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# A Study of Energy Consumption and Drying Rate: Comparison of Continuous and Intermittent Drying Methods of Rough Rice

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## ABSTRACT

Rice is one of the oldest-cultivated plants in the world. In terms of cultivated land, it occupies the second largest area after wheat. One of the most critical challenges to meet human demand in the rice production industry is to produce and process this product with the least energy consumption in the shortest duration and with the highest quality. Drying accounts for about 20%-25% of the total energy used in the processing of this product. It has a considerable impact on the final product quality. In this study, we intend to compare continuous and intermittent drying methods of paddy in terms of energy consumption and drying rate. The experiments were conducted using Hashemi rice variety. The drying experiments were conducted at 4 drying temperatures of 40, 50, 60, and 70°C via continuous, two-stage intermittent drying, and three-stage intermittent drying methods. Energy consumption, total drying duration, and process duration were measured for each drying test. The results showed that applying tempering operation between drying stages significantly reduced the energy consumption and the total drying duration. Three-step drying at a temperature of 60°C led to the lowest amount of energy consumption (2566 kJ) and the total drying duration (40 min).

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## INTRODUCTION

Rice is one of the oldest-cultivated plants in the world. It is a staple food for over half of the world's population and provides essential nutrients such as carbohydrates, vitamins, and minerals. Rice is also a good source of energy and is low in fat and cholesterol. After wheat, it occupies the largest area of cultivated land in the world (Alves Pereira et al., 2020; Müller et al., 2022; Zahra et al., 2022). According to the statistics published by the World Food Organization (FAO) in 2022, the global production of rice was about 776 million tons. Also, the total amount of production and cultivated area of paddy in Iran was 1.5 million tons and 400000 hectares, respectively, in year 1401. Due to the world's population growth, the demand for the production and planting of rice increases every year. Considering the limitations of energy resources, water resources, cultivated area and environmental problems, one of the most important challenges in order to meet the human demand in the rice production industry is the producing with the least energy consumption and process duration as well as highest quality (Aquerreta et al., 2007; Chayjan et al., 2019; Cnossen et al., 2002; Mukhopadhyay & Siebenmorgen, 2018; Nasrnia et al., 2024; Zhao et al., 2020). Therefore, one of the main solutions is to increase the production efficiency in different operation units specially in drying process. Converting the freshly harvested paddy to the white rice includes drying, cleaning, husking, whitening, polishing and grading stages. So, in order to convert paddy into white rice and to prevent the biological spoilage, it is necessary to reduce the moisture content (MC) of freshly harvested paddy kernels to a safe level of 12-14% d.b. (Khodadadi et al., 2022; Mabasso et al., 2023; Maldaner et al., 2021; Nasrnia et al., 2024; Nosrati et al., 2022; Song & Wei, 2021; Sun & Zhang, 2022; Wang et al., 2023; Zahra et al., 2022).

Drying is a process that consumes a lot of energy and accounts for about 20% to 25% of the total energy required for processing. This high energy consumption is due to the need to remove moisture from materials, which requires significant heat. Additionally, maintaining consistent temperature and airflow throughout the drying process further adds to the energy demands. The efficiency of the drying equipment also plays a critical role in the overall energy usage. This has a substantial impact on the costs and quality of the final product. Energy consumption yield of the process and head rice yield (HRY) after dehydration are the two main indices for evaluating the drying process of biological products. The global crisis of energy limitations and the demand for high-quality dried products have challenged the researchers to develop innovative drying methods. As a result, providing methods to promote and improve energy consumption in the heating process is very critical and should be studied (Golmohammadi et al., 2015; Kumar et al., 2014; Tiris et al., 1996). Meanwhile, one of the main concerns of food processing industries is the duration of the process, as well as the quality of the products. Regarding the drying process, any solution that could minimize the duration required for eliminating moisture from the product to reach the desired MC value, also can reduce operation costs by reducing energy consumption, increasing drying rate, and enhancing the quality (Cnossen et al., 2002; Mabasso et al., 2023; Song & Wei, 2021; Song et al., 2022; Sun & Zhang, 2022; Zahra et al., 2022).

