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Research Article

Mathematical Modelling and Optimisation of Low-Temperature Drying on Quality Aspects of Rough Rice

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Rice when harvested normally has a high moisture content of 20–25% which requires immediate drying, reducing its mass loss and preventing it to spoil. This situation is more crucial with the areas under humid tropical conditions, where moisture and temperature mainly play an important role in deteriorating the quality of rough rice. Keeping the importance of quality attributes of rough rice, the study was carried out to assess the effects of low-temperature drying and suggest an optimum condition. Response surface methodology (RSM) with a central composite design was employed to study the effects of variables, i.e., temperature (X_1), time (X_2), and air velocity (X_3) on responses, i.e., head rice yield (HRY), hardness, lightness, and cooking time. The experimental data were fitted to the quadratic model, studying the relationship between independent and dependent variables. The results revealed that the HRY, hardness, lightness, and cooking time increased with increasing variables, whereas for HRY, it particularly increased and then decreased. It was observed that temperature had more influence on the quality of rough rice followed by time and velocity. Results for analysis of variance revealed that the quality aspects of rough rice were significantly ($p < 0.05$) affected by temperature and time, whereas for velocity, it only significantly affected hardness. The optimal drying conditions predicted by RSM for variables were 25°C, 600 min, and 1 m·s^{-1}, and the optimal predicted HRY, hardness, lightness, and cooking time were 73.93%, 38.28 N, 71.40, and 27.58 min respectively. Acceptable values of R^2, Adj R^2, and nonsignificance of lack of fit demonstrated that the model applied was adequate and can be used for optimization. The study concluded that the RSM with a central composite design was successfully used to study the dependence of quality aspects of rough rice at low temperature and can be utilized by the rice processing industries.

1. Introduction

Rice as a staple food is being consumed by a large proportion of the world's population, making it one of the most demanding cereals [1]. Rice when harvested has a moisture content ranging from 16 to 28% (w.b.) depending on its method, variety, and location [2]. This rough rice with high moisture due to enzyme activity and mold growth is subjected to elevated respiration rates [3], which thereby reduces the quality of rough rice [4]. This situation of high moisture content makes it a crucial problem for further processing and storage purposes, especially for the areas coming under humid tropical climates [5]. For milling, it is recommended that the moisture of rough rice should be 13%, and for storage purpose, it should be 10–13% [6]. Drying in this regard plays a significant role to reduce the moisture as required accordingly, which if delayed in turn will reduce the grain quality increasing its postharvest losses. The rate of drying during process is further affected by various factors, i.e., moisture content, drying air temperature, airflow rate, and relative humidity [7]. Siebenmorgen et al. [8] stated that the rice should be harvested at optimal moisture content to maximize the milling quality. In order to reduce the losses, the rough rice as harvested should be dried down at the required moisture content for further processing [9]. Drying as function of moisture has an impact on mechanical, sensory, and nutritional properties of products [10]. As a whole, the quality of kernel has an utmost importance to rice industry, out of which head rice yield and colour are considered to be the main indices [11, 12]; other than this, the rice quality parameters include pasting and chemical and sensory quality [13, 14].

Several researchers have demonstrated their investigations to improve the quality of different rough rice varieties by various drying methods. Schluterman and Siebenmorgen [15] reported that drying at high temperature creates moisture content gradients within kernels, which then leads to fissure formation reducing the quality of milling. This causes a reduction in head rice yields as the fissures in kernel reduces the mechanical strength leading to its breakage. Column and cross flow dryers generally operate at 45–78°C [16]. Inprasit and Noomhorm [9] reported that some multistage driers operate at temperatures ranging from 80 to 200°C, which in result for rapid drying leads to kernel fissuring. Bonazzil et al. [17] in their study stated that air with high capacity can adversely affect the quality of rough rice. Siebenmorgen et al. [18] reported that a moisture content gradient between the surface and centre of the kernel is being established due to evaporation from outer layers. Tensile and compressive stresses within kernels resulted due to moisture content gradient and, if increased, leads to increase in kernel fissuring and breakage [19–21]. Hashemi et al. [22] conducted a study on reduction of fissure formation and head rice yield when subjected to different temperatures. Hypothesis regarding fissuring of rice when dried at high temperature and low relative humidity has also been explained by Jia et al. [23] and Zhang et al. [24]. Cnossen and Siebenmorgen [25] reported that fissuring of rice in general occurs when kernel temperatures exceed the kernel's glass transition temperature. A thin-layer drying experiment using a temperature of 30–35°C was conducted by Iguaz et al. [26]; they reported that the drying of rough rice was greater influenced by temperature as compared to relative humidity, where velocity was significantly affected at a drying temperature of <30°C. A theoretical model for predicting drying kinetics was developed by Kahveci et al. [27]; they reported temperature as the main factor which influenced the drying of rough rice. Cihan et al. [28] developed a diffusion-based model describing intermittent drying of thin-layer rough rice at 40°C.

