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Multi-Objective Investigation and Optimization of Paddy Processing in a Hot Air Dryer

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Abstract

In order to investigate the convective drying of paddy kernels, process time, required energy and head rice yield (HRY) were experimentally measured for different combination of air temperature (40, 55 and 70 °C), velocity (0.6, 1 and 1.4 m/s), drying bed height (18, 25 and 32 cm), and final moisture content of paddy (8, 10 and 12% wet basis). According to the results, at higher temperatures, and for the end-products with higher moisture contents, lower energy was required for drying process, but by increasing the air velocity and sample's bed height the amount of consumed energy increased. The conducted experiments also showed that by changing the drying parameters, HRY varied from 36.32 to 80.56 %. The response surface methodology (RSM) and desirability factor were also used to find optimized conditions and showed that for samples with bed height 18 cm, the convective drying with 59 °C, 0.6 m/s, until the final moisture content of 0.09% wet basis, provides a maximum desirability of 0.791.

Keywords

deep-bed drying, energy consumption, head rice yield, multi-objective optimization

1 Introduction

In order to maintain the quality and increase the shelf life of agricultural products, they must be dried artificially [1]. Drying of agricultural and food products is an important and critical step since it not only needs to consume a great amount of energy but also could cause significant quality degradation of the final product if practiced inappropriately [2]. So, the wide variety of dried foods consumed daily and the human desire to conserve natural resources – by reducing energy consumption as well as product quality detrition – emphasizes the need to fully understand the dehydration process [3].

Proper drying has recently become one of the important challenges in agri-food production section where numerous scientific studies have been conducted by researchers. With scientific and technological advancements, traditional drying methods have been replaced by industrial dryers due to their prominent disadvantages [4]. In spite of extraordinary benefits and increasing utilization, industrial dryers face some serious problems mainly consumption great amounts of energy and destructive effects on product quality [5].

After corn and wheat, among the cereals, rice (*Oryza sativa*) has the third most cultivated worldwide area and is accounted as a vital food source for about 40% of the world's population [6]. Due to the importance of rice in the food basket of a great number of people as well as the energy consumption crisis in recent decades, numerous scientific studies have been conducted and reported on drying process of rice kernels from different aspects of view. For example, Timm et al. [7] conducted a research work to assess the influence of drying temperature and bed depth in an infrared dryer on different quality indices such as color, head rice yield, intensity of endosperm fissures, cooking time, and hardness. Lang et al. [8] studied the roles of drying temperature and long-term storage under different atmospheres on phenolic content of black rice. Truong et al. [10] investigated the influence of drying temperature and tempering on physical and chemical properties of rice kernels in a fluidized bed dryer. Junka et al. [9] investigated of optimal conditions for drying and storage of purple rice by considering quality parameters including total phenolic content and antioxidant activity.

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Despite the use of modern drying methods for rice drying, hot air fixed bed dryers are still the most common and cost-effective drying method for this product due to their undeniable advantages. Therefore, optimizing the drying conditions for this product in these dryers is of particular importance. On the other hand, to achieve optimal conditions, all effective factors in the drying process must be considered. By reviewing the studies reported by other researchers, it was found that the comprehensive optimization of rice drying conditions in a deep-fixed-bed dryer by considering all the important influencing factors has been neglected.

1.1 Scope and objective

By considering the shortcomings of the previous scientific work reported on rice drying process, determining the optimal conditions for rice drying in semi-industrial conditions was the main motivation to conduct this study. To this end, the main drying factors including temperature and velocity of the entering air into chamber, drying bed height and final moisture content of paddy kernels were practiced in different levels; and the process times, consumed energy and *HRY* determined experimentally. Response surface method was also used to obtain the optimized drying variables.

2 Methodology

2.1 Drying experiments

Freshly harvested and threshed paddy (Sazandegi variety) was prepared from a local rice-field, and transferred to laboratory in vacuum-packed bags. Before conducting drying experiments, paddy bags were stored at controlled temperature of about 4 °C. By practicing standard procedure (drying at 130 °C for 24 h) described by ASAE [11] with 5 replications, moisture content of the fresh harvested kernels was found to be 21 ± 0.02% (wet basis).

