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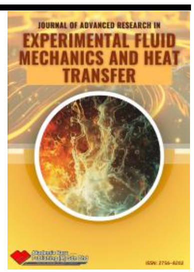

Enhancing Energy and Exergy Efficiency in Hot Air-Drying System using IoT-Controlled Adaptive Air Recirculation

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ABSTRACT

Traditional hot air-drying systems consume substantial energy, often accounting for up to 60% of industrial operational costs, presenting significant challenges for sustainable manufacturing processes. Current drying systems rely on static air recirculation settings that cannot adapt to real-time changes in moisture content, leading to inefficient energy utilization and poor energy quality optimization. This study develops an Internet of Things (IoT)-controlled hot air-drying system featuring adaptive air recirculation to enhance both energy and exergy efficiency through dynamic real-time control. We investigated the effects of varying air recirculation rates (0%, 25%, 50%, and 75%) across three temperature settings (50°C, 60°C, and 70°C) on specific energy consumption (SEC) and exergy efficiency using fresh pork slices as experimental material with IoT-enabled servo motor control for adaptive recirculation adjustment. The findings indicate that higher temperatures combined with increased air recirculation substantially reduce SEC, achieving reductions of up to 50% under optimal conditions (70°C and 75% recirculation). Furthermore, exergy efficiency improved by up to 42.1%, reflecting a significant decrease in exergy destruction. This IoT-enabled adaptive system demonstrates a robust strategy for minimizing energy consumption and optimizing energy quality in drying processes, providing critical insights for sustainable and high-efficiency drying applications.

1. Introduction

Hot air drying is an essential process utilized across various industries, including food processing, agriculture, and pharmaceuticals, for effective moisture removal. Its primary objective is to reduce moisture content, which in turn extends shelf life, enhances product safety, and maintains overall quality. Studies by Darvishi *et al.,* [1], Liu *et al.,* [2], and Onwude *et al.,* [3] have demonstrated the critical importance of optimizing drying parameters to maintain product integrity while improving process efficiency. However, traditional hot air-drying methods are energy-intensive, often accounting for up to 60% of total operational energy consumption in industrial contexts, as reported

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by Kemp [4] and Mujumdar [5]. This scenario poses significant challenges in an era increasingly focused on energy efficiency and sustainability. Recent advancements in drying technology aim to mitigate these energy concerns while preserving product integrity. Research by Ju *et al.,* [6] and Teymori-Omran *et al.,* [7] has shown promising results in energy-efficient drying strategies. Studies by Urbano *et al.,* [8] have highlighted the importance of energy performance analysis in drying systems. A notable innovation is the integration of internet of things (IoT) systems into drying processes. IoT-based systems enable real-time monitoring and dynamic control of critical parameters such as temperature, humidity, and airflow—resulting in substantial energy savings.

Studies by Miano *et al.,* [9] and Mishra *et al.,* [10] have demonstrated the effectiveness of IoT implementation in drying applications. Among these parameters, air recirculation has emerged as a pivotal factor in enhancing energy efficiency by minimizing heat loss and optimizing drying kinetics, as evidenced by research conducted by Afzali *et al.,* [11] and El-Mesery *et al.,* [12]. Despite the advantages of air recirculation, many current drying systems rely on static settings, limiting their adaptability to variations within the drying chamber. Research by Zohrabi *et al.,* [13] has highlighted the potential of enhancing energetic performance through exhaust air recirculation in convective dryers. While significant advancements have been made in IoT-driven systems for temperature and humidity control, dynamic regulation of air recirculation remains underexplored. Most existing research relies on fixed recirculation rates, constraining the system's ability to adapt to real-time fluctuations in drying conditions. Moreover, although exergy analysis has proven effective in evaluating energy quality in thermal systems, as demonstrated by Nazghelichi *et al.,* [14] and Aghbashlo *et al.,* [15], its comprehensive application in IoT-controlled drying systems is still in its early stages.

Current literature reveals three critical knowledge gaps that limit the development of energy-efficient drying systems. First, most existing research on air recirculation systems relies on static operational settings, preventing systems from adapting to real-time changes in moisture content and drying kinetics during different phases of the drying process. Second, while IoT technology has been successfully implemented for temperature and humidity monitoring and control, as shown by previous studies [9,10], the integration of IoT with dynamic air recirculation control based on real-time moisture content feedback and drying rate analysis remains insufficiently explored. Third, although exergy analysis provides valuable insights into energy quality utilization in thermal processes [14,15], its systematic integration with IoT-controlled adaptive drying systems for comprehensive energy optimization has not been thoroughly investigated.

This study introduces a novel IoT-controlled hot air drying system that uniquely integrates three innovative components: (i) real-time adaptive air recirculation control driven by moisture content slope analysis and drying rate feedback, (ii) servo motor-based dynamic adjustment of recirculation rates (0%, 25%, 50%, 75%) during different drying phases, and (iii) comprehensive energy and exergy analysis integrated with IoT monitoring for simultaneous energy consumption reduction and energy quality optimization. This represents the first systematic approach to combine adaptive IoT control with detailed thermodynamic analysis in hot air-drying systems, establishing a new paradigm for smart drying technology that addresses both energy efficiency and energy quality simultaneously. This research addresses critical industrial and environmental challenges by developing technology that has the potential to significantly reduce specific energy consumption while maintaining product quality standards. The integration of real-time adaptive control with comprehensive thermodynamic analysis provides a robust framework for sustainable drying applications, offering substantial economic benefits through reduced operational costs and environmental advantages through decreased energy consumption. The findings will advance the field of smart manufacturing systems and contribute to Industry 4.0 implementations in food processing, pharmaceutical, and agricultural sectors, providing a scalable solution for energy-intensive drying operations.

Therefore, this study aims to bridge the identified research gaps by developing and comprehensively evaluating an IoT-controlled hot air-drying system with real-time adaptive air recirculation control. The specific objectives are to: (i) develop an IoT-enabled adaptive control system that dynamically adjusts air recirculation rates based on real-time moisture content feedback and drying rate slope analysis, (ii) systematically evaluate the impact of varying recirculation rates (0%, 25%, 50%, and 75%) on both specific energy consumption and exergy efficiency across different temperature conditions (50°C, 60°C, and 70°C), and (iii) establish a comprehensive analytical framework combining energy and exergy analysis for optimizing drying system performance and minimizing energy waste in industrial drying applications.

2. Methodology

2.1 Materials

Fresh pork slices were selected as the experimental material, sourced from a local supermarket in Thailand. These samples were specifically chosen for their high initial moisture content, essential for evaluating the impact of IoT-based air volume control on the drying process. The initial moisture content, determined using the AOAC-2019 standard [16], averaged 240 ± 5% (dry basis). To ensure uniformity, the pork slices were precisely cut to dimensions of 10 cm × 1 cm × 1 cm using a commercial-grade meat slicer.

2.2 Experimental Setup

This study utilized a custom-designed hot air-drying system integrated with IoT technology for real-time monitoring and dynamic control of essential parameters, optimizing energy and exergy performance. The system modulated air recirculation rates based on product moisture content, employing an electric heating element to maintain a consistent thermal environment with regulated temperature and humidity. A 5V servo motor controlled the air recirculation damper, enabling precise adjustments informed by real-time data from SHT45 temperature and humidity sensors positioned at the chamber's inlet and outlet. Data was transmitted to a cloud-based platform (Blynk) for remote monitoring and control, allowing operators to adjust temperature, humidity, and recirculation rates in real-time.