In the continuous drying method, as the drying process passes, the moisture content of the surface layers rapidly decreases. In contrast, the inner and central layers have a high level of moisture content. This difference in the moisture content of different layers of the kernel will cause moisture content gradients (MCGs), glass transition, and state changes within the starchy part of the rice kernel, which can ultimately cause quality loss and decrease the market value of the final product. To overcome this problem, a multi-stage intermittent drying (MSID) method is suggested to reduce the moisture content to the safe target level (12-14% d.b.). Previous studies result show that the use of intermittent drying method considering the glass transition concept, will significantly improve the drying rate and the quality of the final product and prevent kernel breakage (Aquerreta et al., 2007;

Chayjan et al., 2019; Cnossen & Siebenmorgen, 2000; Dong et al., 2009; Odek et al., 2021; Prakash & Pan, 2012; Yang & Jia, 2004).

Also, the multi-stage intermittent drying (MSID) method can greatly reduce energy consumption. In this method, the freshly harvested product is dried under determined conditions to a certain level of moisture content considering the kinetics of MC. The product is then placed in an isolated chamber to prevent it from absorbing moisture from the surrounding environment. This causes moisture content transfer from the inner layers to the outer layers. This prevents kernel surface shrinkage and the creation of moisture content gradients (MCGs) that lead to the formation of initial cracks within the grain. The process of keeping the product under specific and isolated conditions to balance the moisture content between the different layers of the rice kernel and thus reduce moisture content gradients is called the tempering operation. Since it is easier to remove moisture from the outer surfaces of the kernel and requires less energy, the tempering operation can reduce energy consumption in the next drying stage as well as prevent quality loss (Alves Pereira et al., 2020; Franco et al., 2020; Mabasso et al., 2023; Nasrnia et al., 2024; Nosrati et al., 2022; Wang et al., 2023).

This study compares the efficiency of intermittent and continuous drying of Hashemi variety rice according to the stated content. Specifically, this refers to the energy consumption and drying rate. In previous studies to determine the best drying conditions of MSID method, considerations have been made based on drying duration or energy consumption separately. In this research, the intermittent drying method is determined considering some dependent values all together, including energy consumption, total drying duration and process duration. By analyzing the obtained results, it will be possible to determine which operational conditions will result in the least amount of energy consumption and the shortest drying and process duration during the drying by MSID method.

## MATERIALS AND METHODS

During the harvest season, 100 kg of freshly harvested Hashemi variety rice was obtained from the research farm of Amol Rice Research Center (Mazandaran province, Iran). Immediately after cleaning the samples of dust and excess parts, they were placed in thick and impermeable polyethylene bags to prevent moisture content (MC) loss. Then, the samples were placed in a refrigerator with a 4ºC temperature until the tests were performed. From each bag, three 100 gr samples were randomly selected and the initial MC of each sample was measured. The average of initial MC was measured to be 23% d.b. following the ASABE (2016) standard method (24 h heating in an oven at 130 ºC) (Mabasso et al., 2023; Nosrati et al., 2022; Sun & Zhang, 2022; Wang et al., 2023). Experiments were conducted using two-factor factorial statistical design in the form of completely randomized block design. Drying tests were performed at three repetitions and three levels of drying method (continuous (CD) method, two-stage intermittent drying method (2SID) and three-stage intermittent drying method (3SID)) and four levels of drying temperature (40, 50, 60 and 70 ºC) as shown in Table 1. All data were analyzed by analysis of variance (ANOVA) procedures using the SPSS statistical software package and treatment means were compared by the least significant difference (LSD) test at significance level of 0.05. Drying operation was carried out using a laboratory hot air convective dryer in the Biosystems Engineering Department (Isfahan University of Technology, Iran). The schematic design of the used dryer and its accessories is shown in Figure 1. Drying was followed until reaching the pre-determined final MC of 12% d.b.

**Table 1.** Different pre-determined levels of experimental treatments for studing continuous drying (CD), two-stage intermittent drying (2SID), and three-stage intermittent drying (3SID) method of Hashemi variety rice samples.