Dehydration experiments were conducted in a convective dryer (described in detail by Torki-Harchegani et al. [12]) based on complete factorial design at different drying air temperatures (40, 55 and 70 °C) and velocities V (0.6, 1 and 1.4 m/s) as well as the bed heights (18, 25 and 32 cm) and average final moisture contents of the kernels bulk (12, 10 and 8% wet basis). During all the experiments, the relative humidity in the lab was controlled and adjusted to be 40% using an ultrasonic humidifier.

Throughput the experiments, average moisture in the paddy bulk (M, wet basis) was instantaneously computed based on its initial value (M_0, wet basis) using Eq. (1) [13]:

$$M = \frac{(M_0 - 1) \times m_0}{m} + 1. \tag{1}$$

In Eq. (1), m_0 and m are mass (kg) of the paddy bulk at beginning of the process and each weighing time, respectively.

2.2 Specific energy consumption

The total consumed energy of the dryer including the blower and heating system (E_t) was experimentally measured using a digital power meter (Ziegler Delta Power, Germany) and the obtained data was used to assess specific energy consumption (SEC, MJ/kg$_{\text{paddy}}$) of the process:

$$SEC = \frac{E_t}{m_0}. \tag{2}$$

2.3 Head rice yield

To determine the head yield rice, the dried paddy samples were dehusked and milled. 500 g of each cleaned dried paddy sample was exactly weighed using the precise electronic balance, and dehusked using the laboratory rubber roll type huller machine. Subsequently, the whole dehulled grains were milled for 30 s to produce white rice kernels using the whitener. Finally, using the laboratory rice grader and a mesh of 5.25 mm, the head rice was separated and *HRY* determined the following equation [14]:

$$HRY = \frac{\text{Mass of head rice (g)}}{\text{Mass of paddy before milling (g)}}. \tag{3}$$

2.4 Determination of optimized parameters

In the present study, RSM/Box-Behnken design was implemented to determine optimum factors of the process and achieve desired targets. Inputs included drying air variables (including temperature and velocity), drying bed height and moisture content of the final dried samples; and time, specific consumed energy and head rice yield were considered as the process traits.

The test parameters as well as the used levels in Box-Behnken are shown in Table 1. In addition, of the model desirability (D) was estimated based on the variables desirability (d_i) in the following form [15]:

$$D = \frac{(d_i \times d_{ii} \times \ldots \times d_n)}{n}. \tag{4}$$

Analysis of variance was used to assess accuracy and effectiveness of the model.

Table 1 Independent variable values and their corresponding levels

Variable	Symbol		Range and levels		
	Un-coded	Coded	Level 1 (L1) Low (−1)	Level 2 (L2) Medium (0)	Level 3 (L3) High (1)
Drying air temperature (°C)	*T*	x1	40	55	70
Drying air velocity (m/s)	*V*	x2	0.6	1.0	1.4
Drying bed height (cm)	*H*	x3	18	25	32
Final moisture content (%)	*M*	x4	8	10	12

2.5 Statistical analysis

For statistical analyzing, SPSS (19.0) and ANOVA procedure were used to evaluate the impact of the pre-treatment and drying variables on the considered indices. Comparison of the means was also done using Duncan's test at $p < 0.05$.

3 Results and discussion

3.1 Process time

Through the experiments, the specific time of the process (*st*, min/kg_{paddy}), defined as the drying time per mass of samples, was determined and the results are represented in Fig. 1. Form the results, the time was significantly ($P < 0.01$) decreased at the higher temperatures. For better evaluation, the results were also given in Table 2. Based on the mean comparison, the average specific time at temperatures of 40, 55 and 70 °C was determined to be 233.10, 94.88 and 43.53 min/kg_{paddy}, respectively.

Ghanbarian et al. argued that by increasing the temperature the rate of transfer of heat between the surrounding environment and samples, as well as the concentration

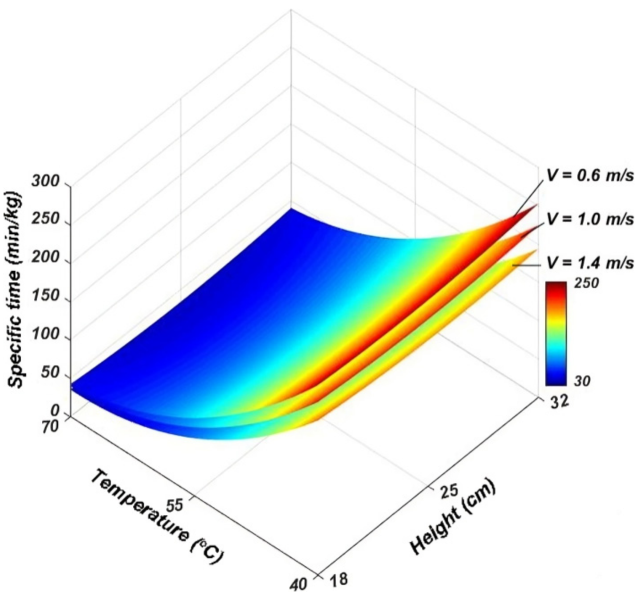

Fig. 1 Variation of specific time (min/kg_{paddy}) with different drying parameters