The adaptive control strategy regulated the servo motor according to the slope of the moisture content curve, continuously assessing the drying rate. When the drying rate decreased, indicating a transition to the constant or falling rate phase, the servo motor increased air recirculation to pre-set rates of 25%, 50%, or 75%. There was no air recirculation during the initial drying period, while air recirculation was applied during the falling rate period to conserve energy. This IoT-enhanced architecture significantly improved monitoring and control, optimizing energy consumption and operational efficiency through automated adjustments based on real-time conditions. Remote access via Blynk further enhanced flexibility, allowing adjustments from any location. Figure 1 illustrates the experimental setup, detailing the layout of the drying chamber, airflow control mechanisms, servo motor, IoT sensors, and control interface. This schematic highlights the system's overall functionality, emphasizing how the integration of IoT and servo motor technology facilitates precise and energy-efficient drying operations.

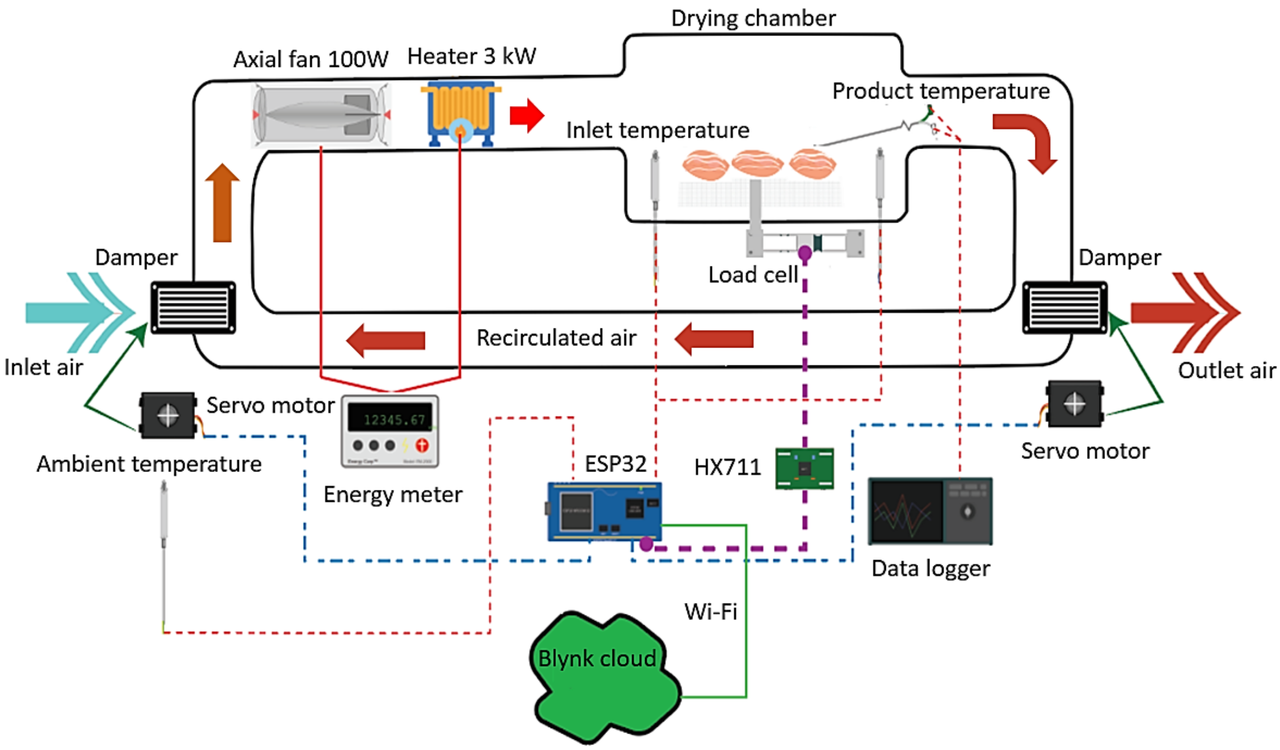

Fig. 1. Schematic of IoT hot air drying

2.3 Experimental Procedure

The drying experiments were conducted at controlled temperatures of 50°C, 60°C, and 70°C, with air recirculation rates of 0%, 25%, 50%, and 75%. Air velocity was maintained at 1.5 m/s. Each cycle began by pre-heating the chamber to the target temperature, after which pork slices were introduced to initiate drying. Moisture content was monitored every 5 minutes using a precision balance integrated with the IoT system, allowing continuous tracking of moisture loss. The process concluded when moisture content reached 60% (dry basis). The IoT-controlled servo motor dynamically adjusted the air recirculation rate based on real-time feedback from temperature and humidity sensors, while total energy consumption was recorded using integrated energy meters.

2.4 Data Analysis

The data collected during the experiments were analysed using several key performance indicators to assess drying efficiency and optimize the drying process. These indicators include moisture content, moisture ratio, drying rate, and specific energy consumption. Additionally, energy and exergy analyses were conducted to evaluate the performance of the system.

2.4.1 Specific energy consumption analysis

The specific energy consumption was systematically evaluated as a function of drying time and energy input to assess the energy efficiency of the drying system under different temperature and air velocity conditions. It was calculated using the following Eq. (1).

$$SEC = \frac{E_{\text{total}}}{m_w} \tag{1}$$

where SEC is specific energy consumption (MJ/kg),$E_{total}$is the total energy consumed during drying (MJ) and W_d is the dry mass of the sample (kg).

2.4.2 Adaptive point recirculation air analysis

Air recirculation adjustments are made based on the slope of the drying rate, indicating drying kinetics. A significant decline in the drying rate signals the transition from free to bound water removal. Increasing the air recirculation rate at this stage helps maintain the temperature gradient while minimizing unnecessary energy input, optimizing both energy and exergy efficiencies. The slope of the drying rate is calculated as shown in Eq. (2) [17].

$$Slope = \frac{\Delta M}{\Delta t} \tag{2}$$

where ΔM is the change in moisture content over time (kg), $\Delta t$is the change in time (h).

2.4.3 Energy analysis

The energy analysis of the IoT-controlled hot air-drying process was performed according to the first law of thermodynamics, which focuses on the conservation and distribution of energy within the system. This analysis aimed to evaluate the energy input, the energy utilized for moisture evaporation, and the associated losses across different air recirculation rates, providing insights for optimizing energy efficiency. The total energy utilized was calculated based on the enthalpy difference between the inlet and outlet air, as described by Eq. (3)[18].

$$EU = \dot{m}_a(h_{a,i} - h_{a,o}) \tag{3}$$

where EU represents the energy utilization (J), $\dot{m}_a$ is the mass flow rate of air (kg/s),$h_{a,i}$ is the specific enthalpy of the inlet air (J/kg), $h_{a,o}$ is the specific enthalpy of the outlet air (J/kg).