Optimization of the drying process is carried out to recommend rapid processing conditions with acceptable product quality and high transmission capacity. It involves the manipulation of inputs that in turn will provide a maximum and minimum output [29]. The response surface method (RSM) is being used by researchers which is an excellent approach to optimize various factors. It is a unique combination of both mathematical and statistical approaches, evaluating the optimal conditions by reducing the number of experiments [30]. RSM's statistical and mathematical techniques are useful in developing, improving, and optimizing processes [31]. Yousaf et al. [32] reviewed combined effects of soaking temperature, soaking time, and steaming time on quality attributes of parboiled rice. Yağci and Göğüş [33] investigated physical and functional properties of extruded snack foods developed from food by-products.

Combination of temperature, time, and air velocity depending on drying conditions tends to increase/decrease the quality of rough rice. Several researchers have being working on various temperatures with various factors, but the mathematical modelling and optimization of low-temperature drying have never been reported. This study was therefore carried out to determine the effects of temperature, time, and air velocity on rough rice, investigating the optimum conditions being affected by indicators and predicting the variables by mathematical modelling.

2. Materials and Methods

The present study was carried out at the College of Engineering, Nanjing Agricultural University. Freshly harvested paddy variety named Yang Jing 687 was first cleaned to remove extraneous material. The paddy having a moisture of 24% was then stored at 4°C in a refrigerator (BCD-232TDek, Hisense, China) until further experimentation [34]. Paddy samples as per design were dried in a laboratory dryer (Figure 1); the drier before each experiment was first operated at 1 hour to stabilize the drying conditions. Samples of rice before drying were sealed and equilibrated to room temperature; this was done to prevent condensation on rice.

2.1. Head Rice Yield (HRY). To determine HRY, a subsample of 250 g rough rice was dehusked using a laboratory Satake rubber roller-type rice husker (THU35C, China) [34] and polished for 60 sec with an abrasive type polisher Satake (CBS300AS, Japan) [32]. Rough rice after dehusking was cleaned, separating the broken grain. HRY which is expressed as a percentage of the whole grain to the total sample [35, 36] was calculated separating the broken grain from whole grain.

2.2. Hardness. Hardness of paddy samples was measured using TMS-Pro machine (FTC Co. USA) with a computer program for data acquisition [37]. Load with a measuring accuracy level of 5% using stainless steel probe was applied to grain samples which were placed horizontally on a base plate (Figure 2). The peak force (N) indicated by the force time curve was recorded as maximum. 10 grains from samples were randomly selected, reporting its average value.

2.3. Lightness. Lightness "L" of rough rice samples was determined using a precision colour reader (HP-200, China). White and black plates provided by the manufacturer were used to calibrate the colour reader. Values of whiteness for rice were determined as a reflective index of the sample surface. The higher the "L" value, the whiter was the rice.

2.4. Cooking Time. The method proposed by Juliano [38] was adopted for determining the cooking time of rice. Weighted 10 g of whole rice from samples were immersed in

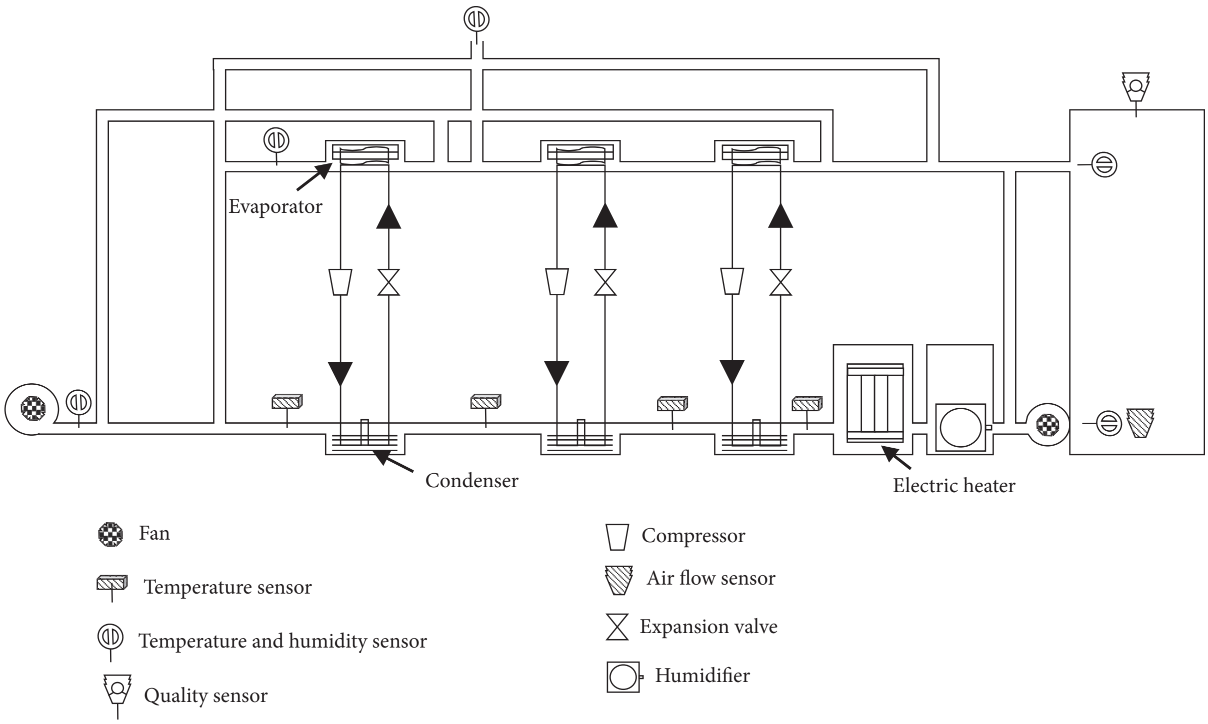

Figure 1: Schematic view of a laboratory dryer.