of interfacial moistness are both increase during the drying process [16]. Consequently, the moisture diffusion improves and the process time is shortened by rising the temperature of drying air. The same finding has been reported for dehydration of red ginseng in a far-infrared dryer [17] and yacón in a convective dryer [18].

According to the experimental results, by increasing the velocity of the air flow the specific drying time is shortened. Fig. 1 clearly shows that the main contribution of air velocity was found at lower drying temperature i.e., 40 °C. It is found from Table 2 that at the velocities of 0.6, 1.0 and 1.4 m/s the average value for the time was obtained about 139.94, 124.63 and 106.95 min/kg_{paddy}, respectively. So, compared with the effect of temperature, theair velocity imposes less effective impact on the specific time of drying process. The phenomenon is mainly due to the reduced boundary layer resistance at the higher air low rates. Detailed discussion for this topic could be found in the study conducted and reported by Tohidi et al. [8]. The same finding could also be observed in several studies such as Elmas et al. [19] and Ojediran et al. [20].

According to outcomes, mean values of the specific time were computed to be 128.76, 118.83 and 123.92 min/kg_{paddy} which were not statistically different ($P > 0.05$). During deep-bed drying process, the resistance against moving of drying air from the bed bottom to its top increases and higher temperature and humidity gradients are induced throughout the bed height. Consequently, this leads to a more prolonged drying process. The phenomenon has been investigated and discussed in detail by Torki-Harchegani et al. [12]. Therefore, it is quite clear to expect an increase in the drying process time with an increase in bed height, as some researchers have pointed out. Conducting an experimental study to dry coarse lignite particles at different drying bed heights, Pusat et al. [21] reported higher beds led to longer time required to dehydrate the particles. Çalban [22] assessed the effect of bed height on dehydration behavior of lignite and observed that the process duration became shorter with the bed height reduction. However, the way the specific time – as defined and

Table 2 Specific time at the practiced drying treatments

Temperature (°C)	Velocity (m/s)	Height (cm)	Specific time (min/kg$_{paddy}$) final moisture content (%, wet basis)		
			8	10	12
40	0.6	18	357.41 ± 16.29	237.65 ± 11.37	179.63 ± 14.19
		25	361.33 ± 18.01	224.89 ± 12.41	162.22 ± 9.67
		32	399.31 ± 21.82	239.93 ± 15.26	163.54 ± 10.18
	1.0	18	327.78 ± 16.93	223.46 ± 16.11	172.22 ± 10.75
		25	319.56 ± 19.54	207.11 ± 13.09	153.33 ± 8.47
		32	362.15 ± 20.13	212.50 ± 17.59	150.00 ± 11.51
	1.4	18	287.65 ± 9.44	198.15 ± 11.72	154.94 ± 9.38
		25	272.44 ± 13.52	180.89 ± 10.45	135.56 ± 10.66
		32	299.31 ± 15.23	181.25 ± 11.07	129.51 ± 9.27
50	0.6	18	149.38 ± 8.37	104.32 ± 9.41	81.48 ± 6.25
		25	148.00 ± 9.12	96.44 ± 6.84	70.67 ± 7.34
		32	169.79 ± 12.55	101.04 ± 8.61	70.49 ± 6.93
	1.0	18	134.57 ± 11.08	95.06 ± 7.68	74.69 ± 6.26
		25	124.89 ± 9.73	84.44 ± 5.15	62.67 ± 7.32
		32	131.60 ± 10.50	83.68 ± 6.94	59.38 ± 5.63
	1.4	18	116.05 ± 8.74	82.72 ± 7.13	66.05 ± 6.41
		25	103.56 ± 9.16	71.56 ± 5.29	54.22 ± 4.09
		32	105.90 ± 10.34	68.75 ± 6.49	50.35 ± 6.15
60	0.6	18	70.99 ± 6.40	51.23 ± 4.03	42.59 ± 3.31
		25	65.78 ± 5.73	44.89 ± 3.76	35.56 ± 3.93
		32	71.18 ± 6.08	44.79 ± 4.16	33.68 ± 2.58
	1.0	18	61.11 ± 5.57	44.44 ± 3.82	37.65 ± 3.41
		25	54.67 ± 4.13	38.22 ± 3.12	30.67 ± 2.35
		32	55.21 ± 4.62	35.76 ± 2.19	28.13 ± 3.77
	1.4	18	52.47 ± 3.19	38.89 ± 3.65	33.95 ± 2.11
		25	44.89 ± 4.75	32.44 ± 2.46	27.56 ±2.55
		32	43.75 ± 3.61	30.21 ± 2.75	24.65 ± 1.99