The mass flow rate of air ($\dot{m}_a$) was determined using following Eq. (4) [19].

$$\dot{m}_a = \rho_a v_a A_{dc} \tag{4}$$

where ρ_a is the air density (kg/m³),v_a is the air velocity (m/s), and A_{dc} is the cross-sectional area of the airflow (m²). The specific enthalpy of the air (h_a) was calculated by considering both sensible and latent heat components, as described is calculated using the following Eq. (5) [20].

$$h_a = C_{pa}(T - T_{ref}) + h_{fg}\omega \tag{5}$$

where C_{pa} is the specific heat capacity of air (J/kg·K), T is the air temperature (K), T_{ref} is the reference temperature (K), h_{fg} is the latent heat of vaporization of water (J/kg), ω is the humidity ratio (kg water/kg dry air). The specific heat capacity of dry air was evaluated using the following equation to account for the humidity content was evaluated using Eq. (6) [21].

$$C_{pa} = 1.004 + 1.88\omega \tag{6}$$

The humidity ratio of air was calculated based on the relative humidity and saturation vapor pressure using Eq. (7) [22].

$$\omega = \frac{0.622\phi P_{vs}}{P-\phi P_{vs}} \tag{7}$$

where ϕ is the relative humidity, P_{vs} is the saturation vapor pressure (Pa), and P is the total air pressure (Pa). The humidity ratio at the outlet is calculated using Eq. (8) [21].

$$\omega_{ao} = \omega_{ai} + \frac{\dot{m}_t}{\dot{m}_a} \tag{8}$$

where ω_{ao} is the outlet humidity ratio (kg water/kg dry air), ω_{ai} is the inlet humidity ratio (kg water/kg dry air), $\dot{m}_t$ is the moisture transfer rate (kg/s), estimated from the change in the sample's mass over time. The moisture transfer rate is estimated using Eq (9) [19].

$$\dot{m}_t = \frac{W_t - W_{t+\Delta t}}{\Delta t} \tag{9}$$

where W_t and $W_{t+\Delta t}$ are the sample weights at time t and $t + \Delta t$, respectively. To assess the efficiency of the system, the energy utilization ratio (EUR), representing the fraction of energy utilized for moisture removal, was calculated using Eq. (10) [21].

$$EUR = \frac{(h_{a,i} - h_{a,o})}{(h_{a,i} - h_r)} \tag{10}$$

where h_r is represents the specific enthalpy of air at equilibrium.

2.4.4 Exergy analysis

Exergy analysis, grounded in the second law of thermodynamics, offers a comprehensive framework for evaluating the quality of energy use in the drying process. Unlike energy analysis, which considers only the quantity of energy input, exergy analysis focuses on the irreversibility that occur during the drying process. These irreversibility manifest as energy losses, primarily in the form of heat transfer to the surroundings and represent the portion of energy that cannot be converted into useful work. This section quantifies the exergy input, exergy output, exergy destruction, and the overall exergy efficiency of the IoT-controlled hot air drying. The exergy of the drying air stream is calculated using the following using Eq. (11).

$$Ex = \dot{m}_a C_{pa}((T_a - T_r) - T_r \ln(T_a/T_r)) \tag{11}$$

where Ex is the exergy of the air stream (J), T_a is the air temperature (K), T_r is the environmental temperature (K).

The exergy input (Ex_i) was calculated based on the inlet air temperature following Eq. (12) [23]. The exergy output (Ex_o) was determined at the outlet air temperature, following Eq. (13) [24]. Whereas, the exergy destruction Ex_{des} represents the irreversibility within the drying system and is defined as the difference between the exergy input and exergy output following Eq. (14) [23].

$$Ex_i = \dot{m}_a C_{pa,i}((T_i - T_r) - T_r \ln(T_i/T_r)) \tag{12}$$

$$Ex_o = \dot{m}_a C_{pa,o}((T_o - T_r) - T_r\, ln(T_o/T_r)) \tag{13}$$

$$Ex_{\text{des}} = Ex_{\text{i}} - Ex_{\text{o}} \tag{14}$$

The exergy efficiency (ψ) of the system, which reflects the system's ability to convert input exergy into useful work, is determined using the following Eq. (15)

$$\psi = \frac{\text{Ex}_i - \text{Ex}_{des}}{\text{Ex}_i} = 1 - \frac{\text{Ex}_{des}}{\text{Ex}_i} \tag{15}$$

where ψ is the exergy efficiency, dimensionless.

3. Results and Discussion

3.1 Specific Energy Consumption

Specific energy consumption (SEC) is a critical metric in drying processes, quantifying the energy needed to evaporate a unit mass of water from the material. Enhancing SEC is essential, as it directly impacts the energy efficiency and operational viability of the drying system. Lower SEC values indicate a more optimized drying process, where energy is effectively allocated for moisture removal, thereby reducing overall energy requirements, as demonstrated in previous studies investigating energy optimization in drying systems [11,15]. In this study, SEC was analyzed at three drying temperatures which are 50°C, 60°C, and 70°C—across various air recirculation (RC) rates (0%, 25%, 50%, and 75%), as illustrated in Figure 2. The results demonstrate a consistent reduction in SEC with increasing drying temperatures, particularly when coupled with moderate to high RC levels. For instance, at 70°C and 75% RC, SEC is significantly minimized compared to the baseline condition of 50°C with no air recirculation (0% RC), underscoring the synergistic effects of temperature and RC on energy savings.

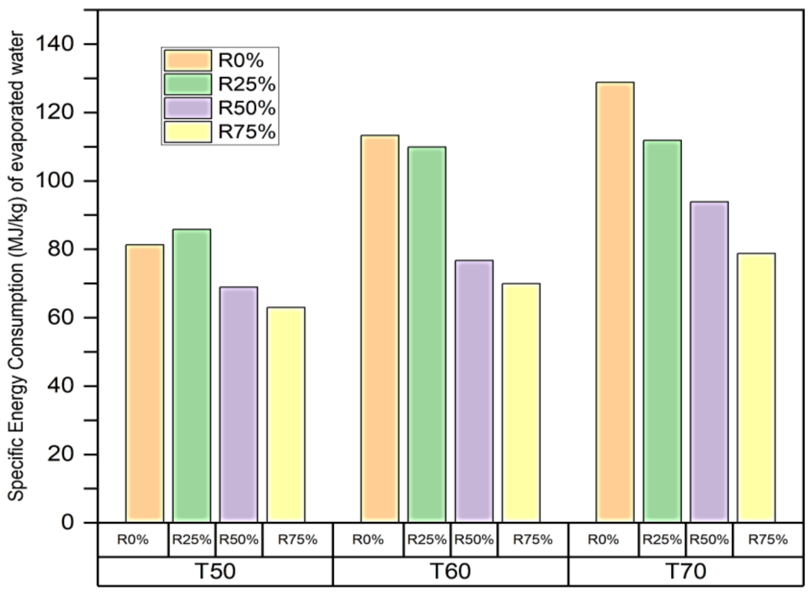

Fig. 2. Specific energy consumption at each drying condition

Data in Figure 2 indicate that higher air recirculation rates correlate with reduced specific energy consumption across all temperature settings. At 50°C, SEC decreases from approximately 80 MJ/kg at 0% RC to around 60 MJ/kg at 75% RC. This trend becomes more pronounced at elevated temperatures: at 60°C, SEC declines from about 125 MJ/kg at 0% RC to approximately 85 MJ/kg at 75% RC, and at 70°C, it drops from around 140 MJ/kg at 0% RC to about 90 MJ/kg at 75% RC. This substantial reduction indicates that air recirculation not only enhances thermal retention within the drying chamber but also reduces reliance on external energy inputs, thereby improving overall energy efficiency, consistent with findings from recent thermal system optimization research [25]. These findings underscore the effectiveness of combining elevated drying temperatures with optimized RC rates in reducing SEC. The trends suggest that drying at 60°C and 70°C with RC rates of 50% or higher offers the most efficient conditions, achieving an optimal balance between energy input and moisture removal efficacy. These insights contribute to advancing energy-efficient drying practices and highlight the importance of strategic parameter control to maximize drying performance, supporting conclusions from previous optimization studies investigating energy efficiency in convective drying systems [2,10].