| Drying temperature (°C) | Drying method | Duration of drying ($D_i$) or tempering ($T_i$) at each stage of MSID | | | | | Expression |
|---|---|---|---|---|---|---|---|
| | | $D_1$ | $T_1$ | $D_2$ | $T_2$ | $D_3$ | |
| | CD | $t_{D1}$ | - | - | - | - | **Tr1** |
| 40 | 2SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | - | - | **Tr2** |
| | 3SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | $t_{T2}$ | $t_{D3}$ | **Tr3** |
| | CD | $t_{D1}$ | - | - | - | - | **Tr4** |
| 50 | 2SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | - | - | **Tr5** |
| | 3SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | $t_{T2}$ | $t_{D3}$ | **Tr6** |
| | CD | $t_{D1}$ | - | - | - | - | **Tr7** |
| 60 | 2SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | - | - | **Tr8** |
| | 3SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | $t_{T2}$ | $t_{D3}$ | **Tr9** |
| | CD | $t_{D1}$ | - | - | - | - | **Tr10** |
| 70 | 2SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | - | - | **Tr11** |
| | 3SID | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | $t_{T2}$ | $t_{D3}$ | **Tr12** |

The momentary MC of rice samples during the drying process was measured aiming to provide drying kinetics applying a digital balance (SARTORIUS GMBH, Sartorius Co., Goettingen, Germany) with an accuracy of 0.01 g. The laboratory scale was installed outside the drying chamber in such a way that it could measure the momentary weight of the sample substrate. Immediately after the first drying stage, the partially dried sample was removed from the drying chamber and placed in a polyethylene bag in order to prevent moisture transfer to the environment during the current tempering stage. A vacuum oven was used to conduct a tempering procedure drying stages in intermittent drying treatments. Tempering operations were done at the same drying temperature in this study. Then, the sealed bag was placed in the oven for a certain duration according to the experimental design. After the tempering stage, the sample was removed from the sealed bag and immediately placed again in the drying chamber. This was done to start the next drying stage.

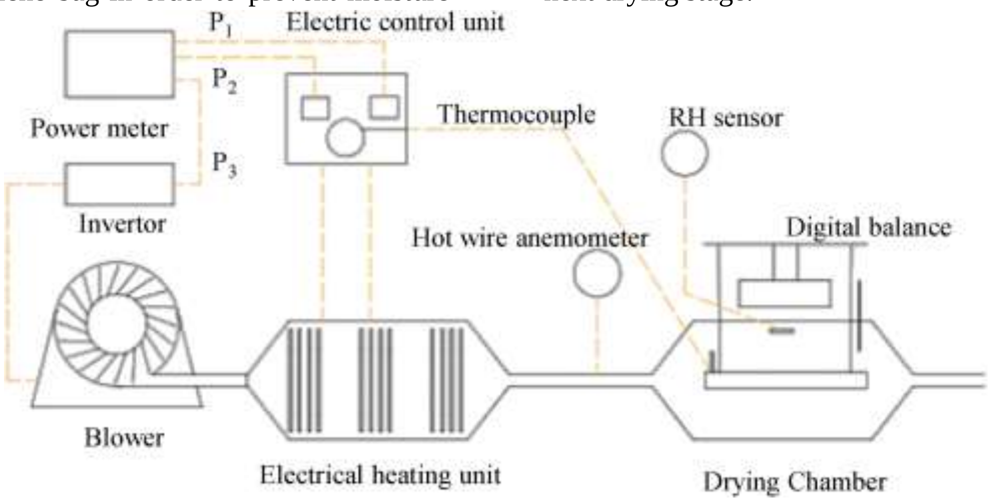


**Figure 1.** Schematic view of convective hot air dryer that was used for experimental tests.

An accurate three-phase digital power meter with an accuracy of 0.01 kWh was installed on the dryer in order to measure the energy consumption of each drying test (model 301 manufactured by TOS Fuse Company (TFC), Khorasan, Iran). During each drying run, electrical parameters, including current, voltage, power, and energy, were measured. The output phases of a power meter were used separately for the blower, the first heating unit, and the second heating unit. Accordingly, the total power ($P_{total}$), total energy ($E_{total}$) and instantaneous power ($P_{ins}$) of each phase were measured and registered. The nominal power of the heating and blower was found to be 2900 and 20 W, respectively. Energy consumption values of other dryer components, including sensors, thermometers, and the psychomotor, were neglected. It was assumed that energy consumption in the tempering stage was negligible compared to the drying stages. Additionally, the drying process was carried out until a MC level of 12% d.b. was achieved.

## RESULTS AND DISCUSSION

The results of variance analysis (ANOVA) indicated that drying temperature and drying method had a significant effect on all dependent variables (i.e. energy consumption values, total drying duration and process duration) at the $p = 0.05$ probability level. So it can be said that, the drying method and the drying temperature had a significant effect on the amount of energy consumption and the drying rate. As a result, the obtained values will be analyzed in the following section. Comparing the results statistically by LSD test, enables appropriate drying condition to be determined in terms of energy consumption and drying rate.