distilled water, which were then cooked vigorously in boiling water. 10 rice kernels from boiled water were randomly selected and then pressed between glass plates to identify the translucent kernels. The process was followed every two minutes, till 90% of kernels have identified translucent kernels.

2.5. Experimental Design. The responses, i.e., HRY, hardness, lightness, and cooking time being affected by the factors temperature, time, and velocity, were investigated by employing response surface methodology with a central composite design (CCD). CCD with three factors at five levels is presented in Table 1. For enabling optimization, the responses should be associated through a linear or quadratic model; a combined quadratic and linear model as shown in equation (1) was therefore used for optimization [39]. The fourteen experiments with a combination of 6 replications as per run and condition arranged by CCD in both coded and actual forms are presented in Table 2. The coded values were calculated using equation (2):

$$y = \beta o + \sum_{i=1}^{k} \beta_i X_i + \sum^{k} \beta_i X_i^2 + \sum_{i=1}^{k} \sum_{i=1}^{k} + \beta_{ij} X_i X_j + e, \quad (1)$$

$$X_i = \frac{X_i - X_o}{\delta X}, \quad (2)$$

2.6. Statistical Analysis. Design Expert® (Ver. 8.0.6, Stat-Ease, Inc., USA) statistical software was used for executing CCD. Analysis of variance (ANOVA) and multiple regressions for interactions of independent variable and responses were performed to test the lack of fit and significance at $p < 0.05$. Values of R^2 and Adj. R^2 were considered to check the adequacy of the model.

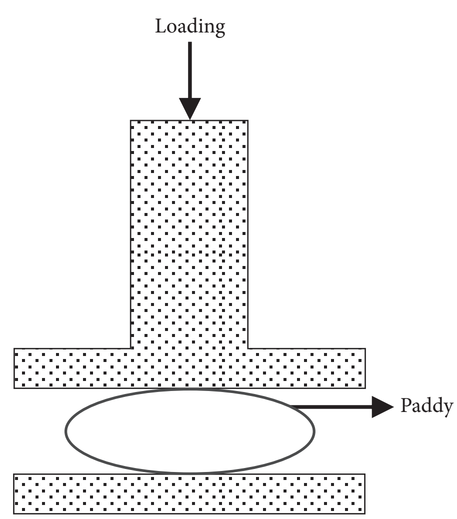

Figure 2: Schematic view of paddy under compression.

Table 1: Experimental ranges in actual and coded form.

Variable	Symbol	Coded values				
		−1.682	−1	0	1	1.682
Temperature (°C)	X_1	16.48	25	37.5	50	58.52
Time (min)	X_2	197.73	300	450	600	702.27
Velocity (m/s)	X_3	0.66	1	1.5	2	2.34

Table 2: Central composite design and experimental process.

Run	Coded form			HRY		Hardness		Lightness		Cooking time	
	X_1	X_2	X_3	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
1	−1	−1	−1	72.54	72.62	23.1	22.93	69.86	68.91	21.4	21.07
2	1	−1	−1	70.55	71.08	48.62	48.59	74.13	73.61	31.5	31.66
3	−1	1	−1	75.23	73.93	35.12	38.28	71.54	71.40	26.7	27.58
4	1	1	−1	66.81	66.52	59.36	63.35	78.33	78.66	33.2	34.86
5	−1	−1	1	71.87	71.58	26.65	25.32	70.17	69.30	23.1	22.51
6	1	−1	1	69.73	70.46	51.62	51.12	74.75	74.34	33.2	33.39
7	−1	1	1	73.86	72.76	41.76	44.46	72.27	72.25	27.5	28.41
8	1	1	1	66.42	65.77	66.83	69.67	79.43	79.84	34.6	36.0
9	−1.682	0	0	70.76	72.03	27.76	26.45	68.24	69.15	22.6	22.6
10	1.682	0	0	65.32	64.86	71.69	69.23	79.64	79.49	39.4	37.88
11	0	−1.68	0	72.93	72.03	29.71	32.2	69.44	70.81	23.7	24.56
12	0	1.682	0	67.47	69.18	66.98	60.72	78.14	77.53	34.6	32.23
13	0	0	−1.68	73.47	73.77	40.76	37.91	70.44	70.94	29.5	28.61
14	0	0	1.682	71.76	72.27	46.16	45.24	72.01	72.27	31.4	30.78
15	0	0	0	72.12	72.35	42.76	42.43	70.11	70.54	30.2	29.58
16	0	0	0	72.97	72.35	43.12	42.43	70.72	70.54	28.6	29.58
17	0	0	0	71.34	72.35	38.97	42.43	70.02	70.54	30.5	29.58
18	0	0	0	72.11	72.35	44.23	42.43	70.12	70.54	29.6	29.58
19	0	0	0	73.11	72.35	40.38	42.43	70.96	70.54	29.8	29.58
20	0	0	0	72.56	72.35	44.45	42.43	71.42	70.54	28.5	29.58

X_1 = temperature; X_2 = time; X_3 = velocity.