investigated in this research – changes with the product height is quite a complex matter and depends on some factors such as the air temperature and velocity, bed height and inherent characteristics of the product.

As expected, the process duration was significantly ($P < 0.01$) increased as desired moisture content of the final product decreased from 12 to 10 and from 10 to 8%, where the required specific time was accounted to be 84.65, 113.14 and 173.73 min/kg$_{paddy}$. The reason for this observation could be related to the amount as well as the type of water that must be removed from the product.

3.2 Specific energy consumption

The results of experiments performed for *SEC* were depicted in Fig. 2. As can be seen, the enhancement in the temperature in the practiced range (40–70 °C) importantly ($P < 0.01$) decreased the *SEC*. According to the results, the *SEC* had a sharp decrease as the drying temperature increased from 40 to 70 °C. The mean values for the specific consumed energy are also given in Table 3.

It is noted that at drying temperatures of 40, 55 and 70 °C, the *SEC* was determined to be 8.62, 4.96 and 2.69 MJ/kg$_{paddy}$, respectively. Such a great reduction was primarily achieved by the reduction in time duration of drying process. The observation is consistent with the outcomes of previous studies conducted on different products such peppermint leaves [16], wormwood leaves [23] and chamomile [24].

In this study the experiments were repeated for different drying air velocities and it was confirmed that at higher air flow rates, more energy was consumed by the drying system. However, relying on the obtained results, the velocity had not an important role ($P > 0.05$) on amount of consumed

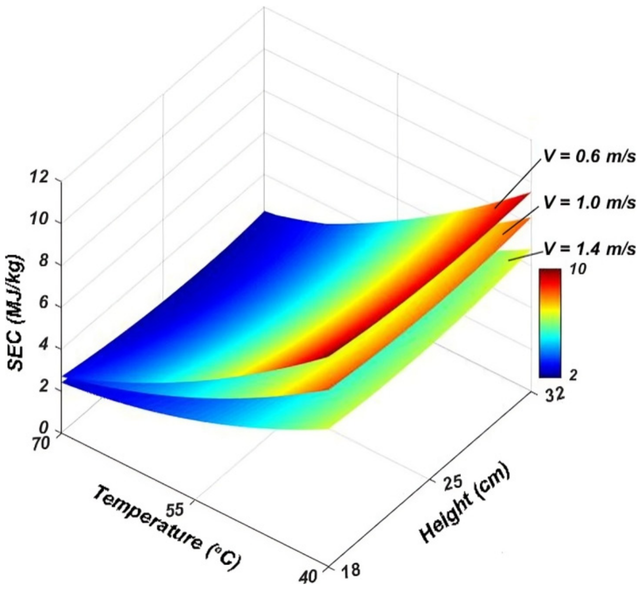

Fig. 2 Variation of specific energy consumption with different drying parameters

energy, and the average values of *SEC* given in Table 3 for three velocity levels 0.6, 1.0 and 1.4 m/s were 4.62, 5.52 and 6.13 MJ/kg_{paddy}, respectively. Although the higher velocities result in the higher moisture removal rates but, generally, the consumed energy is mainly increased because of shorter interaction time between the air flow and the object. The increased amounts of energy consumption at higher drying air velocities are also confirmed by some related works such as Ye et al. [25], Ononogbo et al. [26], Chen et al. [27], and Karami et al. [28].