### Analyses of total drying duration and process duration

The moisture content (MC) kinetics of Hashemi variety rice samples for drying methods including continuous drying (CD), two-stage intermittent drying (2SID) and three-stage intermittent drying (3SID) at different drying temperatures are shown in Figures 2 to 5. So, the means of process duration and the total drying duration were provided and were presented in Table 2. The results of means comparing of process durations using LSD test at significance level of 0.05 is shown in Figure 6. The comparison of the obtained values showed that using the multi-stage intermittent drying method compared to the continuous drying method at drying temperature of 40°C greatly reduced the process duration (sum of tempering and drying durations). But at other temperatures of 50, 60 and 70°C, the process duration did not decrease significantly. So that, even the process duration was increased slightly. This is due to the use of tempering operations between drying stages. In general, in all three drying methods (i.e. CD, 2SID, and 3SID) the process duration decreased by increasing the drying temperature. In the 2SID and 3SID method, the process duration increased significantly by increasing the drying temperature from 60°C to 70°C. At drying temperature of 60°C, the process duration did not change significantly by increasing the number of drying stages. The lowest process duration was obtained at the drying temperature of 60°C using 2SID method (Tr8, 66 min), and the longest process duration was related to drying at the drying temperature of 40°C in the CD method (Tr1, 222 min). So that drying at low temperatures was very time-consuming due to the low effective diffusion coefficient, and was not economically viable. Therefore, it can be said, at temperatures of 40, 50 and 70°C, using the intermittent drying method not only does not reduce the process duration, but it increased the process duration to some extent. On the other hand, increasing the number of drying stages at temperatures close to the glass transition temperature (60°C) does not have a significant effect on the process duration. Therefore, the effect of increasing the number of drying stages on drying duration and energy consumption can be more useful for determining the appropriate intermittent drying plan.

**Table 2.** The duration of each drying/tempering stage, the total drying duration, and the total process duration during drying the Hashemi variety rice in continuous drying (CD), two-stage intermittent drying (2SID), and three-stage intermittent drying (3SID) method at different drying temperatures.

| Drying temperature (ºC) | Expression | Duration of drying ($D_i$) or tempering ($T_i$) at each stage (min) | | | | | Process duration (min) | Total drying duration (min) |
|---|---|---|---|---|---|---|---|---|
| | | $t_{D1}$ | $t_{T1}$ | $t_{D2}$ | $t_{T2}$ | $t_{D3}$ | | |
| 40 | Tr1 | 222 | - | - | - | - | 222 | 222 |
| | Tr2 | 60 | 35 | 50 | - | - | 145 | 110 |
| | Tr3 | 30 | 15 | 20 | 20 | 75 | 160 | 125 |
| 50 | Tr4 | 85 | - | - | - | - | 85 | 85 |
| | Tr5 | 40 | 20 | 40 | - | - | 100 | 80 |
| | Tr6 | 20 | 20 | 15 | 30 | 23 | 108 | 58 |
| 60 | Tr7 | 69 | - | - | - | - | 69 | 69 |
| | Tr8 | 30 | 19 | 17 | - | - | 66 | 47 |
| | Tr9 | 15 | 15 | 15 | 15 | 10 | 70 | 40 |
| 70 | Tr10 | 71 | - | - | - | - | 71 | 71 |
| | Tr11 | 30 | 30 | 23 | - | - | 83 | 53 |
| | Tr12 | 30 | 20 | 20 | 30 | 1 | 101 | 51 |