Table 3: Analysis of variance (ANOVA).

Source	HRY (%)	Hardness (N)	Lightness	Cooking time (min)
X_1-temperature	50.21**	170.39**	173.53**	140.15**
X_2-time	7.89**	75.69**	73.37**	35.27**
X_3-velocity	2.22	5**	2.87	2.82
X_1 X_2	13.89**	0.013	4.37	2.71
X_1 X_3	0.07	0.00076	0.078	0.022
X_2 X_3	0.0074	0.55	0.14	0.089
X_1^2	22.13**	4.07	34.74**	0.4
X_2^2	4.40	2.26	32.04**	1.25
X_3^2	0.66	0.1	2.78	0.012
R^2	0.91	0.96	0.97	0.95
Adj. R^2	0.83	0.93	0.94	0.90
Lack of fit	4.80	4.40	3.61	4.93

3. Results and Discussion

3.1. Model Description and Accuracy. The variables temperature, time, and velocity as per design were evaluated observing their effects on the responses, i.e., HRY, hardness, lightness, and cooking time. The statistical parameters of responses are presented in Table 3; all models were found to be statistically significant ($p < 0.05$).

Acceptable values of R^2 with 0.91, 0.96, 0.97, and 0.95 for HRY, hardness, lightness, and cooking time respectively, indicated that the model for the present study suitably described the responses. Lack of fit was observed to be nonsignificant, which describes the model to be valid.

3.2. Effect of Variables on HRY. Effect of the process parameters on response is illustrated in Figure 3. The results revealed the HRY was significantly affected by process factors temperature and time, whereas velocity was observed to be nonsignificant (Table 3). Maximum HRY with 75.23% was observed for run three at the temperature, time, and velocity of 25°C, 600 min, and 1 m·s^{-1}, whereas the minimum was observed with 65.32% for run ten at the temperature, time, and velocity of 58.52°C, 450 min, and 1.5 m·s^{-1}. Acceptable values of R^2, Adj. R^2, and nonsignificance of lack of fit indicated the appropriateness of the model. The optimised values generated by software for HRY is 73.93% at the temperature, time, and velocity of 25°C, 600 min, and 1 m·s^{-1}. The interaction between the variables as illustrated in Figure 1 represents that the temperature had more influence on HRY followed by time and velocity. It was observed that HRY particularly increased with increasing temperature and time to a certain point, after which it decreased with increasing temperature and time. The enhancement in HRY resulted due to hardening and compaction by gelatinization of starch. Likitrattanaporn [40] and Calderwood and Webb [41] reported that rough rice when dried to a grain temperature of 45.8°C increased its HRY but