Multiple regression analysis was employed to investigate the relationship between drying temperature, air recirculation rate (RC), and specific energy consumption (SEC) in the IoT-controlled hot air drying. This statistical approach provided a comprehensive understanding of how these parameters interact to influence energy efficiency during the drying process, yielding insights into optimizing temperature and RC to minimize energy consumption. The polynomial regression model derived from this analysis is shown in Eq. (16). This model demonstrates a high coefficient of determination (R^2 = 94.05%), indicating that 94.05% of the variation in SEC is explained by changes in temperature and RC.

$$SEC = -140 + 6.25\text{Temp} + 0.733RC - 0.0342\text{Temp}^2 - 0.00158RC^2 - 0.01920\,\text{Temp} \times RC \tag{16}$$

As shown in Figure 3, the 3D surface plot illustrates the interaction between temperature and air recirculation rate (RC), indicating that higher temperatures combined with increased recirculation rates synergistically reduce specific energy consumption (SEC). The graph reveals a significant reduction in SEC when both parameters are simultaneously elevated, particularly at higher temperatures. This finding suggests that strategically adjusting temperature and RC can effectively lower energy consumption during the drying process.

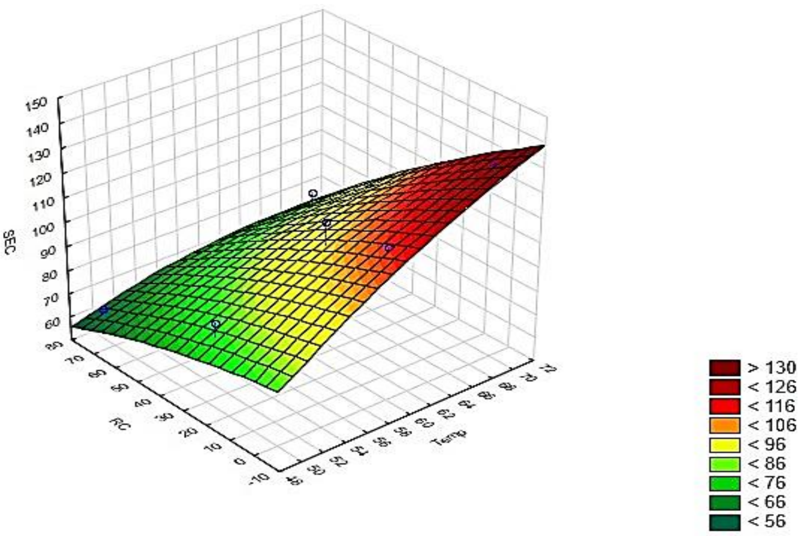

Fig. 3. Influence of temperature and recirculation rate on specific energy consumption

Table 1 presents the coefficients of the regression model. While the individual effects of temperature and air recirculation rate do not achieve statistical significance at the 0.05 level (P = 0.270 for temperature and P = 0.258 for RC), the interaction term significantly influences Specific Energy Consumption, with a P-value of approximately 0.072. This finding underscores the importance of jointly adjusting both parameters to optimize energy efficiency. These interaction effects corroborate prior research highlighting the significance of multi-variable control in enhancing drying efficiency. These interaction effects corroborate findings from prior research highlighting the significance of multi-variable control in enhancing drying efficiency [2,11]. Table 2 summarizes the overall performance of the regression model, showing an adjusted R^2 of 89.10% and a predicted R^2 of 76.25%. These values indicate that the model is not only reliable but also effective in predicting SEC under various drying conditions. The standard error of the regression (S=6.97337) is reasonably low, reflecting the model's precision in capturing the relationship between the studied variables.

Table 1
Coefficients of the regression model for predicting specific energy consumption

Term	Coefficient	SE coefficient	T-value	P-value	Variance inflation factor (VIF)
Constant	-140	153	-0.92	0.394	
Temperature	6.25	5.14	1.22	0.270	434.80
RC	0.733	0.586	1.25	0.258	66.25
Temp*Temp	-0.0342	0.0427	-0.80	0.454	433.00
RC*RC	-0.00158	0.00322	-0.49	0.640	12.25
Temp*RC	-0.01920	0.00882	-2.18	0.072	56.80

Table 2
Model summary for regression analysis of specific energy consumption

Standard error (S)	R^2	Adjusted R^2	Predicted R^2
6.97337	94.05%	89.10%	76.25%

The regression model's robustness was evaluated using analysis of variance (ANOVA), detailed in Table 3. The results reveal statistical significance, with an F-value of 18.98 and a P-value of 0.001, confirming the model's capability to explain variance in specific energy consumption (SEC). ANOVA highlights the critical interaction between temperature and air recirculation (RC) influencing SEC, while variance inflation factor (VIF) values in Table 1 indicate minimal multicollinearity among predictors, ensuring reliable regression coefficients. This regression analysis demonstrates the potential of IoT-based control systems to dynamically adjust temperature and air recirculation (RC), enhancing energy efficiency in hot air drying. The model's accurate predictions of specific energy consumption (SEC) enable real-time optimization, highlighting the importance of adaptive control strategies in minimizing energy consumption while maintaining drying quality.

Table 3
Analysis of variance for the regression model predicting specific energy consumption

Source	Degrees of freedom (DF)	Adj SS	Adj MS	F-value	P-value
Regression	5	4615.04	923.01	18.98	0.001
Temperature	1	71.82	71.82	1.48	0.270
RC	1	76.10	76.10	1.56	0.258
Temp*Temp	1	31.12	31.12	0.64	0.454
RC*RC	1	11.76	11.76	0.24	0.640
Temp*RC	1	230.45	230.45	4.74	0.072
Error	6	291.77	48.63		
Total	11	4906.81			

3.2 Energy Utilization

Energy utilization in drying systems measures the fraction of total energy effectively used for moisture removal, contrasting with losses from irreversibility's like heat dissipation. Maximizing energy utilization is crucial for enhancing overall energy efficiency and reducing operational costs by ensuring that a significant portion of energy directly contributes to moisture evaporation, as supported by previous studies [2,15]. Figures 4 to 6 depict the behavior of energy utilization (EU) at three drying temperatures which are 50°C, 60°C, and 70°C—across varying air recirculation rates (RC) of 0%, 25%, 50%, and 75%. As illustrated in Figure 4, at 50°C, EU is maximized at 0% RC, indicating optimal direct energy use for moisture removal. However, as the recirculation rate increases to 25%, 50%, and 75%, EU exhibits a clear downward trend, with the 75% RC condition resulting in the lowest EU. This decline in EU at higher RC levels is primarily due to retained thermal energy within the drying chamber, which reduces the necessity for additional external energy inputs. However, this also limits the energy allocated specifically for moisture evaporation, potentially impacting overall drying efficiency, as reported in previous drying optimization studies [6,11].

