times T^2)^{0.5} 338.72 \leq T_{\text{abs}} \leq 533.16.$$

2.8 | Calculation of the GHG Emissions

The GHG emissions from the combined IR-convective dryer were determined through an indirect approach by referencing the electricity usage during the drying process. The calculation of GHG emissions for evaporating 1 kg of water from the sample was done as follows [62]:

$$\text{Specific GHG emission} = K_{\text{GHG}_{\text{mod}}} \times \text{SEC}. \quad (19)$$

$$K_{\text{GHG}_{\text{mod}}} = K_{\text{GHG}} \times \frac{1}{1 - L_{\text{T\&D}}} \times \frac{1}{1 - L_d}. \quad (20)$$

The GHG emission factor (K_{GHG}) is influenced by the combination of energy sources employed in energy production. In our work, the power plant employs a combined-cycle system for electricity generation, utilizing dual-fuel capabilities. The primary fuel source is natural gas. In the event of a gas supply shortage, the plant can run on fuel oil. Based on the report of Nazari et al. [63], the emission factors for natural gas consumed in combined cycle power plants in Iran are 450 g/kW h for CO_2 , zero for SO_2 , and 2.95 g/kW h for NO_x . In contrast, these values for gas oil are 622 g/kW h for CO_2 , 2.32 g/kW h for SO_2 , and 3.78 g/kW h for NO_x . Additionally, the loss in transmission and distribution ($L_{\text{T\&D}}$) is set at 13.13% [64], while the domestic loss (L_d) is estimated at 7% [62], considering the conditions in Iran. Therefore, the GHG emissions were calculated according to the Table 3.

The GHG emissions analysis in this study has considered operational energy consumption and excluded embodied emissions from dryer construction materials.

2.9 | Quality Assessment

2.9.1 | Determination of Water Activity (a_w)

The exact measurement of a_w for the samples was done by a water activity instrument (lab swift, Novasina, Switzerland) at 25°C. In order to do this, each sample (~1 g) was placed in a sample cup. Once the samples had reached equilibrium, the values of a_w were recorded.

2.9.2 | Determination of TA

The pH-differential technique was used to measure the TA content as outlined in the procedure described by Rodríguez-Ramírez et al. [65]. About 0.5 g dried samples of the EPPW were mixed with 10 mL 1% HCl in methanol (CH_3OH) solution. A total of 1 mL from each extracted sample was separately combined with buffers

at pH levels of 1.0 and 4.5. Subsequently, the absorbance readings were taken at 510 and 700 nm. The TA concentration (C) was calculated in terms of milligrams of cyanidin-3-glucoside (CGE) equivalents per liter (mg/L), and the final values were expressed based on the dry matter ($\text{mg CGE} \cdot 100 \text{ g}^{-1} \text{ dm}$) of the sample [65].

$$A = (A_{510 \text{ nm}} - A_{700 \text{ nm}}) \text{pH}_1 - (A_{510 \text{ nm}} - A_{700 \text{ nm}}) \text{pH}_{4.5}, \quad (21)$$

$$C = \frac{A \times M_w \times \text{DF} \times 1000}{\epsilon \times l}; \quad \text{TA} = \frac{C \times V}{1000 \times W}, \quad (22)$$

where A is the absorbance of the samples, M_w (g/mol) is the molecular weight of CGE (449.2), DF is the dilution factor (1), ϵ (L/mol-cm) is the molar extinction coefficient (26,900), l (cm) is the path length (1), W (g) is the weight of sample, and V (mL) is the sample volume.

2.10 | Uncertainty Analysis

Various factors, including instrument choice, operating conditions, data recording practices, and calibration methods, may introduce uncertainties and errors in experimental studies. Consequently, to validate the repeatability and accuracy of the computed parameters, uncertainty needs to be analyzed and assessed. In this work, the analysis was conducted using the Holman methodology and the following equation [43, 62]:

$$W_F = \left[\left(\frac{\partial F}{\partial y_1} w_1 \right)^2 + \left(\frac{\partial F}{\partial y_2} w_2 \right)^2 + \dots + \left(\frac{\partial F}{\partial y_n} w_n \right)^2 \right]^{0.5}, \quad (23)$$

where W_F is the total uncertainty of the results, ∂F is the uncertainty function, w is the dimensional shape factor, and w_n is the uncertainties in the independent variables.

Table 4 displays the uncertainties associated with both the measured and calculated experimental parameters.

2.11 | Statistical Analysis

In order to determine how IR power, sample thickness, and UH-air velocity affected each of the responses under study, the analysis of variance (ANOVA) was utilized. The following list represents some key indicators employed to evaluate whether the model is suitable and accurate, as analyzed by the Design Expert Software version 12 (Stat-Ease Inc, Minneapolis, USA).

1. p -value (or probability value): This statistical metric is a number that helps determine whether the results of a study are significant. In the present analysis, it was applied to evaluate the model terms at a 95% confidence level. Consequently, effects with p -values less than 0.05 are considered significant.
2. Coefficient of determination (R^2) and adjusted coefficient of determination (R_{adj}^2): These indicators should ideally approach one.
3. Adequate precision (AP): A value greater than four is considered ideal.
4. Coefficient of variation (C.V.): This parameter demonstrates the dispersion of the data and can be described as a percentage, with values less than 10% being desirable.

TABLE 3 | Modified GHG emission factor ($K_{\text{GHG}_{\text{mod}}}$) for the combined cycle power plant.

Fuel type	Greenhouse gas (g/kW h)		
	CO_2	SO_2	NO_x
Natural gas	557.1	0	3.65
Gas oil	769.91	2.87	4.68

TABLE 4 | Uncertainty of experimental measurements and calculated parameters.

Parameters	Uncertainty
Experimental measurements	
Temperature	$\pm 1^{\circ}\text{C}$
Air velocity	$\pm 0.1\text{ m/s}$
Weight loss	$\pm 0.1\text{ g}$
Relative humidity	$\pm 2\%$
Thickness	$\pm 0.01\text{ mm}$
a_w	± 0.01
Calculated parameters	
MR	± 0.0027
DR	$\pm 0.00065\text{ g water/g dm} \cdot \text{min}$
D_{eff}	$\pm 0.036 \times 10^{-10}\text{ m}^2/\text{s}$
E_a	$\pm 0.83\text{ kJ/mol}$
SEC	$\pm 0.414\text{ kW h/kg [water evaporated]}$
SMER	$\pm 0.0055\text{ kg/kW h}$
EE	$\pm 0.37\%$
GHG _{Natural gas} emission	$\pm 0.265\text{ g/kg water}$
GHG _{Gas oil} emission	$\pm 0.368\text{ g/kg water}$
TA	$\pm 5\text{ mg CGE} \cdot 100\text{ g}^{-1}\text{ dm}$

5. Lack of fit (LoF): A *p*-value for LoF greater than 0.05 suggests that the model is adequate for predicting outputs since it is not statistically significant compared to pure error.

The models were maintained in their hierarchy, but the effects that were not significant (*p* > 0.05) were eliminated from them.

3 | Results and Discussion

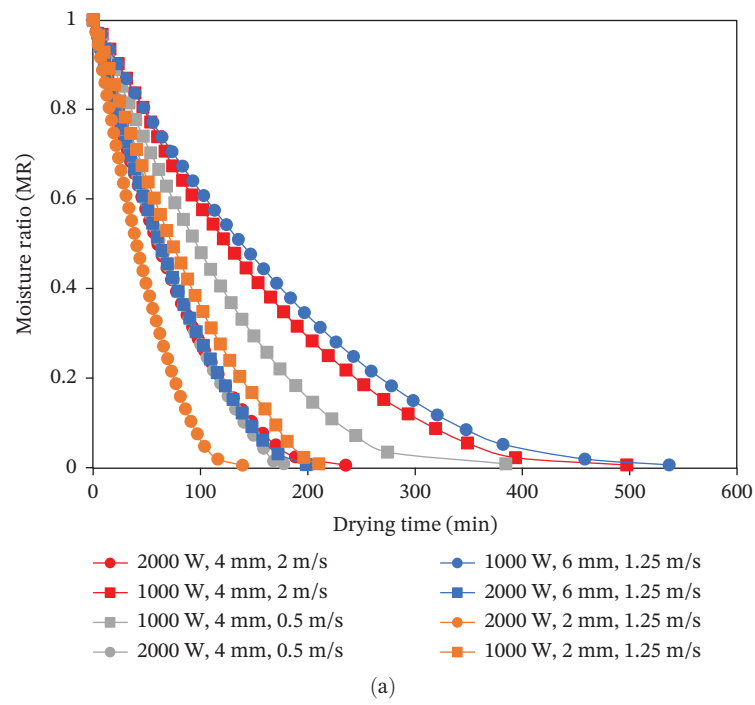
3.1 | Drying Kinetics of EPPWs

Figure 2a–c illustrate the connection between the MR of EPPW while drying at various IR power, sample thickness, and UH-air velocity. It can be observed that the MR reduces steadily and exponentially as the drying time increases. Figure 2d–f show that after an initial short period of drying, the DR attains a maximum value and then pursues a falling rate in all drying conditions. Moisture movement in the product is primarily governed by diffusion under all conditions, as indicated by the curves, which show a rapid decrease at the beginning, followed by a gradual decline with increased drying time. Increased temperature differences between the sample and the drying medium, facilitated by increasing the number of IR lamps in the drying chamber, resulted in a shorter drying time due to higher drying temperatures.