As can be seen in Fig. 2, for constant temperature and velocity, the change in drying bed height had no specific influence on the specific energy consumption. In case of the moisture content, the longer drying process resulted in considerable ($P < 0.05$) more energy consumption to dry the paddy. As revealed in Table 3, the mean value at the moisture levels of 8, 10 and 12% was calculated to be 7.55, 4.97 and 3.76 MJ/kg_{paddy}, respectively.

3.3 Head rice yield

The results of current study for the head rice yield are illustrated in Fig. 3. It can be easily found that at higher temperatures and drying bed heights the head rice yield of dried products decreased. By using higher drying temperatures and air velocities, the removal of moisture intensifies and higher internal and external stress field is induced in the grains. When it comes to the influence of the bed height on the *HRY*, the higher non-uniformity of moisture content of the paddy kernels could be the main reason for the obtained results. Furthermore, it is noted from the results given in Table 4 that the *HRY* was higher for more dried grains.

Beheshti et al. [29] investigated the influence of drying temperature on cracking of two paddy varieties in the milling process. Their findings revealed that increasing drying temperature (varied in 40–55 °C range) continuously resulted in higher cracking percentage. They stated that the drying process duration increased maybe due to higher temperatures accelerate moisture removal from the grains causing tensile and compressive stresses at the grains surface and center, respectively.

Alizadeh et al. [30] performed an experimental research work and studied milling performance of three different rice verities and reported that, for all the varieties, the HRY was continuously increased by decreasing the final moisture content from 12 to 10, from 10 to 8 and from 8 to 6%. Nasirahmadi et al. [31] reported that decreasing the final moisture content from 12 to 8% resulted in higher *HRY* values for both the parboiled and unparboiled Fajr and Tarom paddy varieties in Iran. Continuous increment in *HRY* of Anber paddy variety by decreasing final moisture content from 16 to 14, from 14 to 12 and from 12 to 10% was observed by Alhendi et al. [32] at all the targeted witnesses of 32, 34 and 36.

3.4 Multi-objective optimization

In this section the temperature and velocity of drying airflow, bed height and moisture content of the dried product were adopted as the main control factors for optimizing the convective drying process of paddy. The least process duration and specific consumed energy and maximum head rice yield were also considered as the desirable responses. Fig. 4 shows individual desirability values for the control factors as well as the response variables. A combined desirability of 0.791 for the optimization is also evident in the Fig. 4. As the factors (*T*, *V*, *H*, and *M*) have been set to be in the optimization range, the desirability function for them is equal to unit. The desirability for the process time, *SEC* and head rice yield was obtained to be 0.8943, 1, and 0.5532, respectively.

Table 5 represents the obtained optimization results. The optimum drying air temperature, the airflow velocity, drying bed height and moisture of the dried grains was found to be 59 °C, 0.6 m/s, 18 cm and 9%, respectively. The associated specific time, *SEC* and *HRY* were

Table 3 Specific energy consumption (MJ/kg $_{paddy}$) at the practiced drying treatments

Temperature (°C)	Velocity (m/s)	Height (cm)	Specific energy consumption (MJ/kg $_{paddy}$) final moisture content (%, wet basis)		
			8	10	12
40	0.6	18	9.44 ± 0.82	6.27 ± 0.73	4.74 ± 0.26
		25	9.54 ± 0.61	5.94 ± 0.32	4.28 ± 0.40
		32	10.51 ± 0.73	6.33 ± 0.41	4.32 ± 0.22
	1.0	18	12.19 ± 0.29	8.31 ± 0.38	6.41 ± 0.27
		25	11.89 ± 0.80	7.71 ± 0.19	5.70 ± 0.34
		32	13.47 ± 0.91	7.91 ± 0.67	5.58 ± 0.30
	1.4	18	14.41 ± 0.79	9.93 ± 0.86	7.76 ± 0.45
		25	13.65 ± 0.83	9.06 ± 0.37	6.79 ± 0.24
		32	15.02 ± 0.97	9.08 ± 0.61	6.49 ± 0.45
50	0.6	18	6.09 ± 0.25	4.26 ± 0.13	3.32 ± 0.19
		25	6.04 ± 0.41	3.93 ± 0.11	2.88 ± 0.21
		32	6.93 ± 0.70	4.12 ± 0.37	2.81 ± 0.18
	1.0	18	7.19 ± 0.61	5.08 ± 0.40	3.99 ± 0.32
		25	6.67 ± 0.55	4.51 ± 0.37	3.35 ± 0.14
		32	7.03 ± 0.62	4.47 ± 0.51	3.17 ± 0.29
	1.4	18	7.76 ± 0.48	5.53 ± 0.36	4.42 ± 0.37
		25	6.93 ± 0.25	4.79 ± 0.31	3.63 ± 0.12
		32	7.08 ± 0.51	4.61 ± 0.39	3.37 ± 0.42
60	0.6	18	3.54 ± 0.26	2.55 ± 0.11	2.12 ± 0.14
		25	3.28 ± 0.37	2.24 ± 0.08	1.77 ± 0.10
		32	3.54 ± 0.29	2.23 ± 0.22	1.68 ± 0.16
	1.0	18	3.89 ± 0.43	2.83 ± 0.25	2.39 ± 0.21
		25	3.48 ± 0.21	2.43 ± 0.16	1.95 ± 0.08
		32	3.51 ± 0.30	2.27 ± 0.34	1.79 ± 0.13
	1.4	18	4.03 ± 0.42	2.99 ± 0.25	2.61 ± 0.17
		25	3.45 ± 0.24	2.49 ± 0.16	2.12 ± 0.11
		32	3.36 ± 0.16	2.32 ± 0.21	1.89 ± 0.09