Figure 5 illustrates EU at 60°C, highlighting the effects of increased temperature. At 0% RC, EU remains high due to the strong vapor pressure gradient that enhances moisture removal. However, as RC rises to 25%, 50%, and 75%, EU declines, though less significantly than at 50°C. This trend indicates that while air recirculation conserves energy, it diminishes the immediate impact on moisture extraction. Although higher temperatures can partially offset EU reduction from recirculation, the overall trend shows decreasing EU with increased RC levels, consistent with findings from recent thermal system research [9,25]. At 70°C, as shown in Figure 6, the impact of air recirculation on energy utilization (EU) becomes more pronounced. EU values peak at 0% RC, maximizing energy input for direct drying. However, as RC increases—particularly at 50% and 75%—EU significantly declines. This substantial reduction in EU at elevated RC levels results from enhanced thermal retention within the drying chamber, which stabilizes the thermal environment but decreases the proportion of energy actively used for moisture removal. The decline at 75% RC underscores the need to balance energy conservation with effective energy utilization in drying processes, as highlighted in recent process optimization literature [12,26].

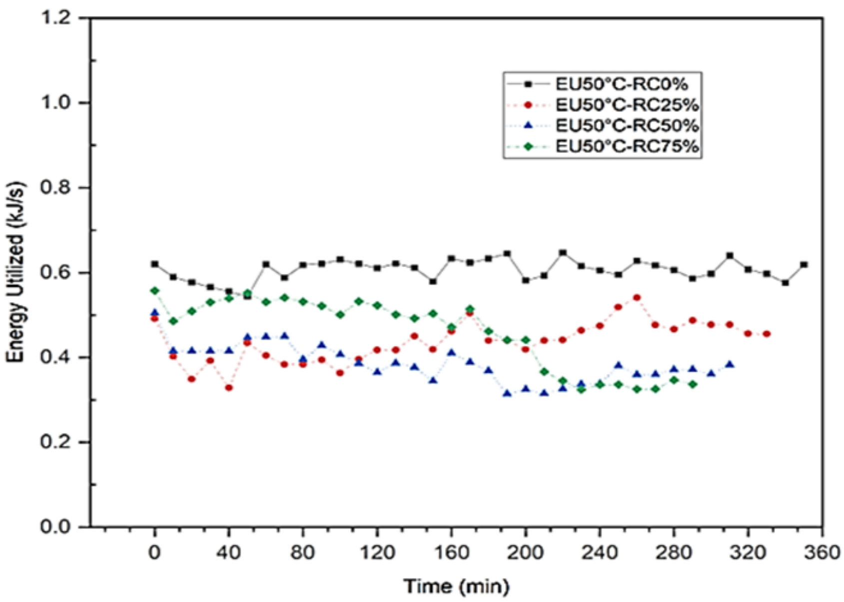

Fig. 4. Energy utilized at 50°C with air recirculation rates of 0%, 25%, 50%, and 75%

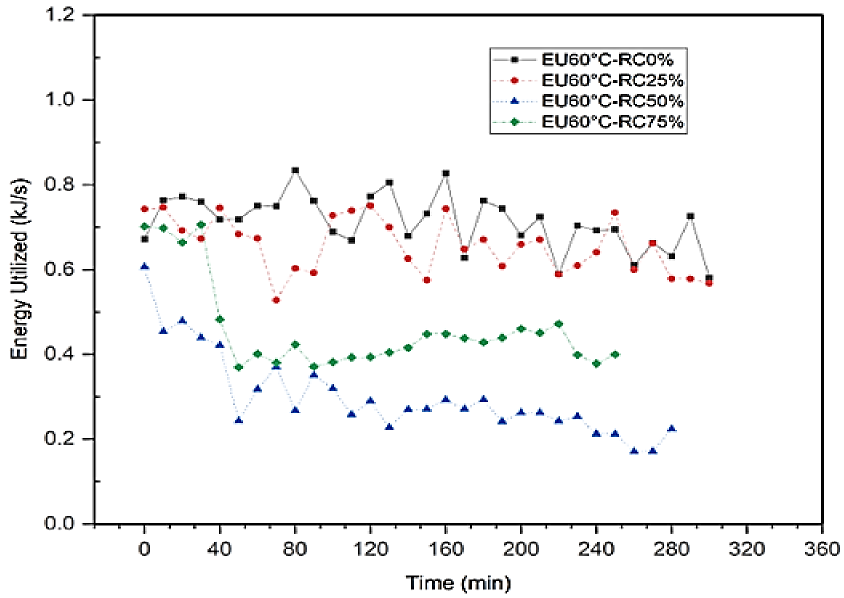

Fig. 5. Energy utilized at 60°C with air recirculation rates of 0%, 25%, 50%, and 75%

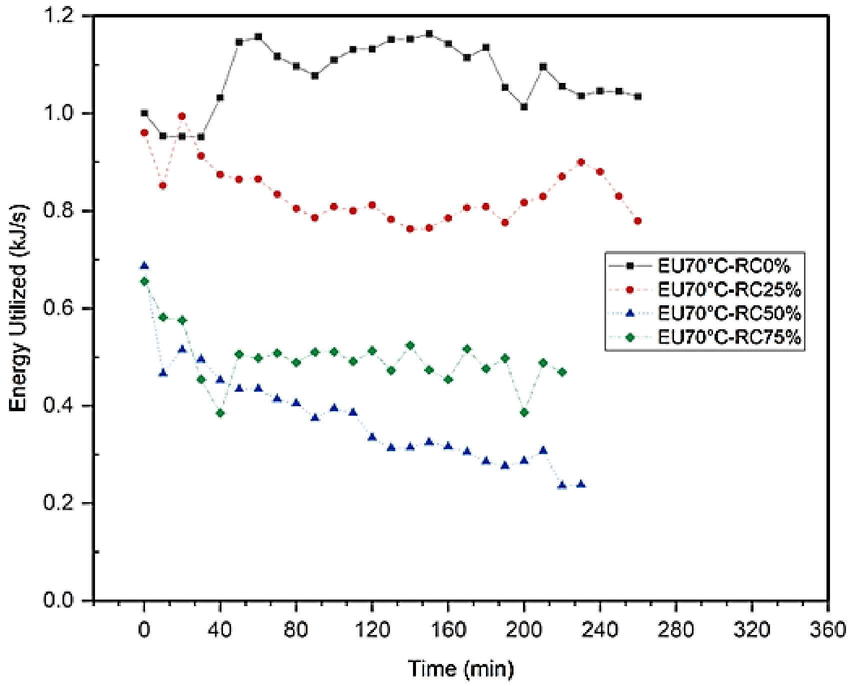

Fig. 6. Energy utilized at 70°C with air recirculation rates of 0%, 25%, 50%, and 75%

The integration of IoT technology in this study enabled dynamic adjustments of air recirculation rates, enhancing control over drying conditions and minimizing energy losses. By adapting airflow based on real-time feedback from drying kinetics, the IoT system maintained optimal conditions throughout the process, ensuring efficient energy use while reducing excess heat loss. This adaptability highlights the importance of smart systems in managing energy utilization and achieving high drying efficiency, as demonstrated in recent smart manufacturing applications by researchers investigating IoT implementations in drying processes [10]. In conclusion, the findings reveal that while higher drying temperatures can enhance energy utilization (EU) at low or zero recirculation rates, increased RC typically diminishes EU due to enhanced thermal retention. This research emphasizes the need to strategically balance drying temperature and air recirculation rates to optimize energy utilization in IoT-controlled drying processes.