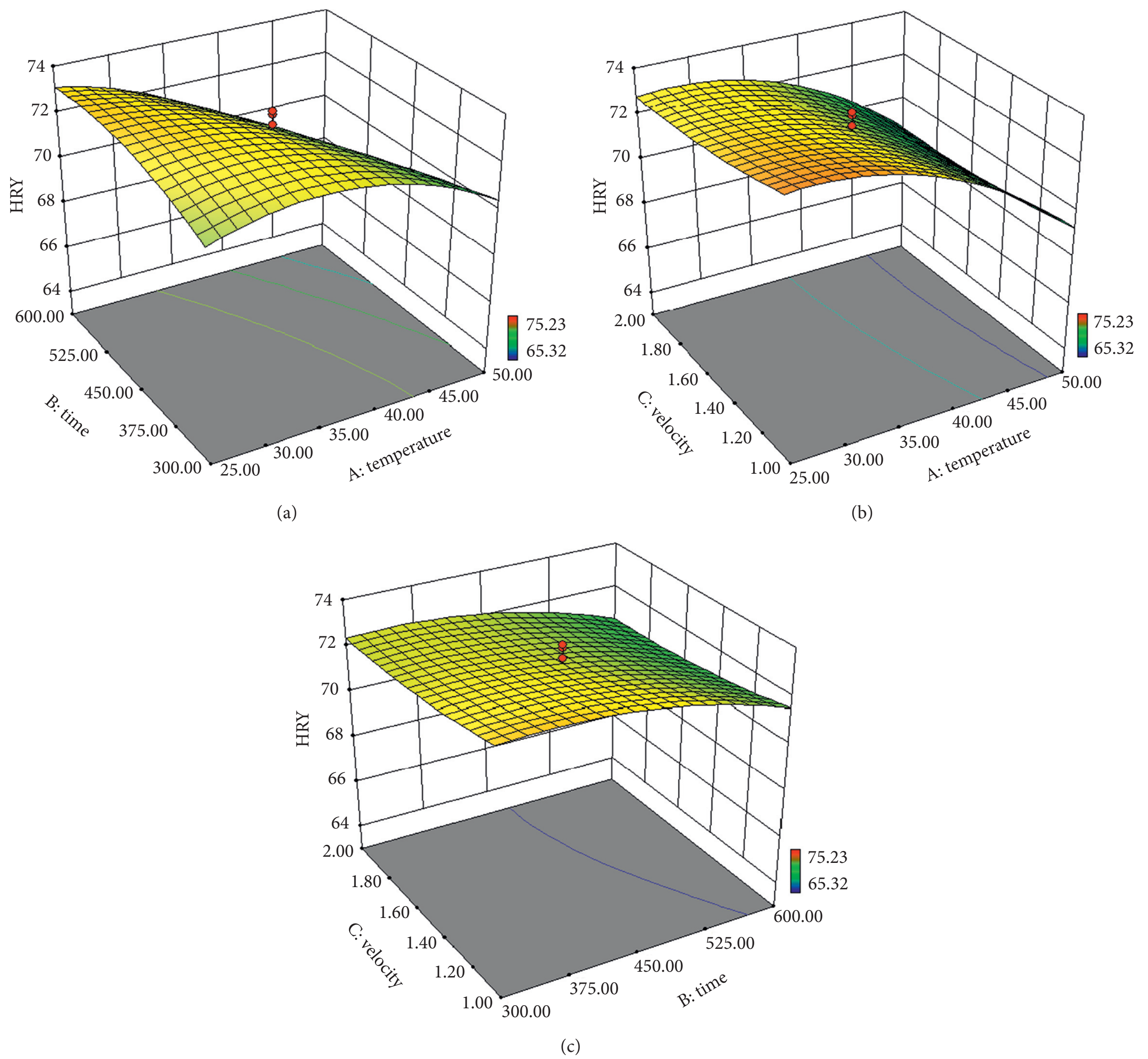

Figure 3: Response surface plots for HRY (%).

decreased when subjected to sun drying due to a high rate of moisture removal. Litchfield and Okos [42] further reported that HRY due to increasing stress in kernel decreased when dried at 60.8°C. The initial increase and then decrease trend in HRY with respect to temperature are in line with those of Yousaf et al. [43]; Akowuah et al. [44]; and Siebenmorgen et al. [45], all of whom reported that the temperature is the main factor on which HRY is mainly depended on. The regression equation for HRY in coded form is given as follows:

$$\text{HRY} = 72.35 - 2.13\,X_1 - 0.85X_2 - 0.45X_3 - 1.47X_1X_2 + 0.10X_1X_3 - 0.034X_2X_3 - 1.38X_1^2 - 0.62X_2^2 + 0.24X_3^2. \quad (3)$$

3.3. Effect of Variables on Hardness. Hardness is one of the important factors to be considered while drying, and increase in hardness will effectively decrease the milling process. The effect of variables and their interactions is shown in Figures 4(a)–4(c). It was statistically observed that temperature, time, and velocity had a significant effect on responses (Table 3). The hardness after drying increased with increasing process factors, where the effect of temperature was remarkably higher than that of time and velocity. The values of hardness ranged from 23.1 N to 71.69 N, reporting higher for run ten at the temperature, time, and velocity of 58.52°C, 450 min, and 1.5 m·s^{-1} and minimum for run one at the temperature, time, and velocity of 25°C, 300 min, and 1 m·s^{-1} (Table 2). The reason for increase in hardness was the moisture removal which was significantly affected by the factors. The absorption of water at higher temperature reduced due to rearrangements of starch granules. Similar results for increasing hardness has also been reported by Kingsly et al. [46]; Inprasit and Noomhorm [9]; Izli [47]; and