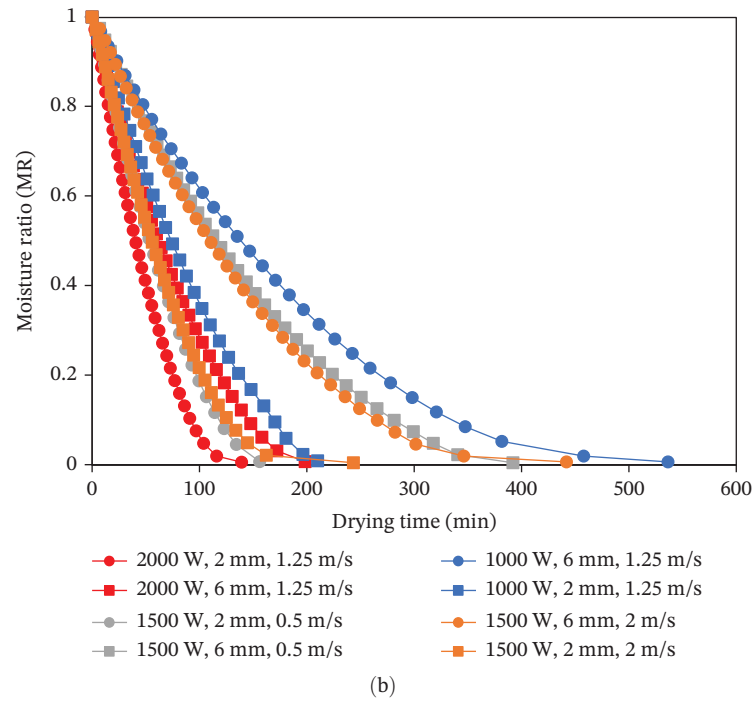
The IR power of 2000 W, sample thickness of 2 mm, and UH-air velocity of 1.25 m/s led to the minimum drying time value

(139.1 min), whereas the maximum value (536.51 min) occurred at 1000 W power, 6 mm thickness, and 1.25 m/s velocity. Indeed, the highest value of drying time was about 3.86-folds longer than the lowest. The results indicated that drying time was primarily affected by IR power and sample thickness, as shown by their *F*-values in the ANOVA results (299.90 for IR power and 261.89 for sample thickness) in Table 5. IR radiation mainly interacts with food matrices by being directly absorbed by water and organic molecules' vibrational modes. This absorption causes volumetric and surface heating, transforming into sensible heat and promoting moisture evaporation. As IR power increases, more IR energy is absorbed by water and is converted to heat almost instantly. This accelerates internal vapor pressure gradients, increases mass transfer toward the surface, and ultimately shortens the drying time [18, 27]. In addition, sample thickness modulates drying by changing the characteristic diffusion path length. Thicker slices impose longer internal paths for moisture to travel to the surface, which increases internal mass transfer resistance and prolongs the falling rate period dominated by diffusion. Thicker samples, therefore, exhibit longer drying times and often different apparent D_{eff} , because internal gradients, structural collapse, and capillary flow dynamics change with thickness and moisture content [66]. Moreover, a relatively faster surface drying (driven by IR) can induce case hardening in thinner or rapidly heated samples when surface moisture loss exceeds inward diffusion, thereby reducing rehydration capacity and creating a surface barrier to vapor transport. These phenomena link directly to observed increases in drying time and the thickness-dependent changes in D_{eff} in our study. In contrast, UH-air velocity had a less significant impact compared to the other two factors. Air velocity influences the convective heat and mass flux at the solid–air interface by modifying the thickness of the aerodynamic boundary layer and the local convective heat transfer coefficient. An increase in UH-air velocity diminishes the boundary-layer resistance, thereby enhancing sensible heat removal from the surface. This cooling effect can lower the surface temperature and partially counterbalance IR heating, resulting in a decrease in the temperature within the drying chamber, as well as a reduction in both product temperature and moisture vapor pressure. Consequently, the moisture driving force and the DR are also decreased. In order to analyze the trend of the main effects at the midpoint, it is evident that raising IR power from 1000 to 2000 W decreased the drying time by 51.35%. However, increasing sample thickness from 2 to 6 mm and UH-air velocity from 0.5 to 2 m/s caused the drying time to grow by 103.01% and 24.33%, respectively. The response surface plot for drying time is shown in Figure 3. Figure 3a–c illustrate the interaction effect of IR power and sample thickness, sample thickness and UH-air velocity, and IR power and UH-air velocity on drying time. The simultaneous increase in sample thickness, along with a decrease in IR power, resulted in a significant increase in drying time. This outcome is expected based on the underlying mechanisms. When IR power is decreased, both the surface temperature and the surface vapor pressure drop. At the same time, an increase in sample thickness creates a longer path for moisture to diffuse internally, which slows down the migration of water from the core to the surface.

IR power (X_1), sample thickness (X_2), and UH-air velocity (X_3), all had linear effects on drying time, according to the ANOVA



(a)



(b)

FIGURE 2 | (Continued)