Table 2 shows that continuous drying (CD) method has a longer total drying duration (sum of the drying durations) than multi-stage intermittent drying (MSID) method. Moreover, the required total drying duration decreased by increasing the number of drying stages. As shown in Figure 7, using the MSID method compared to the CD method, generally reduced the total drying duration. This reduction was intensive at 40°C. At the drying temperature of 40°C, increasing the number of drying stages from 2SID to 3SID slightly increased the total drying duration. But at the drying temperatures of 50°C and 60°C, increasing the drying stages from 2SID to 3SID, significantly reduced the total drying duration. At a temperature of 70°C, increasing the number of drying stages, did not have a significant effect on reducing the total drying duration. Thus, it can be said that at drying temperatures close to the glass transition line (50°C and 60°C), increasing the number of drying stages in an intermittent manner can significantly reduce the total drying duration. On the other hand, in all drying methods including CD, 2SID, and 3SID, the total drying duration decreased by increasing drying temperature from 40°C to 60°C, but by increasing drying temperature from 60°C to 70°C, the total drying duration increased slightly. The results showed that the lowest amount of total drying duration was observed at drying temperature of 60°C and 3SID method (Tr9, 40 min). Also, the longest total drying duration was related to drying at 40°C and CD method (Tr1, 222 min). Therefore, by using multi-stage intermittent drying method and suitable drying temperature close to glass transition temperature, the rate of drying operation can be improved. Thus, the MSID method at low temperatures did not significantly decrease the total drying duration (Figure 7). Using a dryer at 60°C shortens total drying duration and improves energy efficiency. Additionally, it can help preserve the quality and structural integrity of dried samples. Therefore, increasing the number of drying stages considerably decreased the total drying duration. However, increasing the number of drying stages had not significant effect on the reduction of the process duration. The results are consistent with other researchers' findings (Cnossen & Siebenmorgen, 2000; Nasrnia et al., 2024; Odek et al., 2021; Perdon et al., 2000). So that the researchers reported that, it is possible to use high drying temperatures to drying rough rice with high drying rate and without quality (HRY) loss. In this manner, they suggest the multi-stage intermittent drying method at high drying temperatures near 60°C for different rice varieties. Also, using drying temperatures above the 60°C can cause the loss of nutrients and useful proteins inside the rice kernel. Therefore, the use of drying temperatures above the 60°C has some limitations according to the qualitative considerations.

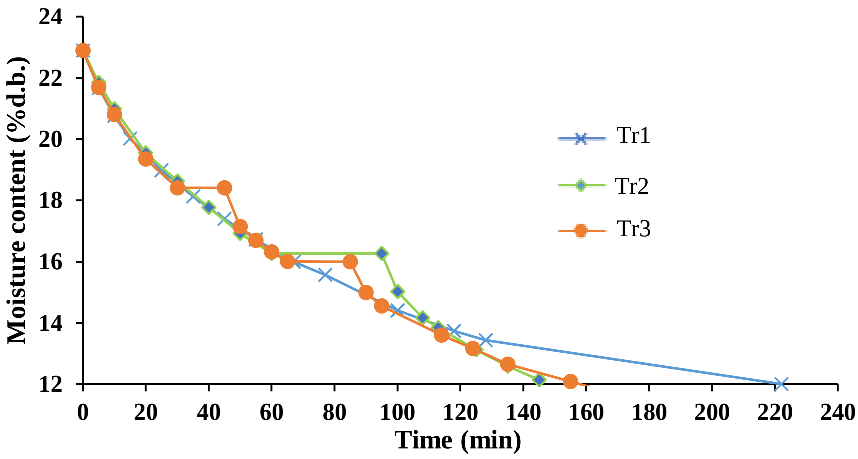


**Figure 2.** Moisture content Changes vs drying process time during drying of Hashemi variety rice samples using continuous drying (Tr1), two-stage intermittent drying (Tr2) and three-stage intermittent drying (Tr3) method at 40ºC.

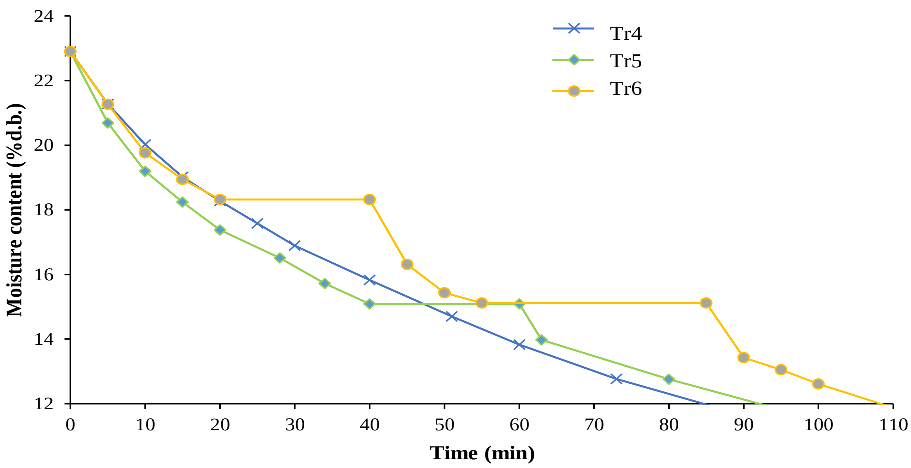


**Figure 3.** Moisture content Changes vs drying process time during drying of Hashemi variety rice samples using continuous drying (Tr4), two-stage intermittent drying (Tr5) and three-stage intermittent drying (Tr6) method at 50ºC.