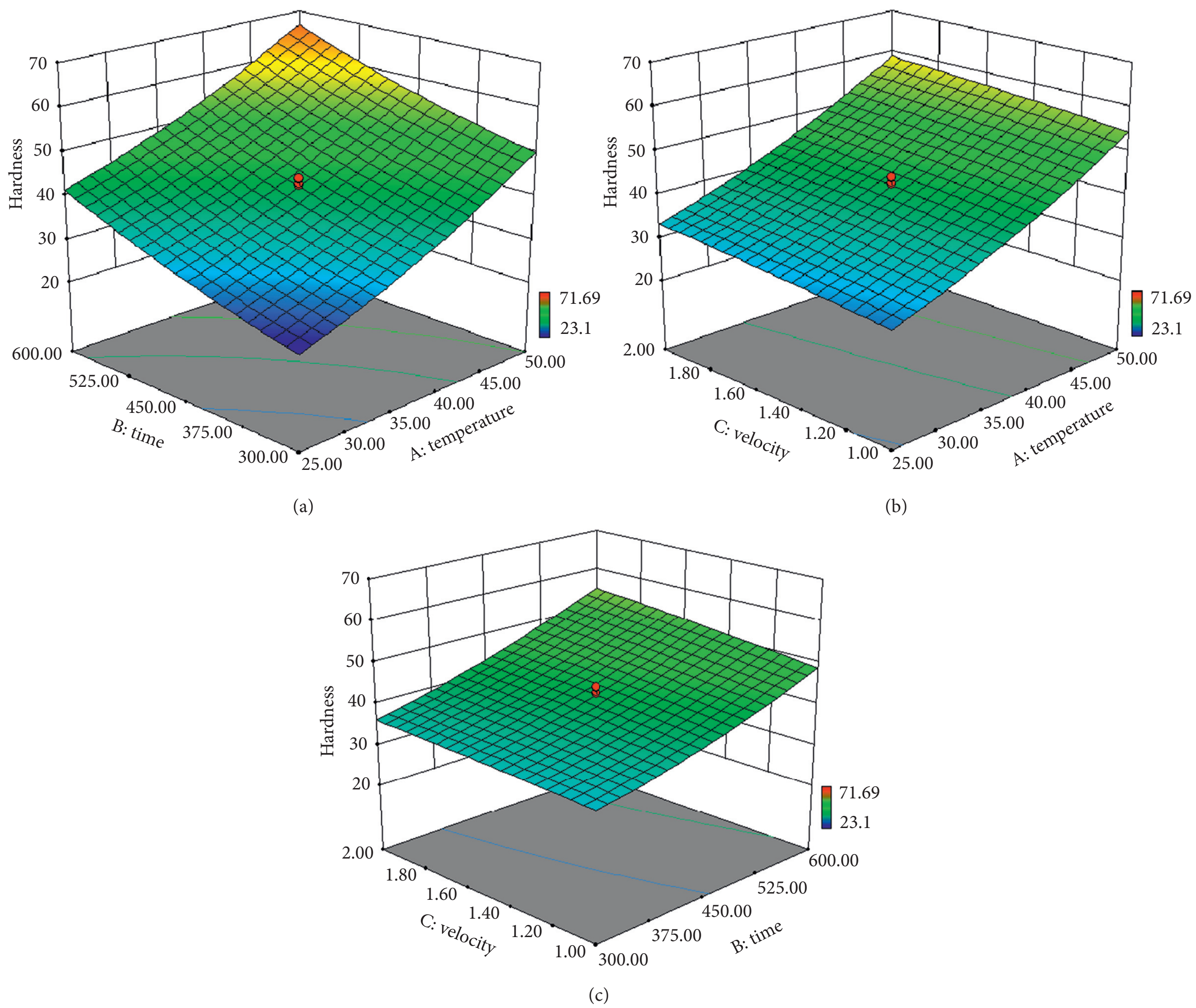

Figure 4: Response surface plots for hardness N.

Kumar et al. [48]. The regression equation for hardness in coded form is given as follows:

$$\begin{aligned} \text{hardness} = {} & 42.43 + 12.72X_1 + 8.48X_2 + 2.18X_3 - 0.15X_1X_2 \\ & + 0.035X_1X_3 + 0.95X_2X_3 + 1.91X_1^2 + 1.43X_2^2 \\ & - 0.30X_3^2. \end{aligned} \quad (4)$$

3.4. Effect of Variables on Lightness. Lightness is an important factor to which market value is directly related. Lightness as per ANOVA was statistically ($p < 0.05$) different for temperature and time, whereas for velocity, it was found to be nonsignificant (Table 3). Effect of variables on the responses and their interactions is shown in Figure 5(a)–5(c). The higher values of R^2, Adj. R^2, and nonsignificance of lack of fit demonstrated that the model work was valid. Maximum and minimum lightness with 79.64 and 68.24 was observed for run ten and run nine at a temperature of 58.52°C, 450 min, and 1.5 m·s^{-1} and 16.48°C, 450 min, and 1.5 m·s^{-1}. The results for low-temperature drying revealed that the lightness of paddy was low at higher moisture content of kernels, which then increased with increasing temperature. Similar increase for low temperature has also been stated by Ziaforoughi et al. [49]; Junka et al. [50]; Kara and Erçelebi [51]; and Kim and Lee [36]. The regression equation for lightness of rough rice in coded form is given as follows:

$$\begin{aligned} \text{lightness} = {} & 70.54 + 3.51X_1 + 2.81X_2 + 0.40X_3 + 0.11X_1X_2 \\ & + 0.085X_1X_3 + 0.11\,X_2X_3 + 1.29X_1^2 + 0.71X_2^2 \\ & + 0.33X_3^2. \end{aligned} \quad (5)$$

3.5. Effect of Variables on Cooking Time. The cooking time of rice was affected by all three factors, where the influence of temperature was greater than others. Effect of temperature