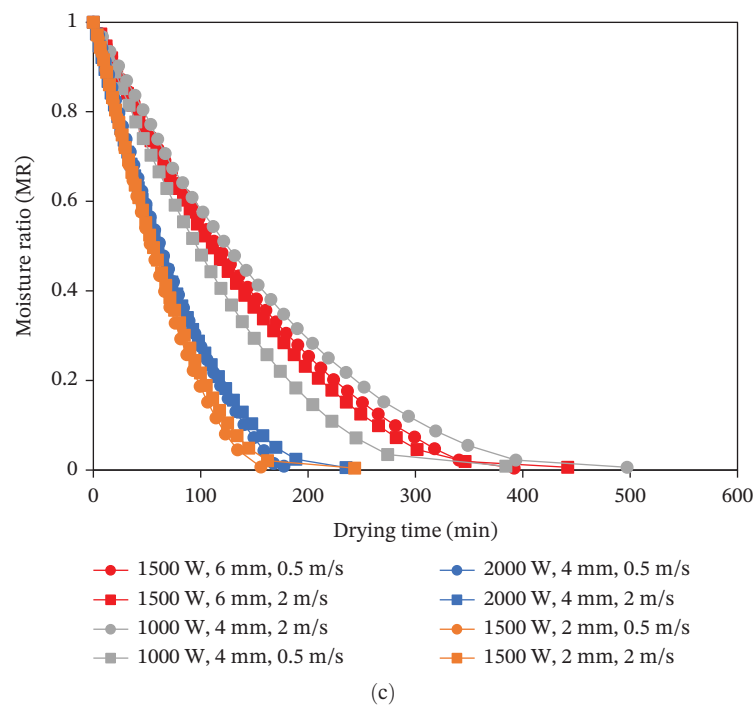
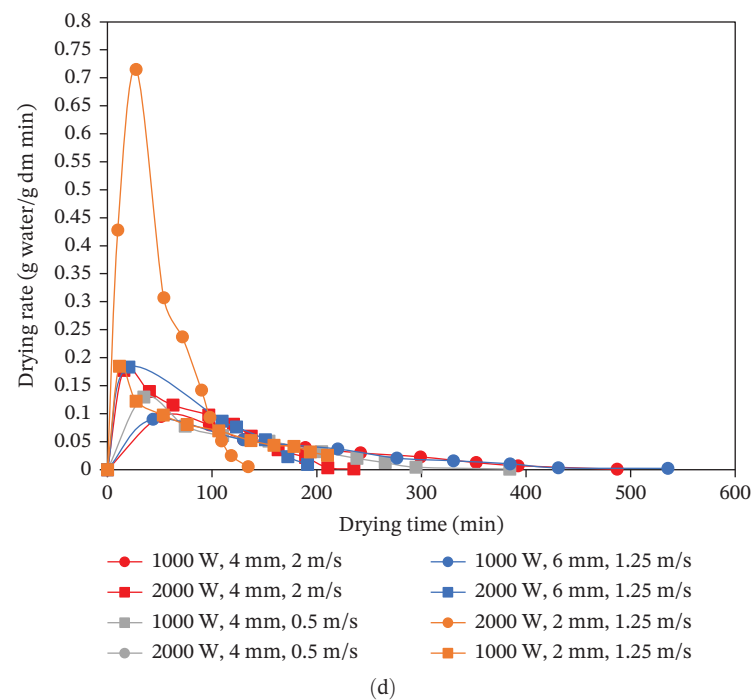
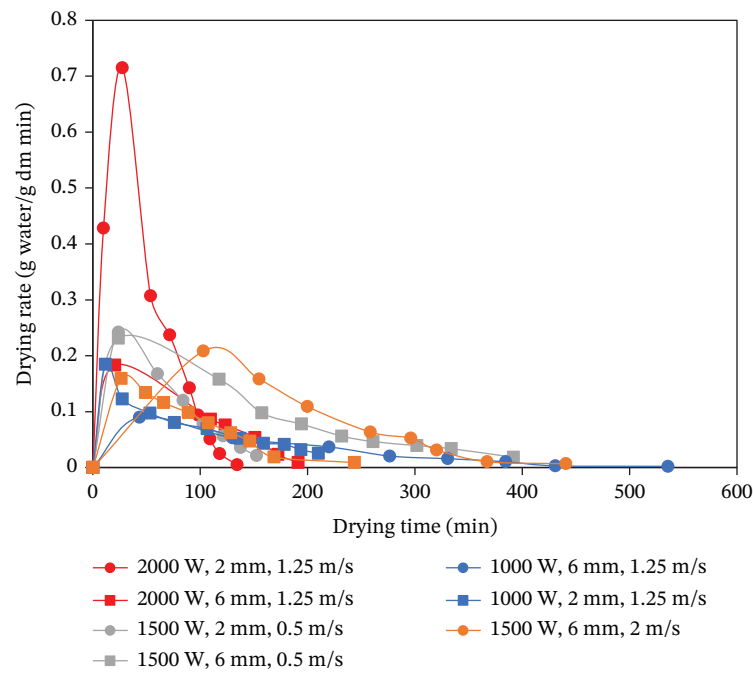
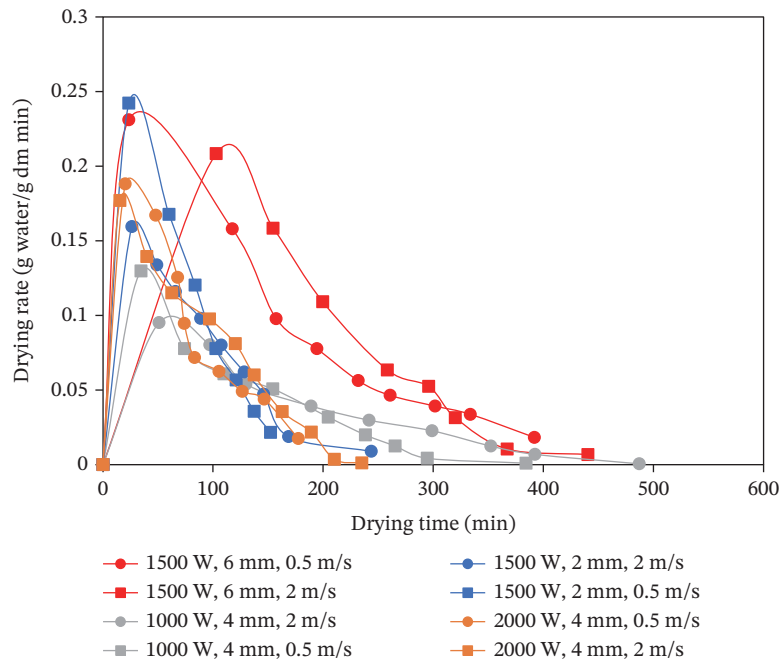


FIGURE 2 | (Continued)



(e)



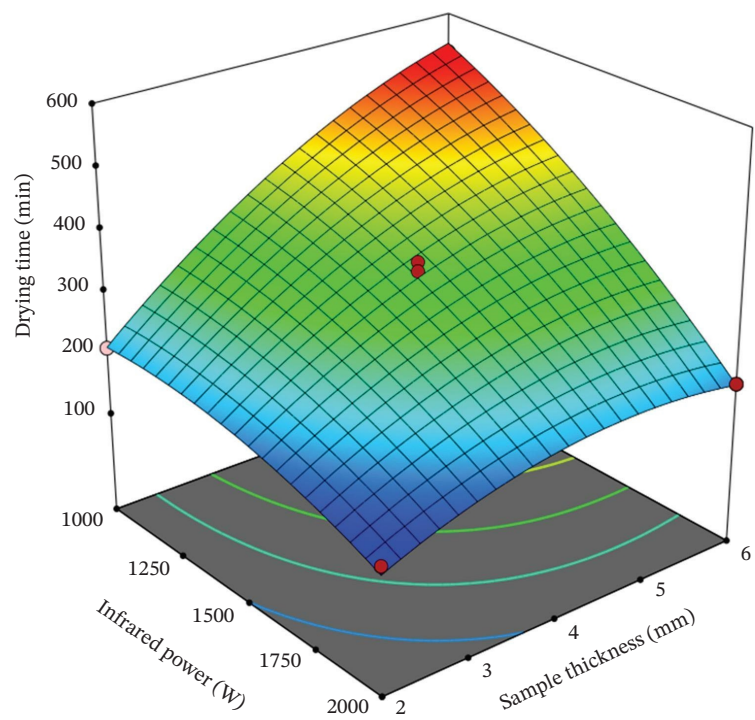
(f)

FIGURE 2 | Comparison of moisture ratio and drying rate of eggplant peel and pulp waste (EPPW) at different (a, d) infrared power (1000, 1500, and 2000 W), (b, e) sample thickness (2, 4, and 6 mm), and (c, f) UH-air velocity (0.5, 1.25, and 2 m/s).

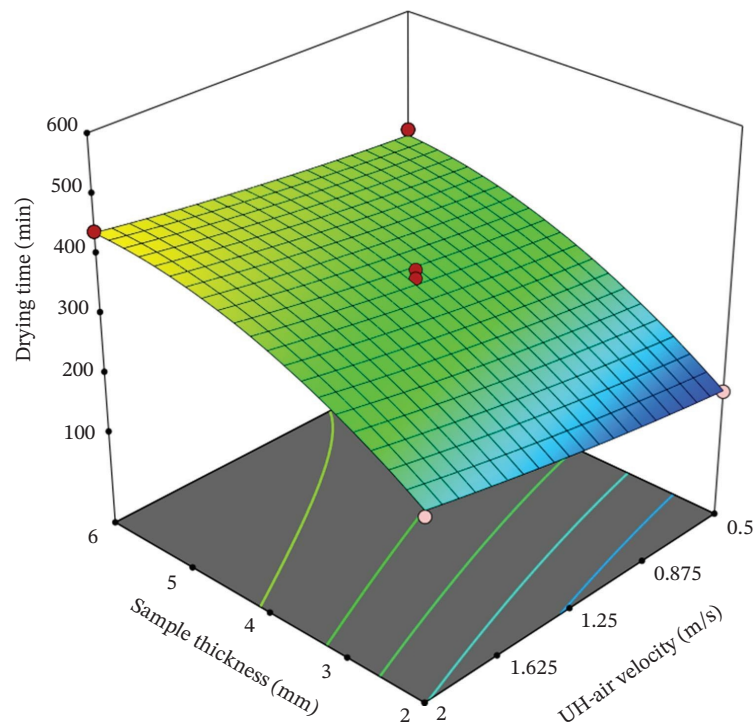
findings (Table 5). In addition, there was an interaction between IR power and sample thickness (X_1X_2), second power of IR power (X_1^2), and sample thickness (X_2^2 ; $P < 0.05$). The final drying time model can be seen in Table 6. The C.V. of 5.70% indicates high reproducibility (low variability) across replicates. A C.V. below 10% confirms that operational parameters effectively controlled drying kinetics. Additionally, the LoF (0.5307) suggests that the quadratic model accurately captures the actual relationship between variables. There is no indication of systematic error.