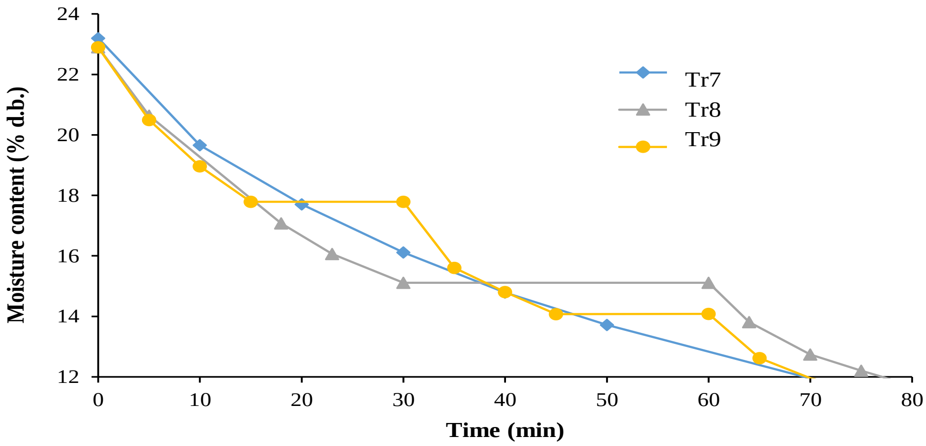


**Figure 4.** Moisture content Changes vs drying process time during drying of Hashemi variety rice samples using continuous drying (Tr7), two-stage intermittent drying (Tr8) and three-stage intermittent drying (Tr9) method at 60ºC.

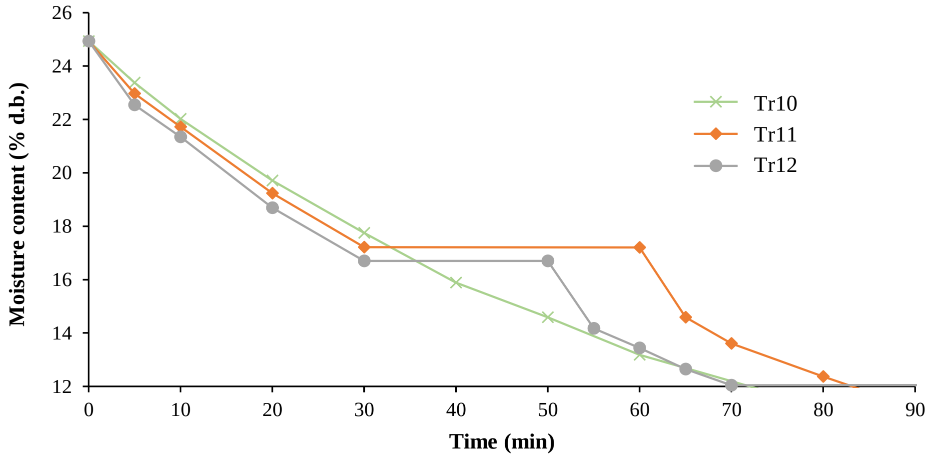


**Figure 5.** Moisture content Changes vs drying process time during drying of Hashemi variety rice samples using continuous drying (Tr10), two-stage intermittent drying (Tr11) and three-stage intermittent drying (Tr12) method at 70ºC.