3.3 Energy Utilization Ratio

The energy utilization ratio (EUR) and exergy destruction (ExDes) are critical indicators for assessing both the efficiency and thermodynamic quality of energy use in drying processes. EUR reflects the proportion of input energy effectively employed for moisture evaporation, while ExDes quantifies energy losses due to irreversibilities within the system. Figures 7- to 9 depict the variations in EUR and ExDes across temperatures (50°C, 60°C, and 70°C) and air recirculation rates (RC) ranging from 0% to 75%, illustrating how adjustments in temperature and RC impact drying efficiency and energy degradation. At 50°C (Figure 7), the energy utilization ratio (EUR) is maximized at 0% air recirculation (RC), indicating efficient energy use for drying. However, as RC increases, EUR declines, suggesting that air recirculation reduces the energy directly available for moisture removal. Interestingly, Figure 7 (7.2) shows that ExDes decreases as RC increases, with the 0% RC condition showing the highest ExDes values and the 75% RC condition showing the lowest values. This trend indicates that while air recirculation reduces EUR, it also minimizes thermodynamic irreversibilities by maintaining a more stable thermal environment within the drying chamber, as reported in previous exergetic performance studies [11].

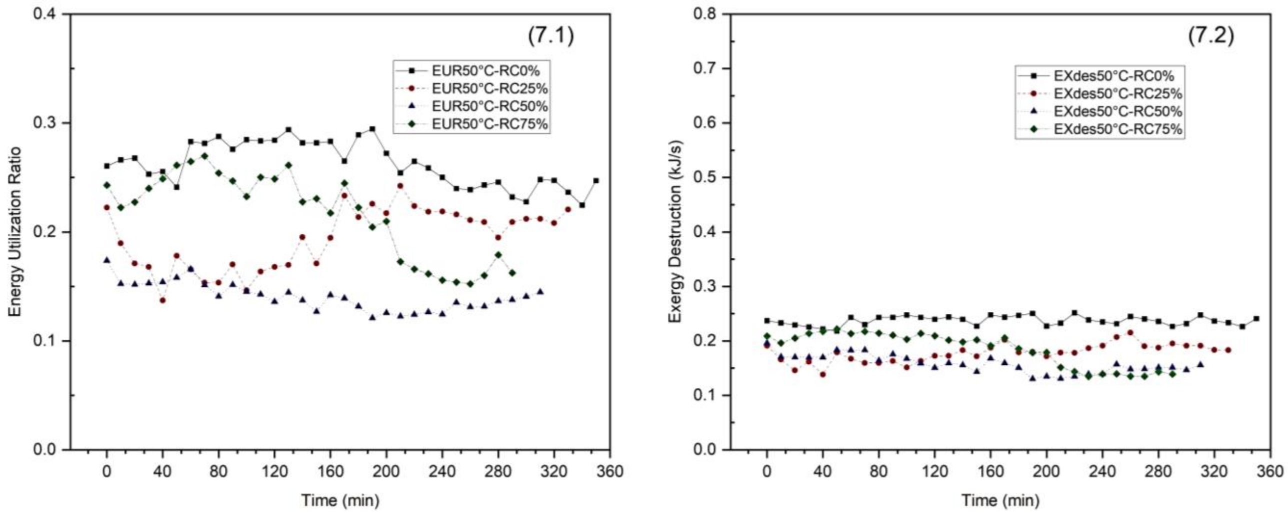

Fig. 2. Energy utilization ratio and exergy destruction at 50°C

At 60°C (Figure 8), the effect becomes more pronounced, with EUR showing similar patterns but lower overall values compared to 50°C. The 0% and 25% RC conditions maintain higher EUR values, while 50% and 75% RC show significantly reduced EUR. Concurrently, Figure 8 (8.2) demonstrates that ExDes decreases substantially at higher RC rates, with 50% RC exhibiting the lowest ExDes values, while 0% and 25% RC conditions show considerably higher values. This inverse relationship between EUR and ExDes highlights the trade-off between direct energy utilization and thermodynamic efficiency, consistent with findings from recent thermal system research [9,25]. At 70°C (Figure 9), EUR sharply declines with higher RC, with 0% RC showing the highest values (approximately 0.28-0.32), followed by 25% RC, while 50% and 75% RC exhibit the lowest values. Correspondingly, Figure 9.2 reveals that ExDes at 0% RC is substantially higher (0.55-0.65) compared to other RC conditions, with 50% RC showing the lowest ExDes values. This pattern indicates that at high temperatures, the relationship between energy utilization and thermodynamic efficiency becomes more critical, as excessive heat without proper recirculation leads to significant exergy losses due to system irreversibilities, as highlighted in recent process optimization literature [7,10].

The IoT-based dynamic control in this study enabled real-time optimization of RC and temperature, effectively balancing EUR and ExDes. The results indicate that while lower RC at high temperatures maximizes direct energy utilization for drying, it also increases thermodynamic irreversibilities. Conversely, higher RC reduces EUR but enhances thermodynamic efficiency by minimizing ExDes. This finding suggests that an optimal balance must be achieved based on specific drying requirements, with IoT-based feedback systems offering precise management of parameters to optimize both energy utilization and thermodynamic performance in advanced drying applications, supporting conclusions from previous optimization studies investigating energy efficiency in thermal systems [2,9].