3.2 | Mathematical Modeling of Drying Curves

The curve fitting Toolbox in MATLAB R2014a software was used for non-linear regression analysis to identify the model coefficients. The coefficients were obtained on the basis of Levenberg–Marquardt (LM) algorithm up to 200 iterations with a confidence interval of 95% and convergence tolerance of 0.00001. Table 7 gives the estimated R^2 , χ^2 , RMSE, and SSE values under various experimental conditions. Among the eight models



(a)



(b)

FIGURE 3 | (Continued)

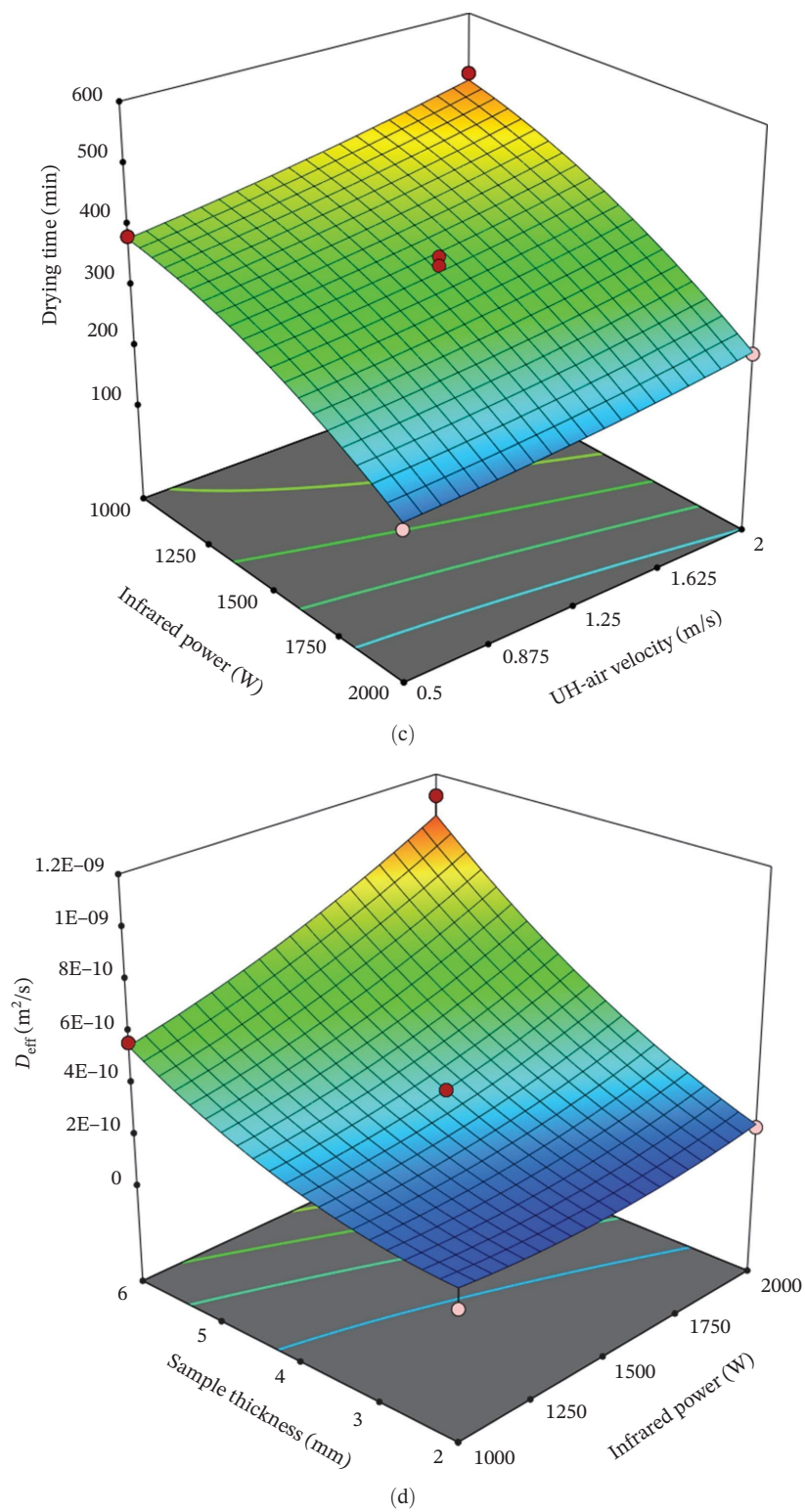


FIGURE 3 | (Continued)

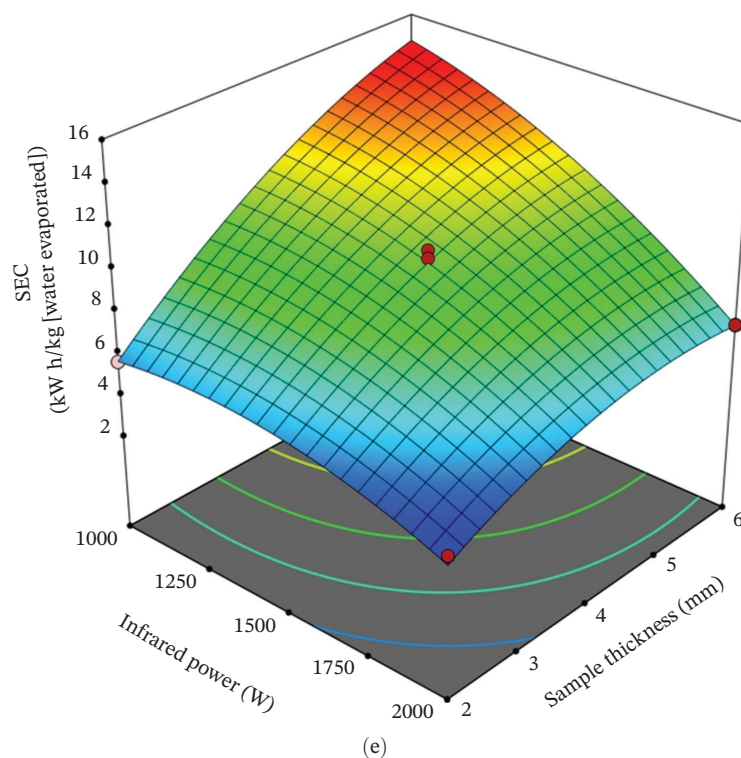


FIGURE 3 | Response surface plots of (a–c) drying time, (d) effective moisture diffusivity (D_{eff}), and (e) specific energy consumption (SEC).

TABLE 6 | Final equation for selected response parameters.

Response	Predictive models	p -Value	R^2	Adj – R^2	AP	C.V. (%)	LoF	Final actual equation
DT	Linear	<0.0001	0.8476	0.8124	16.97	16.39	0.0176	$DT = -531.885 + 0.460X_1 + 250.599X_2 + 101.055X_3 - 0.067X_1X_2 - 1.22 \times 10^{-4}X_1^2 - 11.43X_2^2$
	2 FI	<0.0001	0.9310	0.8896	16.92	12.57	0.0406	
	Quadratic	<0.0001	0.9901	0.9773	30.89	5.70	0.5307	
	Cubic			Aliased ^a				
D_{eff}	Linear	<0.0001	0.8682	0.8377	17.51	24.73	– ^b	$D_{\text{eff}} = 6.388 \times 10^{-10} - 7.202 \times 10^{-13}X_1 - 1.694 \times 10^{-10}X_2 + 1.141 \times 10^{-13}X_1X_2 + 2.175 \times 10^{-11}X_2^2$
	2 FI	<0.0001	0.9252	0.8803	15.42	21.24	– ^b	
	Quadratic	0.0001	0.9737	0.9399	20.10	15.05	– ^b	
	Cubic			Aliased ^a				
SEC	Linear	<0.0001	0.8396	0.8026	16.62	15.05	0.0108	$SEC = -16.025 + 0.016X_1 + 6.518X_2 + 2.203X_3 - 1.551 \times 10^{-3}X_1X_2 - 4.480 \times 10^{-4}X_1^2 - 0.299X_2^2$
	2 FI	0.0001	0.9103	0.8565	14.99	12.84	0.0167	
	Quadratic	<0.0001	0.9903	0.9778	31.34	5.05	0.3881	
	Cubic			Aliased ^a				
TA	Linear	0.0028	0.6485	0.5674	8.38	20.45	0.0110	$TA = -805.443 + 0.845X_1 + 111.961X_2 - 2.826 \times 10^{-2}X_1X_2 - 2.20 \times 10^{-4}X_1^2 - 49.262X_3^2$
	2 FI	0.0253	0.7087	0.5340	7.11	21.23	0.0079	
	Quadratic	<0.0001	0.9763	0.9458	19.77	7.24	0.3262	
	Cubic			Aliased ^a				

Note: DT, D_{eff} , SEC, TA, p -value, R^2 , Adj – R^2 , AP, C.V., and LoF are drying time (min), effective moisture diffusivity (m^2/s), specific energy consumption (kW h/kg [water evaporated]), total anthocyanin content ($\text{mg CGE} \cdot 100 \text{ g}^{-1} \text{ dm}$), probability value, coefficient of determination, adjusted coefficient of determination, adequate precision, coefficient of variance, and lack of fit, respectively.

^aIt is not possible to estimate all effects because the experimental matrix has fewer unique combinations than a full-factorial design. Final actual equation is not available for aliased models.

^bThe standard error for effects is 0.

TABLE 7 | Statistical results obtained for prediction of drying kinetics of eggplant peel and pulp waste (EPPW).