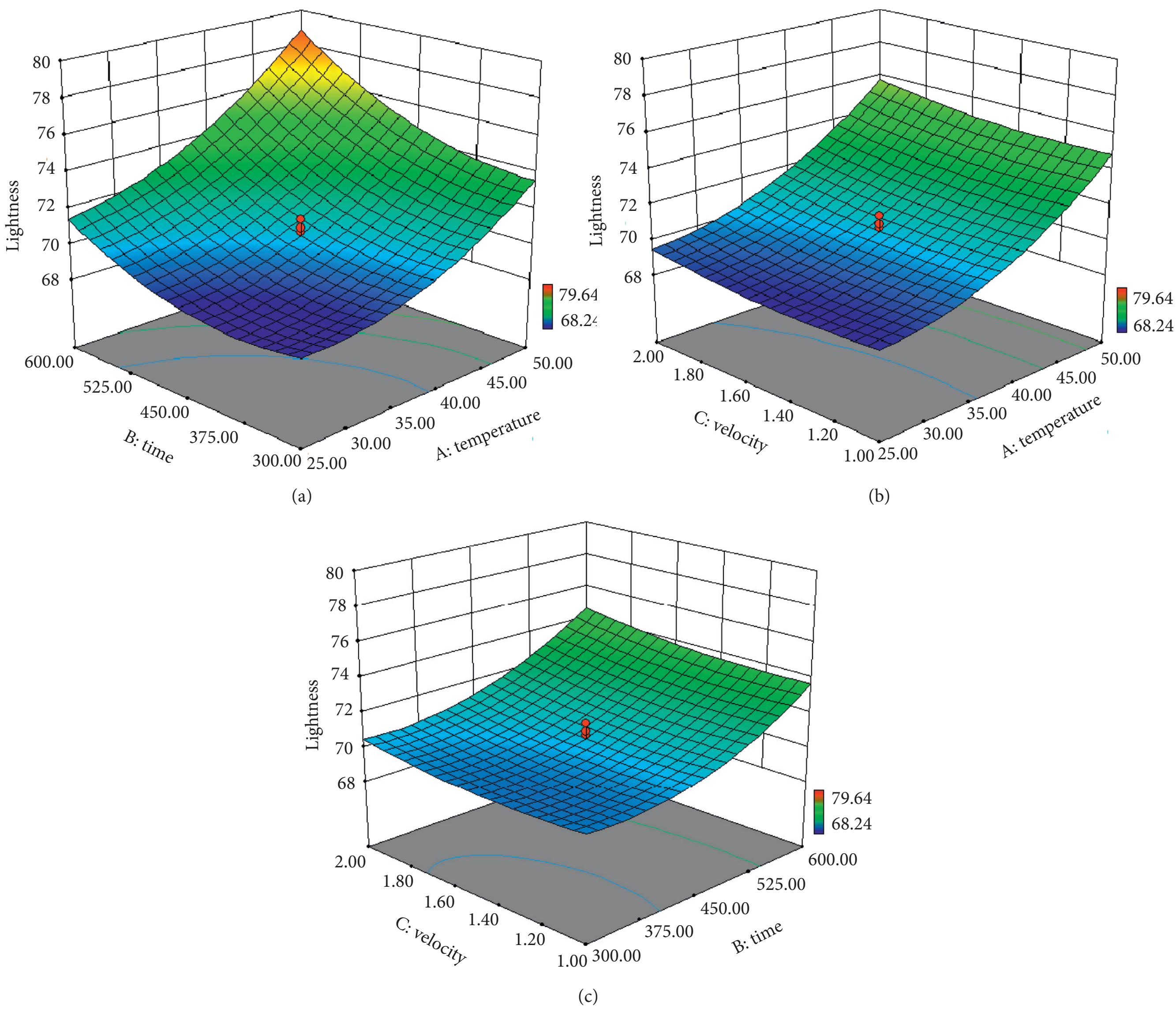

Figure 5: Response surface plots for lightness.

and time as presented in Table 3 was statistically different, whereas the velocity was observed to be nonsignificant ($p < 0.05$). Effect of factors with their interactions is illustrated in Figure 6(a)–6(c). The maximum and minimum cooking time with 39.4 min and 21.4 min was observed for run ten and one at the temperature of 58.52°C, 450 min, and 1.5 m·s^{-1} and 25°C, 300 min, and 1 m·s^{-1}, respectively. Increasing cooking time and water absorption occurred due to gelatinization of starch at higher drying temperature. The absorption of water was higher when subjected to high temperature [9] and is higher for the rice having higher gelatinization temperature at the same cooking temperature and time [52]. The regression equation for cooking time of rough rice in coded form is given as follows:

$$\begin{aligned}\text{cooking time} = {} & 29.58 + 4.54X_1 + 2.28X_2 + 0.64X_3 \\ & - 0.82X_1X_2 + 0.075X_1X_3 - 0.15X_2X_3 \\ & + 0.24X_1^2 - 0.42X_2^2 + 0.041X_3^2. \end{aligned} \quad (6)$$

3.6. Optimisation. Design Expert® software was used to solve the regression equations for determining the optimum values for independent variables and selected responses. The optimal conditions predicted by RSM for variables temperature, time, and velocity were 25°C, 600 min, and 1 m·s^{-1}, and optimal predicted HRY, hardness, lightness, and cooking time were 73.93%, 38.28 N, 71.40 and 27.58 min,