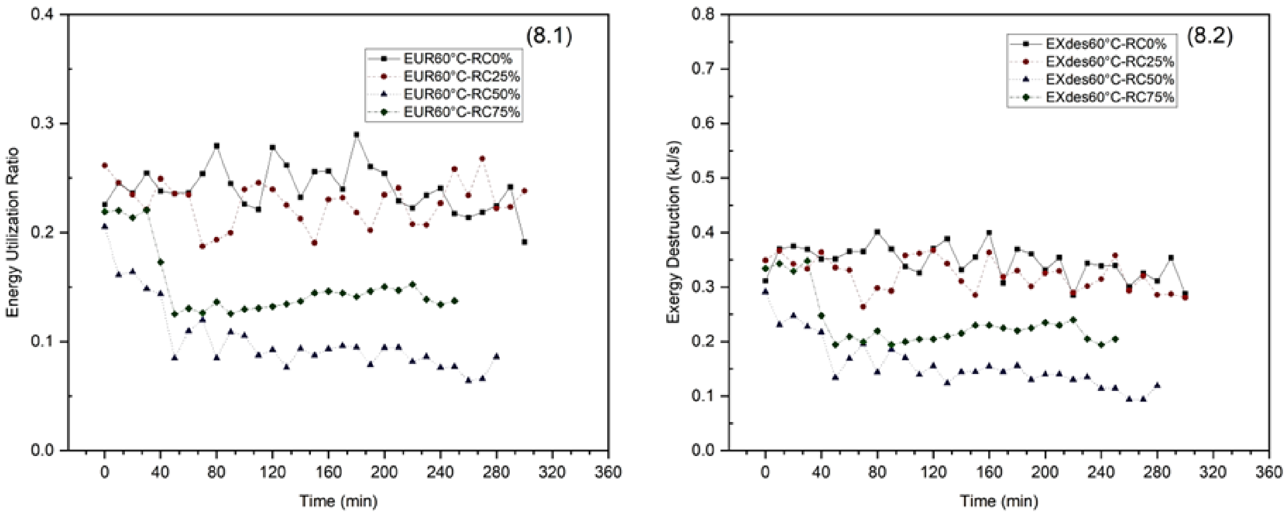

Fig. 3. Energy utilization ratio and exergy destruction at 60°C

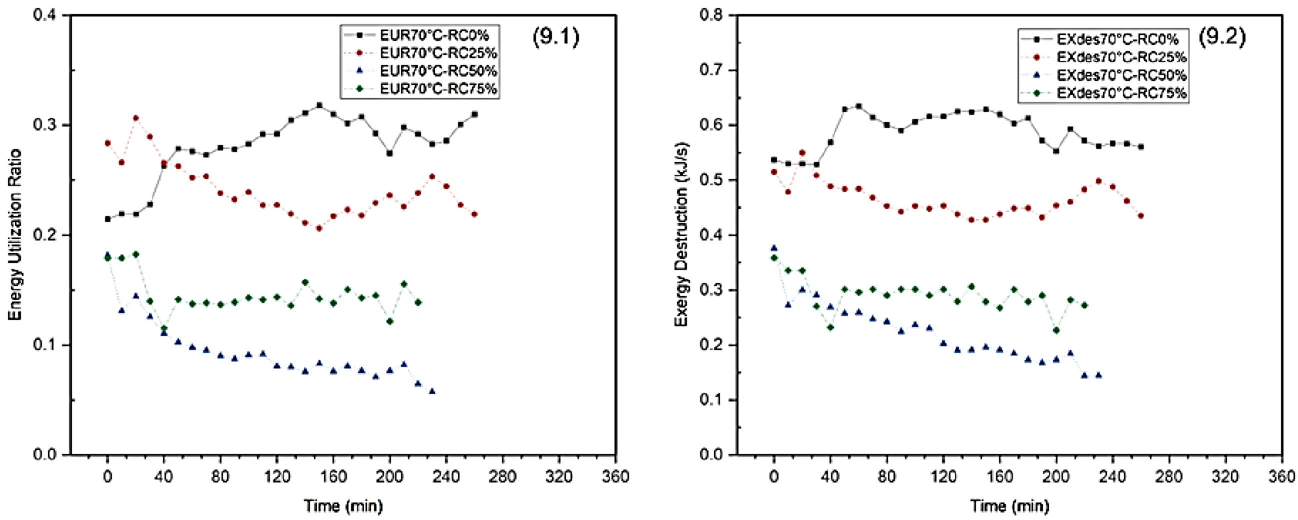

Fig. 9. Energy utilization ratio and exergy destruction at 70°C

3.4 Exergy Efficiency

Exergy efficiency (ExEff) is a key metric in analyzing drying processes, representing the fraction of total exergy input effectively utilized for moisture removal. It reflects the efficiency of energy conversion into useful work, thereby reducing system irreversibilities. Conversely, exergy destruction (ExDes) quantifies energy losses from non-ideal heat transfer, offering insights into thermodynamic efficiency, as demonstrated in previous exergetic analysis studies [11]. Figures 10 to 12 depict variations in ExEff and ExDes at temperatures of 50°C, 60°C, and 70°C with air recirculation (RC) rates of 0%, 25%, 50%, and 75%. At 50°C, Figure 10 (10.1) reveals that ExEff increases with higher RC up to 50%, where it peaks at approximately 0.75. The 50% RC rate shows consistently higher ExEff values throughout the drying period compared to other RC rates. However, when RC increases further to 75%, ExEff shows a slight decrease, suggesting there is an optimal recirculation rate beyond which additional recirculation provides diminishing returns. Meanwhile, Figure 10 (10.2) demonstrates that ExDes decreases as RC increases, with the 0% RC condition showing the highest ExDes values (approximately 0.23-0.25) and the 75% RC condition showing the lowest values (0.10-0.15). This trend indicates that increased recirculation reduces thermodynamic irreversibilities by minimizing heat loss to the environment, consistent with findings from recent thermal optimization research [9].

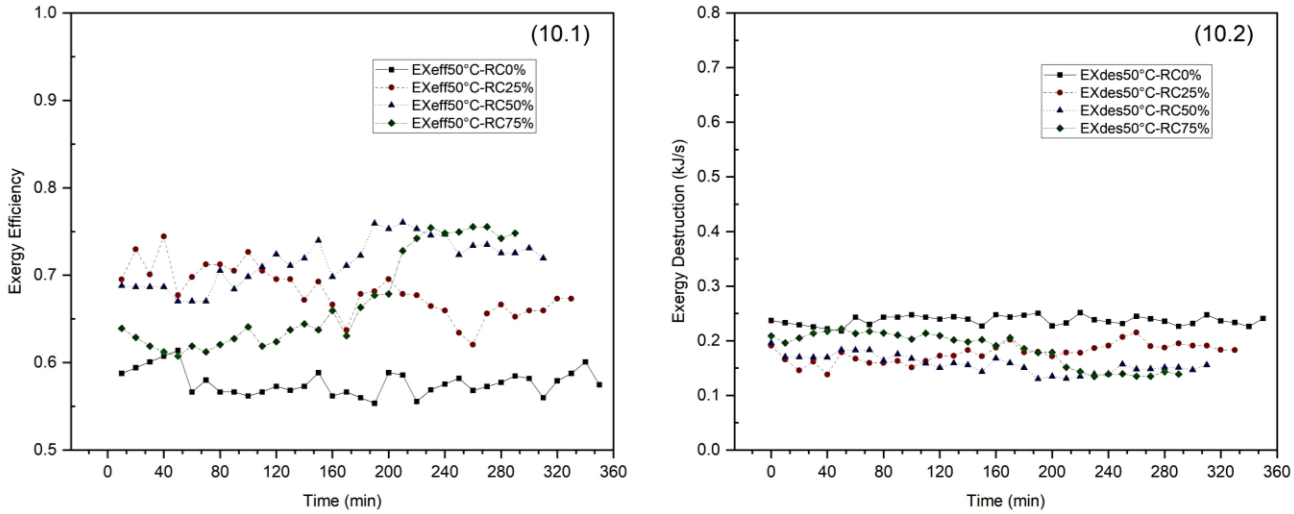

Fig. 10. Exergy eefficiency and exergy destruction at 50°C

At 60°C, the effect of air recirculation on exergy performance becomes more pronounced. As shown in Figure 11 (11.1), ExEff increases significantly with higher RC rates up to 50%, reaching peak values of approximately 0.85-0.90, which represents the highest exergy efficiency observed across all temperature conditions. The 50% RC condition consistently outperforms other recirculation rates throughout the drying process. Concurrently, Figure 11 (11.2) shows that ExDes decreases substantially at higher RC rates, with the 50% RC condition exhibiting the lowest ExDes values (approximately 0.10-0.15), while 0% and 25% RC conditions show considerably higher values (0.30-0.40). This inverse relationship between ExEff and ExDes confirms that optimized recirculation stabilizes the thermal environment within the drying chamber, significantly reducing energy degradation, as documented in recent energy analysis studies [25]. At 70°C, the highest temperature studied (Figure 12 (12.1)), ExEff at 50% RC reaches 0.85-0.90, followed by 75% RC (0.80), 25% RC (0.70), and 0% RC (0.58-0.62). Figure 12 (12.2) shows ExDes at 0% RC is substantially higher (0.55-0.65), with the 50% RC condition showing the lowest values (0.15-0.20), as demonstrated in recent thermodynamic optimization studies [9].