Model	Range of			
	R^2	RMSE	SSE	χ^2
Newton	0.9663–0.9865	0.0335–0.0529	0.4076–0.8123	1.1240×10^{-3} – 2.8050×10^{-3}
Logarithmic	0.9977–0.9999	0.0034–0.0139	0.0040–0.0637	1.1437×10^{-5} – 1.9409×10^{-4}
Henderson and Pabis	0.9798–0.9907	0.0277–0.0409	0.2352–0.4818	7.7356×10^{-4} – 1.6874×10^{-3}
Page	0.9961–0.9987	0.0114–0.0179	0.0445–0.1098	1.3084×10^{-4} – 3.2204×10^{-4}
Wang and Singh	0.9992–0.9998	0.0034–0.0083	0.0009–0.0206	1.1453×10^{-5} – 6.9632×10^{-5}
Parabolic	0.9908–0.9999	0.0013–0.0277	0.0007–0.2345	1.7829×10^{-6} – 7.7653×10^{-4}
Weibull distribution	0.9995–0.9999	0.0012–0.0065	0.0006–0.0140	1.4434×10^{-6} – 4.3308×10^{-5}
Midili and Kucuk	0.9994–0.9999	0.0015–0.0072	0.0008–0.0175	2.2475×10^{-6} – 5.1980×10^{-5}

Note: R^2 and χ^2 are coefficient of determination and reduced Chi-square, respectively. The Adj – R^2 values matched the R^2 values to four decimal places. Abbreviations: RMSE, root mean square error; SSE, sum squared error.

moisture diffusion variability in heterogeneous eggplant waste (sponge effect), but remains acceptable for biological materials [75].

The slope of the Arrhenius equation was utilized to calculate the activation energy of the samples. As shown in Figure 5, the E_a values were obtained at 42.06, 40.36, and 31.84 kJ/mol for sample thicknesses of 2, 4, and 6 mm, respectively. This indicates that D_{eff} values are temperature-sensitive. Activation energy of different food materials and agricultural products was placed ranging from 12.7 to 110 kJ/mol [35]. The E_a is decreased by increasing the thickness of product. The higher E_a value for the thickness of 2 mm suggests that the thin samples show higher sensitivity against temperature. That is, during the drying process, a small temperature change leads to significant variation in diffusivity value in comparison with the thicker samples. Similar results were reported by others for apple slices [76, 77], pumpkin samples [27, 35], kiwi slices [35, 78], and strawberry fruit leather [79].

3.4 | Evaluation of SEC, SMER, and EE

As illustrated in Figure 6, the SEC values were observed between 4.18 and 14.30 kW h/kg [water evaporated], and SMER values ranged from 0.07 to 0.24 kg/kW h. The minimum SEC and maximum SMER were recorded at 2000 W, 2 mm, and 1.25 m/s, and maximum SEC and minimum SMER were obtained at 1000 W, 6 mm, and 1.25 m/s. The observed decline in SEC and increase in SMER during the drying process can be attributed mainly to the effects of operational parameters on the reduction of drying time. Özdemir et al. [80] provided similar findings while drying kiwi-fruit utilizing IR. Based on a comparison of identical runs, the SEC value diminished by an average of 42.89% as IR power rose from 1000 to 2000 W. In contrast, when the sample thickness increased from 2 to 6 mm, SEC went up by 109.91%, and when the UH-air velocity increased from 0.5 to 2 m/s, it grew by 22.82%. The more effect of sample thickness compared to the other parameters thoroughly complied with its F -value (339.02) in Table 5. This energy consumption reduction was because of the heating effect of IR power that decreased the drying time significantly, just as thickness showed the same effect. This is fundamentally linked to lower diffusion resistance to moisture

transport. IR heating penetrates the material, creating a sharp internal moisture gradient that overcomes resistance and accelerates diffusion. Thinner samples reduce resistance by shortening the diffusion path, though surface hardening can partially offset this effect. Conversely, increasing UH-air velocity raises SEC because faster airflow cools the surface, increasing surface resistance by reducing the moisture evaporation rate. This prolongs drying and forces the system to expend more energy to overcome resistance. Motevali et al. [81], Kocabiyik et al. [82], and Tezcan et al. [83] had similar observations for mushroom, tomato slices, and dill leaves, respectively. Regarding Figure 3e, it is beheld that a reduction in IR power and a rise in sample thickness simultaneously lead to an increase in SEC. Besides, the IR power effect on SEC at low thickness is much lower than its effect on SEC at a higher one.

The ANOVA of SEC (Table 5) indicated that the combined drying process had an impact on the SEC of EPPW. The linear term of IR power, sample thickness, UH-air velocity, the interaction between IR power and sample thickness, and the second power of IR power and sample thickness were found to be the influencing factors. The final equation for SEC is represented in Table 6. Low C.V. (5.05%) confirms precise control over energy inputs (IR power and UH-airflow).

The EE values varied between 4.71% and 15.94%, showing that higher IR power, combined with reduced sample thickness and UH-air velocity, improves EE. The EE results for drying EPPW were computed using Equation (16), as shown in Figure 6. The combination of 2000 W, 2 mm, and 1.25 m/s yielded a maximum efficiency of 15.94%, while the setup with 1000 W, 6 mm, and 1.25 m/s resulted in a minimum efficiency of 4.71%. Teymori-Omran et al. [84] dried apple slices in a combined hot air–IR dryer (HA–IR) using various strategies. Results indicated that the highest EE occurred with the IR750 method at 10.25%, while the lowest was with the HA55–IR250 method at 3.61%. Additionally, the EE of the combined method with higher IR levels (HA55–IR750) was also under 5%. They explained this decline by the significant energy consumption of the air heating system during drying. In a separate study, Geng et al. [85] examined potato drying using a combined IR-hot air dryer. They focused on three factors: drying air temperature (40, 55, and 70°C), air

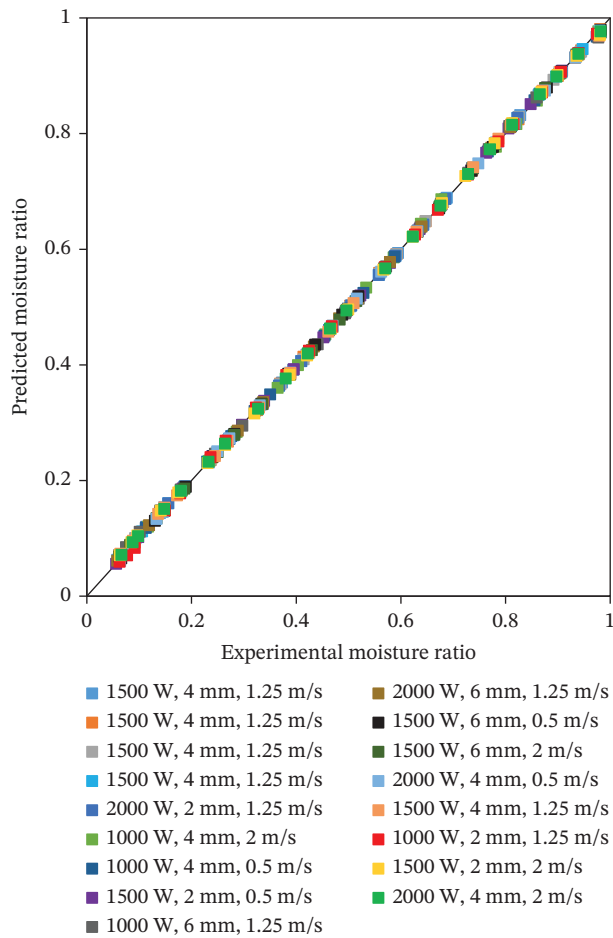


FIGURE 4 | Comparison of predicted moisture ratio by Weibull distribution model and experimental values at different conditions.

velocity (1, 1.5, and 2 m/s), and IR power (225, 450, and 675 W) with a sample thickness of 5 mm. The EE values ranged from 2.42% to 6.84%. They found that the EE of the process increased with higher drying air temperatures and greater IR power, while it decreased with higher airflow velocities.