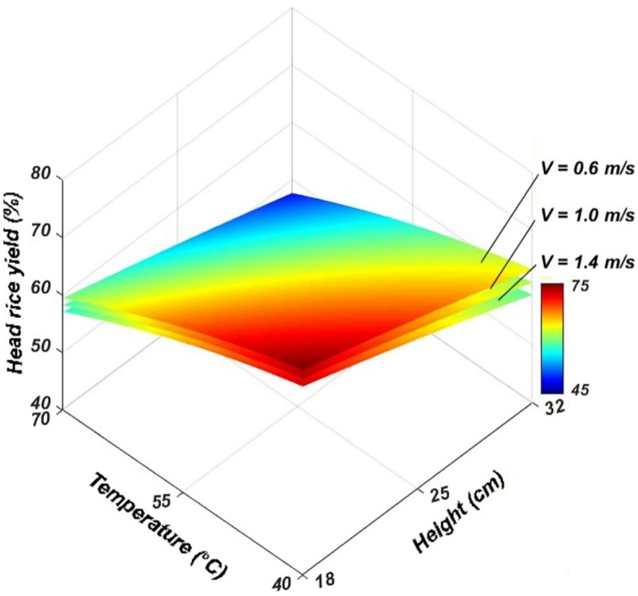

Fig. 3 Variation in head rice yield (%) with different drying parameters

estimated to be 105.63 min/kg$_{paddy}$, 4.57 MJ/kg$_{paddy}$ and 70.68%, respectively at the optimized drying conditions proposed by the optimization procedure.

The RSM model accuracy was evaluated by drying the paddy at the predicted optimized conditions. From the results (Table 5), 1.96, 2.22 and 2.76% relative error was observed between the experimental and expected specific time, *SEC* and *HRY*, respectively. Therefore, it could be stated that the model has successfully optimized the drying factors as well as predicted drying variables.

4 Conclusion

In this study, the convective air drying of paddy kernels was investigated under different levels of temperatures and velocities of airflow, as well as the bed height and final moisture content of end-products. The dependent variables were specific time duration of process, required energy to