## Analyses of energy consumption

Throughout the drying process of the Hashemi variety rice samples under different defined drying conditions, the mean energy consumption of the heating units of the dryer ($E_{Di}$), the energy consumption of the blower unit ($E_{Blower}$), and the total energy consumption of the dryer ($E_{total}$) are provided in Table 3. The results of mean comparison of total energy consumption using LSD test are shown in Figure 8. Those indicate that, at all drying methods (CD, 2SID, and 3SID), the total energy consumption was significantly reduced by increasing the drying temperature from 40°C to 60°C thanks to the lower amounts of heating durations. However, increasing the drying temperatures from 60°C to 70°C led to higher total energy consumption. This is related to the large MC gradients created in high drying temperatures that lead to surface shrinkage and consequently evaporation limits. According to Figure 8, using the intermittent drying method significantly reduced total energy consumption. At the drying temperature of 40°C, increasing the number of drying stages from 2SID to 3SID had not considerable effect on reducing energy consumption and partially increased that. But at the temperature of 50°C and 60°C, increasing the number of drying stages from 2SID to 3SID, significantly decreased total energy consumption. So, intermittent drying method at temperatures close to the glass transition temperatures (50°C and 60°C) were significantly effective on energy consumption reduction. The findings of some related studies confirm this issue (Cnossen et al., 2002; Nasrnia et al., 2024). They reported that using the temperatures near glass transition line in MSID method can locate the rice layers in the rubbery state with higher diffusion coefficient. This finally improves the drying rate and energy efficiency. Also, at the drying temperature of 70°C, by increasing the number of stages from 2SID to 3SID, the amount of energy consumption did not change much enough. The lowest amount of energy consumption was obtained at the drying temperature of 60°C applying the 3SID method (Tr9, 2566 kJ). The highest amount of energy consumption was obtained at the drying temperature of 40°C using the CD method (Tr1, 6926.4). Therefore, it can be said that using the intermittent drying method at the proper drying temperature can significantly reduce energy consumption. By increasing the drying temperature from 40°C to 60°C, energy consumption overall decreases, but by increasing the temperature from 60°C to 70°C in all drying methods, the amount of energy consumption increased significantly. As mentioned above, the shortest total drying duration was also observed under the 3SID method at 60°C (Tr9, 40 min). So, multi-stage intermittent drying method can reduce energy consumption and total drying duration compared to continuous drying method.

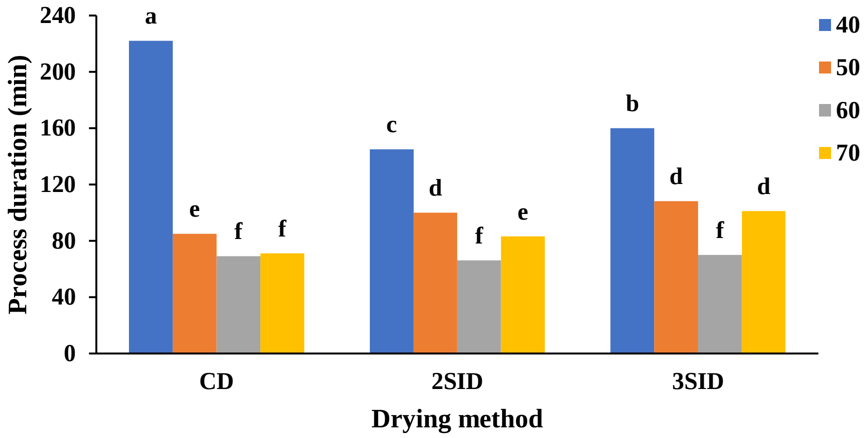


**Figure 6.** Process durations (sum of tempering and drying durations) of different drying methods (continuous drying (CD), two-stage intermittent drying (2SID), and three-stage intermittent drying (3SID)) during drying Hashemi rice variety at drying temperatures of 40, 50, 60, and 70 ºC.

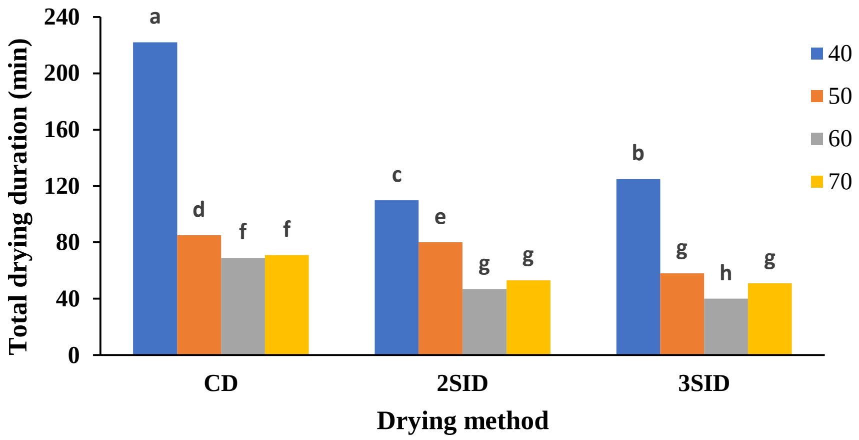


**Figure 7.** Total drying duration (sum of drying durations) of different drying methods (continuous drying (CD), two-stage intermittent drying (2SID), and three-stage intermittent drying (3SID)) during drying Hashemi rice variety at drying temperatures of 40, 50, 60, and 70ºC.