3.5 | Evaluation of GHG Emissions

Table 9 outlines the impact of IR power, sample thickness, and UH-air velocity on GHG emissions. Accordingly, the CO₂ emissions ranged from 2.33 to 7.97 g/kg [water] for natural gas and from 3.22 to 11.03 g/kg [water] for gas oil, demonstrating a substantial reduction of approximately 70.8% for both fuel types. The SO₂ values for natural gas were zero under all conditions, whereas the highest value for gas oil was 0.0411 g/kg [water] and the lowest is 0.0120 g/kg [water]. The lowest and highest NO_x levels for natural gas were 0.0153 and 0.0522 g/kg [water], respectively; for gas oil, they were 0.0196 and 0.0669 g/kg [water]. Overall, the results indicate that gas oil has a higher GHG emission profile compared to natural gas across all evaluated conditions. A pollutant-specific breakdown revealed that CO₂ accounted for the overwhelming majority of total emissions for both natural gas and gas oil. For natural gas, CO₂ accounted for approximately 99.35% of total emissions, with NO_x contributing only 0.65% and SO₂ being negligible. Similarly, for gas oil, CO₂ constituted about 99.03% of total emissions, followed by NO_x (0.60%) and SO₂

(0.37%). These results indicate that CO₂ is the principal contributor to the overall GHG footprint of the drying process, whereas SO₂ and NO_x played a comparatively minor role. All maximum values occurred at 1000 W, 6 mm, and 1.25 m/s, while the minimum values were recorded at 2000 W, 2 mm, and 1.25 m/s. The GHG emissions reduced as IR power increased and as sample thickness and UH-air velocity decreased, which can be attributed to lower energy consumption. To quantitatively verify that the trend in GHG emissions mirrored that of the SEC, a correlation analysis was conducted. As shown in Equations (24) and (25), a linear regression analysis between SEC and the corresponding GHG emissions (for both natural gas and gas oil) yielded $R^2 = 1$, indicating a perfect linear relationship. This confirms that variations in GHG emissions directly reflect changes in SEC. Kaveh et al. [11] reported that CO₂ emissions in a combined cycle plant using natural gas varied from 23.62 to 74.25 kg/kg [water], while emissions from oil gas ranged from 32.65 to 102.63 kg/kg [water] during the IR drying of green peas. These findings indicated that CO₂ emissions were influenced by the level of IR power applied during the drying process. They observed that higher IR power resulted in lower CO₂ emissions, likely due to shorter drying times facilitated by a rise in mass transfer rate. Kaveh et al. [86] demonstrated that declining sample thickness and increasing the IR power led to reduced GHG emissions throughout the IR drying of pear slices. The highest CO₂ and NO_x emissions recorded were 214.46 and 1.18 kg/kg [water], respectively, at 500 W and 6 mm when using gas oil as fuel in a gas turbine power plant. Conversely, the lowest CO₂ and NO_x emissions were observed at 38.14 and 0.16 kg/kg [water], respectively, belonging to a gas turbine-natural gas power plant at 1000 W and 2 mm.

$$\text{GHG emissions}_{\text{Natural gas}} = 0.5607 \times \text{SEC} + 2 \times 10^{-6}. \quad (24)$$

$$\text{GHG emissions}_{\text{Gas oil}} = 0.7775 \times \text{SEC} + 3 \times 10^{-6}. \quad (25)$$

3.6 | Water Activity

The main factor that prevents or limits microbial growth is water activity. The modulation of microbial response, food stability, and identification of the type of microorganism present in food are all dependent on a_w as a crucial factor. The effect of a_w on vegetative microorganisms and spores is one of the most complex factors that influences microbial growth, survival, and death in food products. Overall, biological and chemical deterioration is minimized when the a_w is reduced to its lowest level. As a result, the physicochemical changes during storage are declined in order to preserve the food [87]. According to Labuza and Altunakar [88], dried foods typically exhibit water activity (a_w) between 0.1 and 0.4, which is considered microbiologically safe. On average, the fresh samples had a moisture content of 92.4%, which was expected due to the high moisture content of the EPPW. Additionally, the average a_w was 0.958. The a_w range under different experimental conditions was 0.221–0.351. The results of various drying assessments suggested that all samples were well-suited for preservation, as indicated by their water activity and moisture content measurements. Furthermore, a statistically significant (ANOVA, $p < 0.05$) disparity was evident in the a_w values among the various samples.

TABLE 8 | Effective moisture diffusivity of eggplant peel and pulp waste (EPPW) under different experimental conditions based on actual values of the operational parameters.

Run	Infrared power (W)	Sample thickness (m)	UH-air velocity (m/s)	D_{eff} (m^2/s)
1	1500	4	1.25	3.631×10^{-10}
2	1500	4	1.25	3.631×10^{-10}
3	1500	4	1.25	3.631×10^{-10}
4	1500	4	1.25	3.631×10^{-10}
5	2000	2	1.25	1.953×10^{-10}
6	1000	4	2	2.318×10^{-10}
7	1000	4	0.5	3.096×10^{-10}
8	1500	2	0.5	1.645×10^{-10}
9	1000	6	1.25	5.654×10^{-10}
10	2000	6	1.25	1.113×10^{-9}
11	1500	6	0.5	7.332×10^{-10}
12	1500	6	2	5.836×10^{-10}
13	2000	4	0.5	5.042×10^{-10}
14	1500	4	1.25	3.631×10^{-10}
15	1000	2	1.25	1.046×10^{-10}
16	1500	2	2	1.418×10^{-10}
17	2000	4	2	4.069×10^{-10}

Note: Runs 1, 2, 3, 4, and 14 represent replicated experiments.

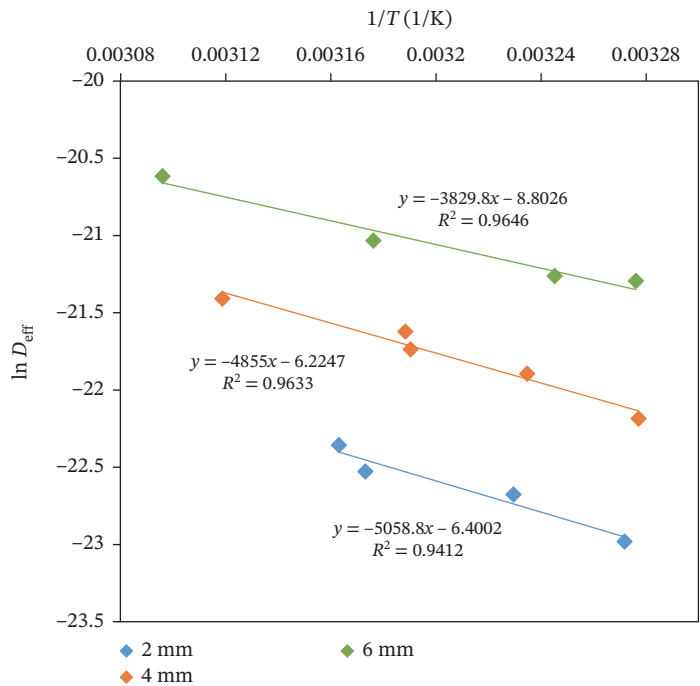


FIGURE 5 | Plot of $\ln D_{\text{eff}}$ vs. $1/T$ at different sample thickness (2, 4, and 6 mm).

3.7 | TA Content

Regardless of the drying conditions, the TAs were higher in the dried samples ($74.94\text{--}290.24 \text{ mg CGE} \cdot 100 \text{ g}^{-1} \text{ dm}$) than in the fresh one ($63.9 \text{ mg CGE} \cdot 100 \text{ g}^{-1} \text{ dm}$, Iranian cultivar). The

highest level of TA was observed at 1500 W, 6 mm, and 0.5 m/s, while the lowest was recorded at 1000 W, 2 mm, and 1.25 m/s. Cultivation techniques have a significant influence on anthocyanin content because anthocyanin concentration rises during the

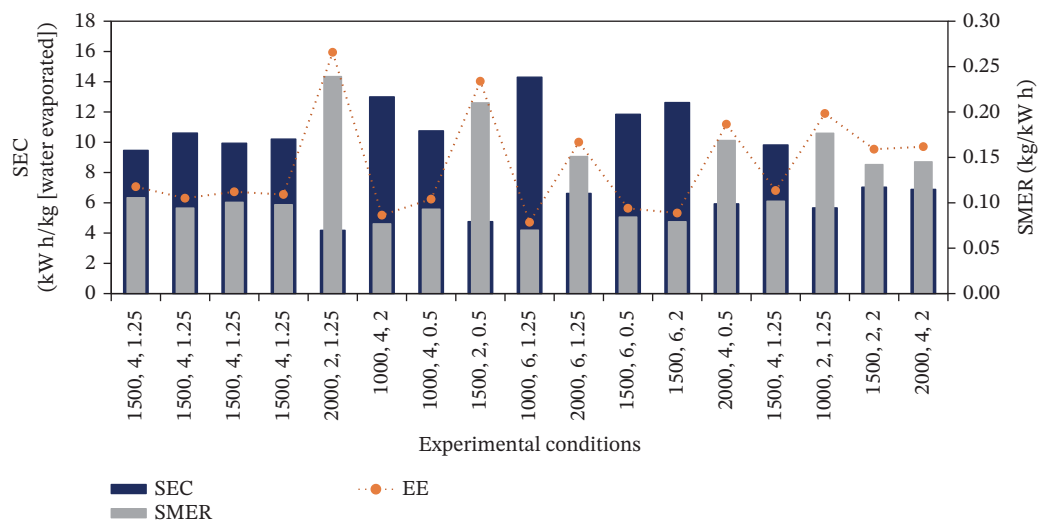


FIGURE 6 | Effect of operational parameters on specific energy consumption (SEC), specific moisture extraction rate (SMER), and energy efficiency (EE) for eggplant peel and pulp waste (EPPW) at different conditions. On the horizontal axis, the first, second, and third numbers for each bar correspond to infrared power (W), sample thickness (mm), and air velocity (m/s), respectively.