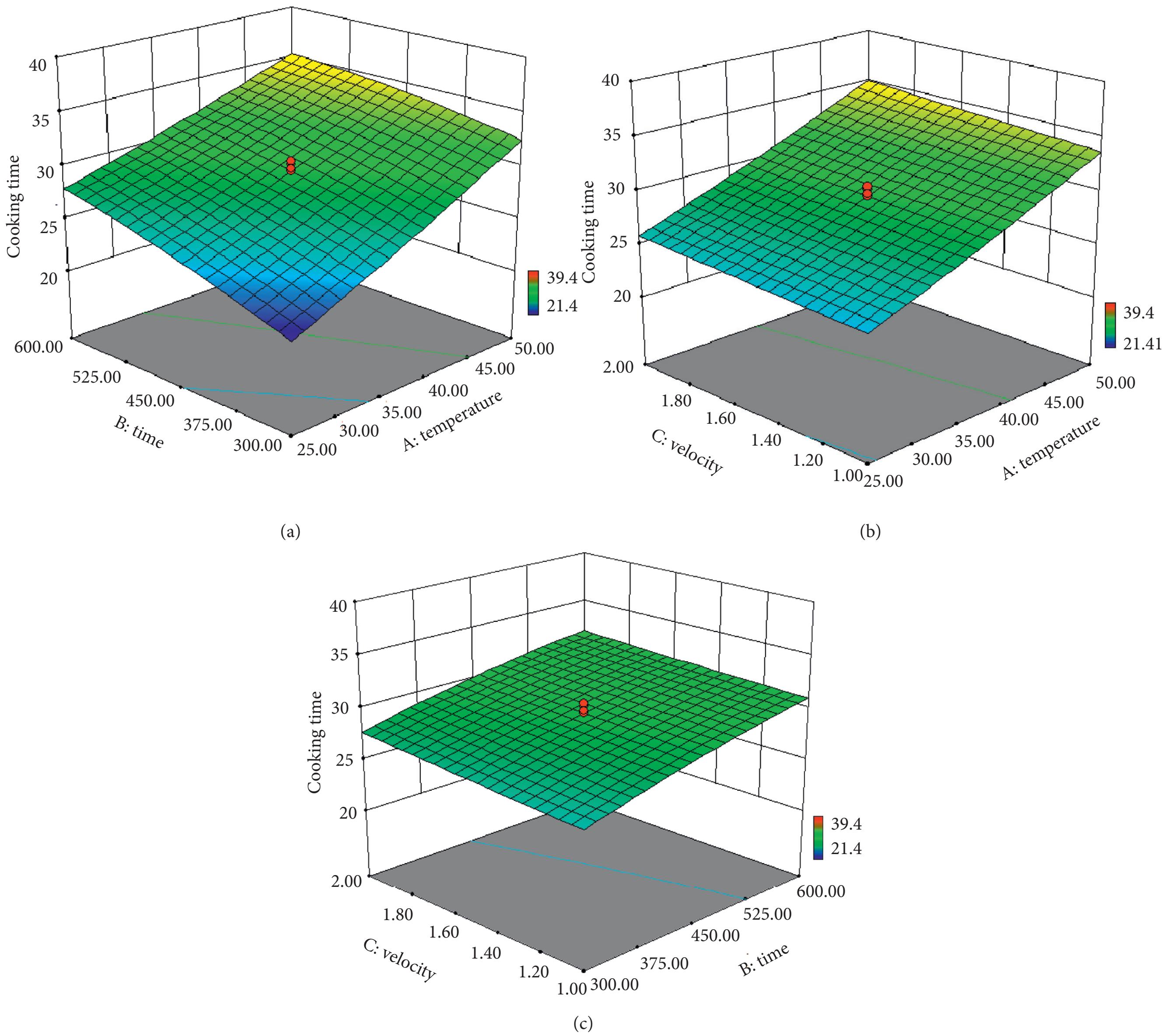

Figure 6: Response surface plots for cooking time.

respectively. The model is deemed to be adequate if the predicted and experimental values observed during validation are close to each other [53]. The close values of predicted and observed values as presented in Table 2 indicate that the model generated was adequate. The results obtained for the current study revealed that the RSM can be used to optimize the quality aspects of rice at low-temperature drying.

4. Conclusion

RSM with a central composite design was designed to investigate the effects of variables, i.e., temperature, time, and velocity on responses, i.e., HRY, hardness, lightness, and cooking time. The results revealed the variables had significant influence on responses; effect of temperature had greater influence on the quality aspects of rough rice followed by time and velocity. The greater values of R^2, Adj R^2, and nonsignificance of lack of fit demonstrated the validity of the model applied. The optimum conditions generated by Design Expert software for temperature, time, and velocity were 25°C, 600 min, and 1 m·s^{-1}, and optimal predicted HRY, hardness, lightness, and cooking time were 73.93%, 38.28 N, 71.40, and 27.58 min, respectively. The outcomes of the study demonstrated the competency of RSM, which can be used in optimizing the low-temperature drying of rough rice. This provided information is very useful and can be utilized by rice processing industries to reduce postharvest losses of rough rice.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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