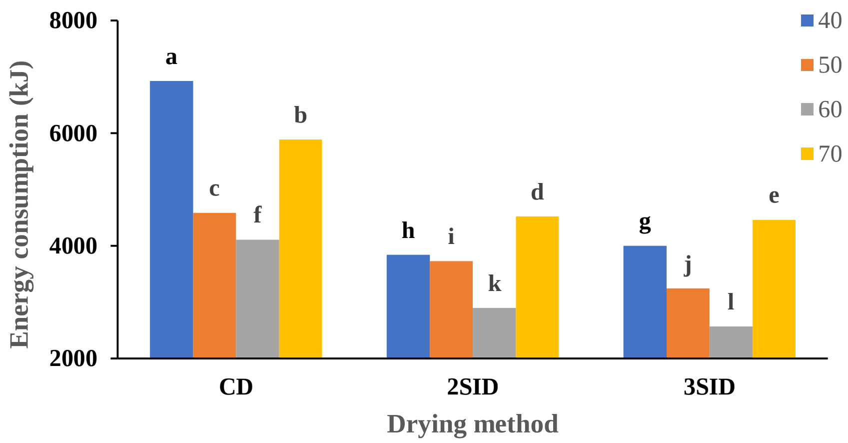


**Figure 8.** Energy consumption of different drying methods (continuous drying (CD), two-stage intermittent drying (2SID), and three-stage intermittent drying (3SID)) during drying Hashemi rice variety at drying temperatures of 40, 50, 60, and 70ºC.

**Table 3.** The energy consumption of each drying stage and the total energy consumption during drying the Hashemi variety rice in continuous, 2SID, and 3SID method at different drying temperatures.

| **Drying temperature (ºC)** | **Expression** | **Energy consumption at drying stages (kJ)** | | | $E_{Blower}$ **(kJ)** | $E_{total}$ (kJ) |
|---|---|---|---|---|---|---|
| | | $E_{D1}$ | $E_{D2}$ | $E_{D3}$ | | |
| | Tr1 | 6660 | - | - | 266.4 | 6926.4 |
| 40 | Tr2 | 1836 | 1872 | - | 132 | 3840 |
| | Tr3 | 936 | 648 | 2268 | 150 | 4002 |
| | Tr4 | 4485 | - | - | 102 | 4587 |
| 50 | Tr5 | 2398 | 1250 | - | 81.6 | 3729.6 |
| | Tr6 | 1093 | 832 | 1250 | 69.6 | 3244.6 |
| | Tr7 | 4025 | - | - | 82.8 | 4107.8 |
| 60 | Tr8 | 1793 | 1049 | - | 56.4 | 2898.4 |
| | Tr9 | 935 | 935 | 648 | 48 | 2566 |
| | Tr10 | 5802 | - | - | 85.2 | 5887.2 |
| 70 | Tr11 | 2511 | 1949 | - | 63.6 | 4523.6 |
| | Tr12 | 2511 | 1708 | 182 | 61.2 | 4462 |

## CONCLUSION

It is proven that applying the tempering operation between the drying stages in the multi-stage intermittent drying (MSID) method reduces the MC and thermal gradients, which in turn allows more efficient moisture evaporation from the kernel surface during the next drying stage. Reduced moisture content gradients lead to a more uniform drying process, which minimizes the risk of kernel cracking and other structural damages. This enhances the overall quality and shelf-life of the dried product. Additionally, it ensures that energy usage is optimized, resulting in cost savings and improved efficiency. Consequently, the drying rate improved and the amount of thermal energy consumed decreased, which led to better drying results. Based on our research, the use of the 3SID method (Tr9) at 60°C is suggested as the most efficient drying condition for the Hashemi variety in terms of energy consumption and drying rate.

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