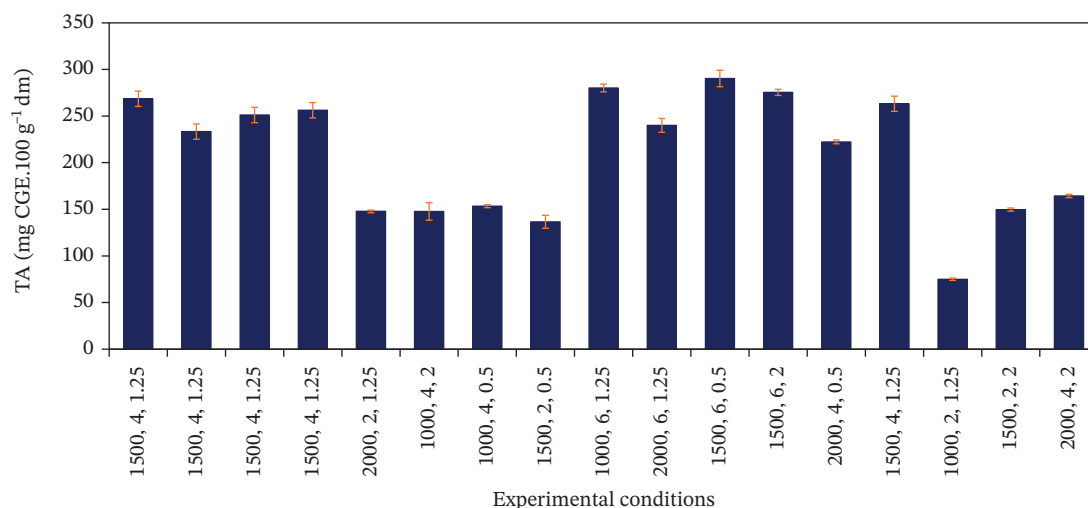


FIGURE 7 | Effect of operational parameters on total anthocyanin content (TA) for eggplant peel and pulp waste (EPPW) at different conditions. On the horizontal axis, the first, second, and third numbers for each bar correspond to infrared power (W), sample thickness (mm), and air velocity (m/s), respectively.

ripening process. Moreover, the anthocyanin content of EPPW may be impacted by variations in harvesting techniques between any two cultivation systems [89, 90]. From Figure 7, it can be seen that the sample thickness had the largest influence on the TA ($F = 181.35$, ANOVA, Table 5). This trend is completely upward, as evidenced by a comparative evaluation of the identical runs. The analysis revealed that with the increase in thickness from 2 to 4 mm, the TA increased by about 51.04%, and from 4 to 6 mm, the TA increased by about 22.71%. In addition, by increasing the UH-air velocity from 0.5 to 1.25 m/s and the IR power from 1000 to 1500 W, the TA increased by about 8.32% and 37.76%, respectively, and declined afterward by around 14.13% and 15.8% respectively. Nonetheless, ANOVA results indicated that UH-air velocity had no significant effect on the TA ($p > 0.05$). Adak et al. [91] found that IR drying raised the TA levels in strawberries. They noted that elevating the IR power from 100 to 300 W increased TA, while raising the temperature from 60 to 100°C

resulted in decreased levels. Thus, although enhancing the IR power from 1500 to 2000 W reduced drying time, it also raised the temperature and caused thermal degradation of the TA. In addition, because the employed radiations fall into the far-IR spectrum, they are biologically active and uniformly transfer heat to the material center without deteriorating the molecules that make up the surface. It is likely that covalent bonds of repeating polymers are broken by far-IR radiation and released antioxidants, such as flavonoids, tannins, carotene, ascorbate, polyphenols, or flavoproteins [92]. Since anthocyanins are a subclass of the broader group of phenolic compounds, they may also have the potential to be released. Additionally, the samples at higher thicknesses are exposed to a longer drying. However, the interaction effect between IR power and sample thickness is significant ($p < 0.05$), but the effect of thickness is outweighed [93]. Thus, the observed increase in TA as a result of the increase in sample thickness can be attributed to these factors. Considering

TABLE 9 | Values of GHG emissions based on fuel type of power plant in different drying conditions.

Infrared power (W)	Sample thickness (mm)	UH-air velocity (m/s)	Fuel type	CO ₂ (g/kg [water])	SO ₂ (g/kg [water])	NO _x (g/kg [water])	Sum of GHG (g/kg [water])
1500	5	1.25	Natural gas	5.27	0	0.0346	5.31
			Gas oil	7.29	0.0272	0.0443	7.36
1500	5	1.25	Natural gas	5.91	0	0.0387	5.95
			Gas oil	8.17	0.0305	0.0496	8.25
1500	5	1.25	Natural gas	5.54	0	0.0363	5.57
			Gas oil	7.65	0.0285	0.0465	7.73
1500	5	1.25	Natural gas	5.69	0	0.0373	5.73
			Gas oil	7.86	0.0293	0.0478	7.94
2000	3	1.25	Natural gas	2.33	0	0.0153	2.35
			Gas oil	3.22	0.0120	0.0196	3.25
1000	5	2	Natural gas	7.24	0	0.0475	7.29
			Gas oil	10.01	0.0373	0.0608	10.11
1000	5	0.5	Natural gas	5.99	0	0.0393	6.03
			Gas oil	8.28	0.0309	0.0503	8.36
1500	3	0.5	Natural gas	2.65	0	0.0174	2.67
			Gas oil	3.66	0.0137	0.0223	3.70
1000	7	1.25	Natural gas	7.97	0	0.0522	8.02
			Gas oil	11.01	0.0411	0.0669	11.12
2000	7	1.25	Natural gas	3.69	0	0.0242	3.71
			Gas oil	5.10	0.0190	0.0310	5.15
1500	7	0.5	Natural gas	6.60	0	0.0433	6.64
			Gas oil	9.12	0.0340	0.0554	9.21
1500	7	2	Natural gas	7.03	0	0.0461	7.08
			Gas oil	9.72	0.0363	0.0591	9.82
2000	5	0.5	Natural gas	3.30	0	0.0217	3.32
			Gas oil	4.57	0.0170	0.0277	4.61
1500	5	1.25	Natural gas	5.47	0	0.0359	5.51
			Gas oil	7.56	0.0282	0.0460	7.64
1000	3	1.25	Natural gas	3.15	0	0.0207	3.17
			Gas oil	4.36	0.0163	0.0265	4.40
1500	3	2	Natural gas	3.92	0	0.0257	3.94
			Gas oil	5.42	0.0202	0.0329	5.47
2000	5	2	Natural gas	3.84	0	0.0251	3.86
			Gas oil	5.30	0.0198	0.0322	5.35

all the mentioned, it can be said that IR drying was not only effective in preserving TA, but its amount also increased after drying. Therefore, it seems that it is possible to achieve the maximum TA levels by setting an optimal condition.

Table 6 also displayed the final equation for TA. The ANOVA results showed that the linear terms of IR power and sample thickness, the interaction between these two variables, and the second power values of both IR power and sample thickness

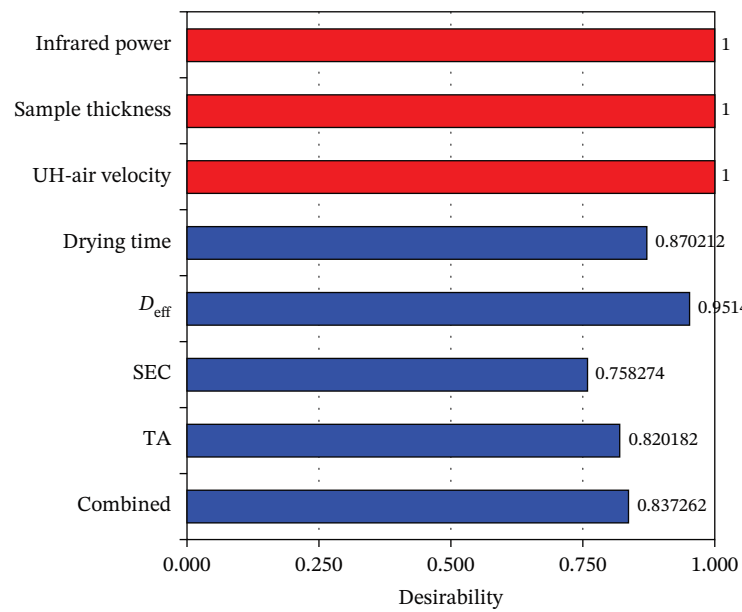


FIGURE 8 | Bar graph of desirability values for optimization drying process of eggplant peel and pulp waste (EPPW).