Table 4 Head rice yield (%) at the practiced drying treatments

Temperature (°C)	Velocity (m/s)	Height (cm)	Head rice yield (%) final moisture content (%, wet basis)		
			8	10	12
40	0.6	18	80.56 ± 1.73	76.70 ± 2.23	70.41 ± 1.10
		25	78.32 ± 2.15	69.49 ± 3.60	62.43 ± 3.27
		32	72.33 ± 1.42	63.00 ± 1.96	55.29 ± 2.59
	1.0	18	81.57 ± 2.39	75.78 ± 3.75	68.28 ± 2.64
		25	77.30 ± 3.01	66.55 ± 2.48	60.16 ± 3.28
		32	69.19 ± 3.68	60.97 ± 2.82	54.17 ± 4.13
	1.4	18	79.74 ± 2.24	72.43 ± 3.14	67.16 ± 2.91
		25	76.39 ± 3.17	64.332 ± 2.71	57.12 ± 3.46
		32	68.07 ± 2.76	59.35 ± 3.92	52.96 ± 3.77
50	0.6	18	76.70 ± 1.57	67.26 ± 2.16	64.32 ± 2.19
		25	72.74 ± 3.38	64.52 ± 4.03	55.09 ± 1.86
		32	65.43 ± 2.61	55.09 ± 3.77	49.30 ± 3.72
	1.0	18	73.35 ± 2.84	68.17 ± 2.91	63.01 ± 2.91
		25	70.61 ± 1.69	61.17 ± 3.46	53.06 ± 4.47
		32	64.32 ± 2.37	52.96 ± 2.61	48.09 ± 3.36
	1.4	18	72.33 ± 3.46	67.06 ± 4.11	61.38 ± 2.73
		25	67.16 ± 1.19	58.23 ± 1.29	52.25 ± 3.14
		32	61.17 ± 2.89	51.43 ± 2.58	46.57 ± 2.99
60	0.6	18	63.20 ± 4.12	55.29 ± 3.27	57.01 ± 1.74
		25	65.64 ± 3.71	56.10 ± 4.10	47.07 ± 4.16
		32	56.30 ± 1.29	46.87 ± 2.96	40.88 ± 2.37
	1.0	18	66.35 ± 2.18	58.43 ± 1.81	51.84 ± 3.10
		25	61.48 ± 3.09	53.06 ± 2.13	42.01 ± 2.38
		32	55.39 ± 2.97	46.36 ± 4.42	36.83 ± 4.02
	1.4	18	62.59 ± 3.62	60.46 ± 3.53	51.13 ± 2.49
		25	59.45 ± 4.12	51.13 ± 2.76	43.22 ± 3.28
		32	53.06 ± 3.36	44.13 ± 2.39	36.32 ± 2.67

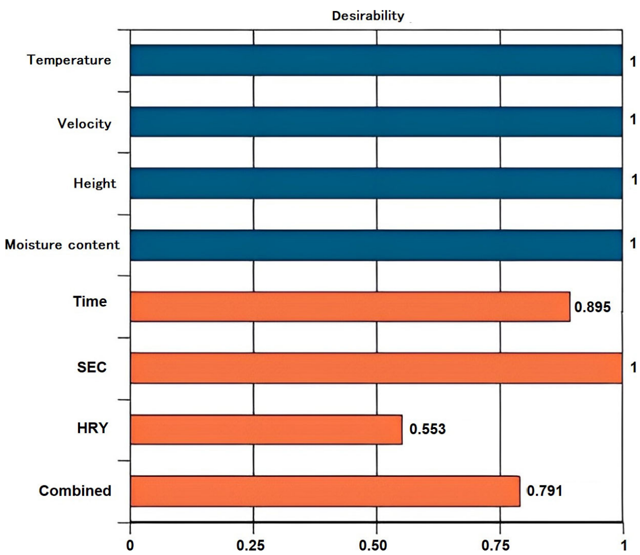

Fig. 4 Individual desirability values of control factors, response variables, and combined optimization

remove unit mass of water from samples and head rice yield (*HRY*). According to the observations and obtained results:

1. Drying at higher temperatures and lower air velocities until higher amount of final moisture content, decreased the consumed energy of drying process.
2. The bed height had no significant influence on the specific drying time and energy consumption.
3. The head rice yield was noted to be increased at lower levels of all the studied drying factors.
4. RSM was also practiced to assess the role of input parameters on the dependent variables and finding the optimum drying conditions.
5. In optimal drying conditions, the specific drying time and energy consumptions were 105.63 min/kg_{paddy} and 4.57 MJ/kg_{paddy}, respectively.
6. The reliability of the responses was investigated through the results of experiments and it was found that the maximum relative error was up to 2.5%.

Table 5 Experimental validation for proposed drying factors by the RSM and desirability function

	Parameters	Goal	Importance	Predicted value	Experimental value	Relative error
Independent variables	Temperature (°C)	In range	+++	58.68	59	–
	Velocity (m/s)	In range	+++	0.6	0.6	–
	Height (cm)	In range	+++	18	18	–
	Moisture content (%)	In range	+++	8.79	9.00	–
Dependent parameters	Specific time (min/kg $_{paddy}$)	Minimize	+++	105.63	107.70	1.96 (%)
	SEC (MJ/kg paddy)	Minimize	+++	4.57	4.67	2.21 (%)
	HRY (%)	Maximize	+++	70.68	68.79	2.76 (%)
	Desirability				0.791	

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