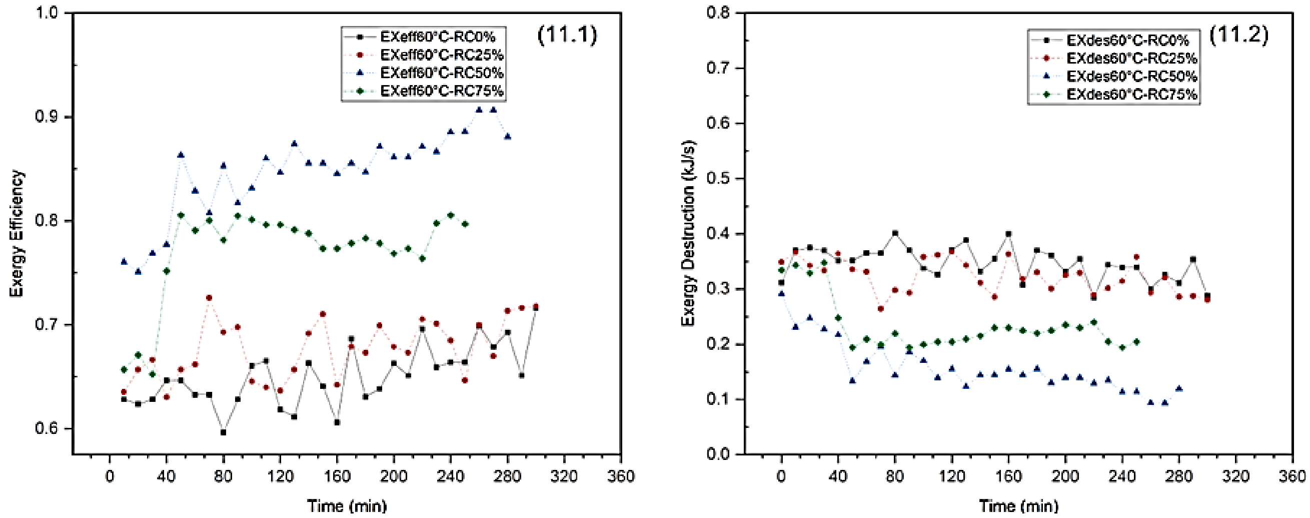

Fig. 11. Exergy efficiency and exergy destruction at 60°C

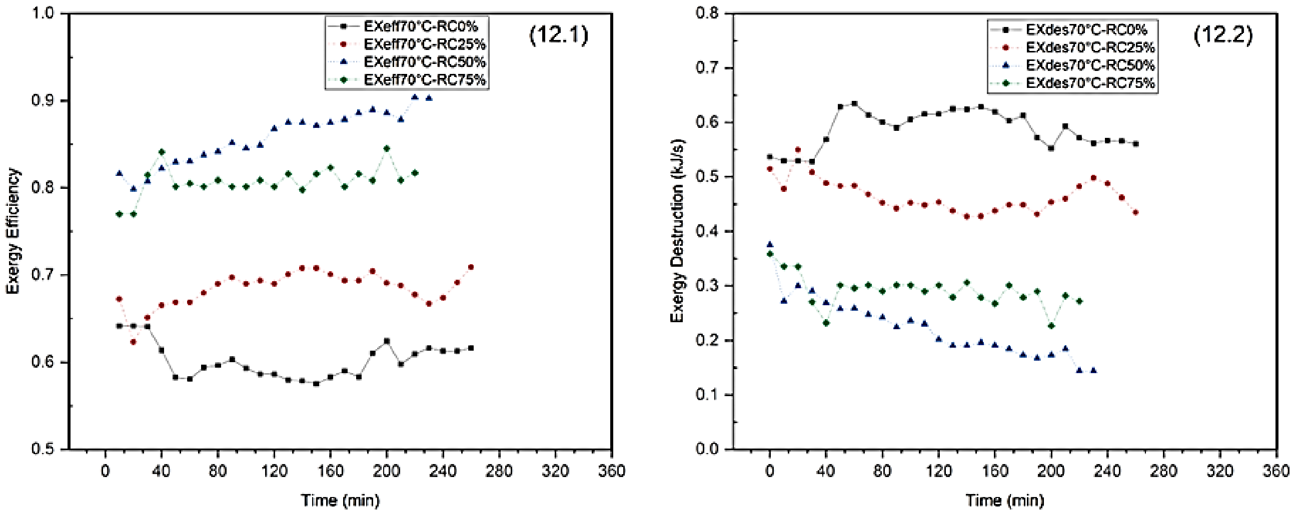

Fig. 12. Exergy efficiency and exergy destruction at 70°C

These findings reveal that 50% RC consistently optimizes exergy efficiency while minimizing exergy destruction across all temperatures. This represents the balance point where thermal energy is retained without compromising the moisture removal driving force. The decline in ExEff from 50% to 75% RC can be attributed to moisture accumulation in recirculated air, which limits drying effectiveness by reducing the vapor pressure gradient, supporting conclusions from previous optimization studies investigating thermodynamic performance in drying systems [2].

4. Conclusions

This study successfully developed an IoT-controlled hot air-drying system with adaptive air recirculation, achieving substantial enhancements in energy and exergy efficiency through real-time control. Experiments conducted at 50°C, 60°C, and 70°C with varying air recirculation rates (0%, 25%, 50%, and 75%) identified optimal parameters for minimizing specific energy consumption (SEC) and maximizing exergy efficiency. The results demonstrated that increasing both temperature and air recirculation significantly optimizes drying performance; specifically, drying at 70°C with 75% recirculation reduced SEC by over 50% compared to baseline conditions (50°C, 0% recirculation). Additionally, higher recirculation rates improved the energy utilization ratio (EUR) by up to 42.1%, reflecting effective energy use through enhanced heat retention. Exergy analysis further indicated that elevated recirculation rates enhance exergy efficiency while concurrently reducing exergy destruction, particularly at moderate to high temperatures. Thus, balancing temperature and recirculation rates is essential for maintaining high energy quality during the drying process. The IoT-enabled control system facilitated dynamic adjustments, optimizing energy efficiency and minimizing exergy destruction in real time. In conclusion, this study underscores the potential of IoT-driven adaptive air recirculation in achieving superior energy and exergy efficiencies. Future research should focus on refining control strategies to further mitigate exergy losses.

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