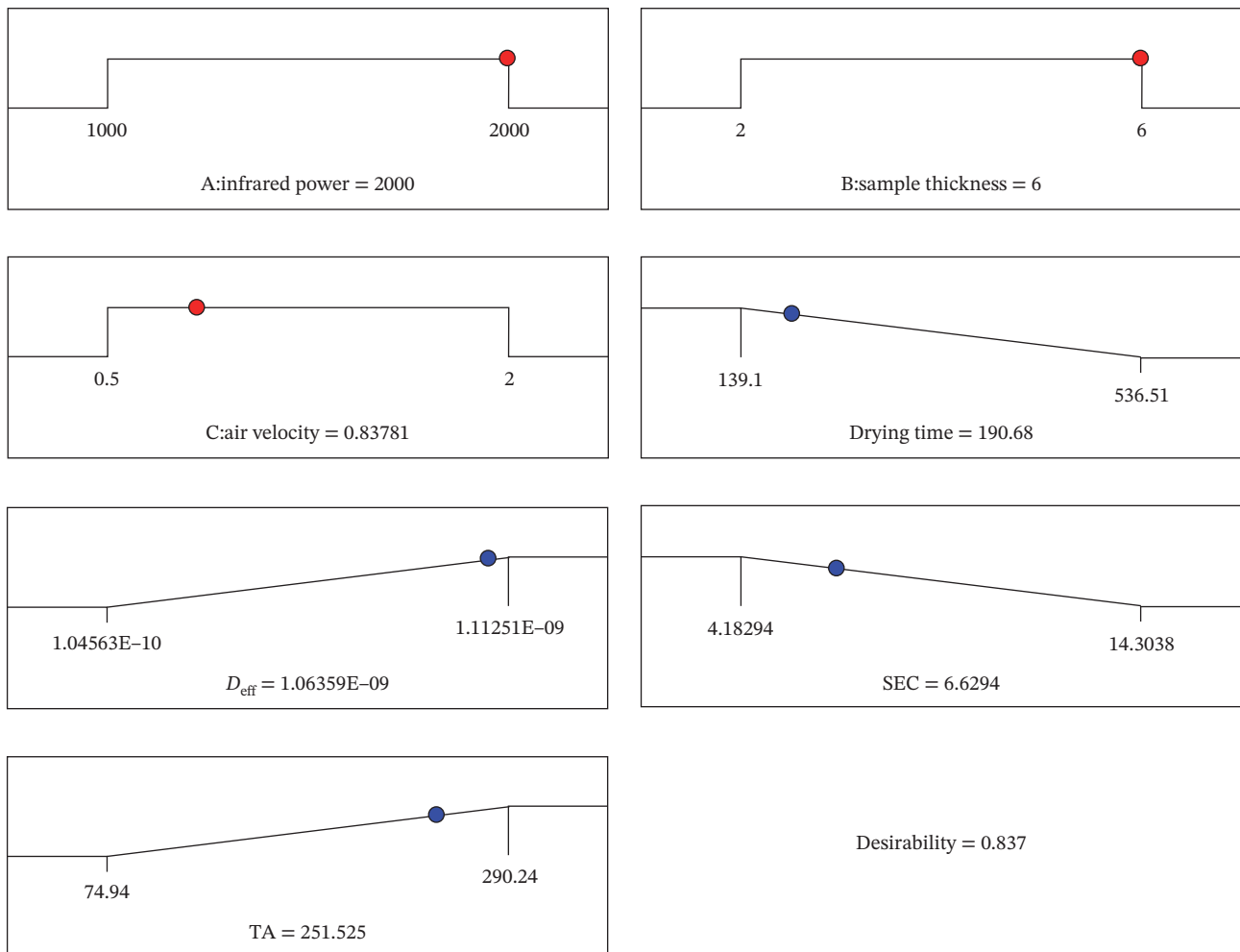


FIGURE 9 | Ramps of numerical optimization.

substantially influenced the TA. In addition, the LoF ($p = 0.3262$) confirmed that the quadratic model adequately described TA retention. Combined with low C.V. (7.24%) and high R^2 (0.9763), this validates the model's use for optimization.

3.8 | Process Optimization and Validation

The Design Expert software's numerical optimization feature was used to optimize the drying conditions of the EPPW samples. The desired goals have been set as the minimum drying time, SEC, maximum D_{eff} , and TA. Furthermore, the control factors (IR power, sample thickness, and UH-air velocity) were chosen to remain in the predefined range. Corresponding importance of goals were selected as 3 for drying time; 3 for D_{eff} ; 4 for SEC, and 5 for TA in multiobjective optimization. The individual desirability values associated with control factors and response variables, along with the results of the combined optimization, yield a combined desirability of 0.837, as displayed in Figure 8. The optimum conditions were detected at 2000 W, 6 mm, 0.84 m/s, and under these optimized parameters, drying time, D_{eff} , SEC, and TA were predicted to be 190.67 min, $1.064 \times 10^{-9} \text{ m}^2/\text{s}$, 6.63 kWh/kg [water evaporated], and 251.52 mg CGE $\cdot 100 \text{ g}^{-1} \text{ dm}$, respectively (Figure 9). To assess the RSM model's prediction accuracy, a single test was performed under determined optimal parameters, resulting in response values of 188.1 min, $1.063 \times 10^{-9} \text{ m}^2/\text{s}$, 6.31 kWh/kg [water evaporated], and 248.84 mg CGE $\cdot 100 \text{ g}^{-1} \text{ dm}$, for drying time, D_{eff} , SEC, and TA, respectively. The obtained results demonstrated a satisfactory alignment between the experimental data and the model's predictions, thereby validating its reliability for the responses. The calculated errors between the experiment outcomes and RSM predictions are as follows:

Drying time = 1.35%; D_{eff} = 0.09%; SEC = 4.83%; TA = 1.07%.

4 | Conclusions

The combined IR-convective drying system improved the processing of EPPW by reducing drying time by up to 74.07% compared to the least efficient condition. It enhanced D_{eff} while lowering SEC by 70.77%, achieved EE values as high as 15.94%, and yielded final anthocyanin contents between 74.94 and 290.24 mg CGE $\cdot 100 \text{ g}^{-1} \text{ dm}$ under the optimized settings of 2000 W, 6 mm, and 0.84 m/s. The findings revealed a significant reduction in GHG emissions of about 70.8% for both fuel types; however, gas oil showed a higher GHG emission profile than natural gas under all assessed conditions. Mathematical modeling met its stated objective by rigorously evaluating multiple thin-layer drying models and confirming that the Weibull distribution model provided the most accurate description of drying behavior, as reflected by consistently high R^2 and low RMSE and SSE values. The study successfully established the drying kinetics of EPPW utilizing combined IR and UH-air convection. Furthermore, it quantified the effects of IR power, sample thickness, and air velocity on various parameters, including drying time, D_{eff} , E_a , SEC, SMER, EE, GHG emissions, a_w , and TA content. Additionally, a multi-objective RSM-based optimization strategy was implemented to identify operational conditions that enhance process time and efficiency, energy performance, and product quality concurrently.

This study fills the gap of quantitative evidence on the controllability and environmental performance of combined IR drying for plant-based wastes and presents a coherent framework for optimizing IR power, sample thickness, and air velocity to improve both process efficiency and product quality. By addressing this gap, the work advances resource-efficient valorization routes for agri-food by-products using carefully parameterized drying conditions. The findings offer a practical framework for designing IR-assisted drying protocols that require low thermal load, improved mass transfer, and reduced emissions, especially for residues rich in heat-sensitive phytonutrients. Meanwhile, the elevated TA content in dried EPPW presents it as a valuable raw material for integrated bioprocessing. Anthocyanin-rich fractions can be used to create bioactive ingredients for functional foods or antioxidants. The remaining lignocellulosic biomass can be processed through methods like anaerobic digestion, pyrolysis, or composting to produce renewable energy, soil-amendment fertilizers, or nutrient-enriched biochars. This process enhances nutrient circularity and positions EPPW as a versatile feedstock within circular bioeconomy strategies.

The GHG emission values reported in this study reflect the electricity-generation profile of Iran and therefore may differ in regions with alternative power-production structures; any broader use of these values should consider typical fluctuations in power-plant performance, including seasonal changes in thermal efficiency and fuel composition. Furthermore, the influence of egg-plant tissue porosity on moisture migration was not quantified, even though porosity governs internal diffusion pathways and contributes to drying resistance in cellular plant matrices. Variations in pore structure, capillary behavior, and cell-wall integrity could contribute to differences in moisture removal rates across samples of different thicknesses or maturity stages. Future studies could address these key limitations. Additionally, extending these operating principles to other agri-food residues and evaluating them under continuous-flow conditions, coupled with a comprehensive technoeconomic assessment, would support industrial-scale implementation and strengthen the contribution of combined IR-convective drying to sustainable bioprocessing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the paper and the supporting information. Any raw data files, needed in another format, are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. ([Supporting Information](#))

Table S1: Coefficients of the Weibull distribution model at different drying conditions.