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Rewale PP
M.Sc. Student, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad, Maharashtra India

IL Pardeshi
Professor, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad, Maharashtra, India

SB Swami
Professor, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad, Maharashtra, India

RC Ranveer
Professor, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad, Maharashtra, India

GA Waikar
Assistant Professor, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad, Maharashtra, India

KC Katkar
Ph.D. Student, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad Maharashtra, India

AVV Dalvi
Associate Dean, College of Horticulture, Mulde, Tal. Kudal, Sindhudurg, Maharashtra, India

Corresponding Author:
IL Pardeshi
Professor, Post Graduate Institute of Post-Harvest Technology and Management, Dr. BSKKV, Killa-Roha, Raigad, Maharashtra, India

Process optimization for hot air puffing of black rice

Rewale PP, IL Pardeshi, SB Swami, RC Ranveer, GA Waikar, KC Katkar and AVV Dalvi

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Abstract
Black rice is gaining popularity as a nutrient-rich superfood, offering more antioxidants and health benefits than brown rice. High temperature short time puffing (HTST) is an effective method for processing grains, allowing them to expand quickly using hot air without oil. With more people leading busy urban lifestyles, there is a growing demand for convenient ready-to-eat (RTE) foods. This study investigates the optimization and quality evaluation of hot air puffing for black rice, focusing on key process variables and storage conditions. Optimal puffing parameters were determined as 18 months of aging of paddy, 19 h soaking of paddy in boiled water and 290 °C of puffing temperature (PT) and 6800 g/h feed rate (FR) for processed paddy in a single-pass in a hot air puffing machine. Under these conditions, the final puffed product achieved a moisture content of 3.70% db, expansion ratio (ER) of 2.69, puffing percentage (PP) of 89.0%, and a colour change (ΔE) value of 14.77. Hot air puffing of black rice revealed dry basis reduction of 4.59% in fibre, 10.19% in fat, 11.54% in protein and 23.93% in ash content during puffing, may be due to high temperature exposure of the product. Aging studies showed a significant improvement in puffing performance over 18 months, with Expansion ratio and Puffing Percentage increasing from 1.14 and 4.87% at 0 months to 2.69 and 89.0% at 18 months, respectively, attributed to probable increase in amylose content.

Keywords: Black rice, Puffing, HTST, optimization, RTE

1. Introduction

Cereals have served as staple meals for human consumption and as livestock feed since the dawn of civilization. The primary cereals consumed globally include wheat, rice, maize, barley, oats, rye, millet and sorghum. More than 50% of the global population depends on rice, an essential grain crop, as their principal source of sustenance. Some rice cultivars have coloured pericarps that are red, brown, or black (sometimes called purple), even though the majority of them produce grains with white pericarps (Maeda *et al*., 2014) [12]. Black rice is a notable-coloured rice variation recognized for its superior nutritional profile, sensory attributes, and significant health advantages (Ito & Lacerda, 2019) [7].

Black rice is scientifically classified as *Oryza sativa L.* which are rich source of nutrient meal. Anthocyanin, an antioxidant pigment, confirms a black colour to the seed. Due to their therapeutic properties and high nutrient content, individuals often utilize the black rice for treatment. The dish, commonly referred to a “long life rice”, is said to enhance longevity and overall well-being (Kong *et al*., 2008). Worldwide, 200 distinct varieties of black rice are cultivated, in which China representing 62% of the overall production. Black rice is alternatively known as purple rice, paradise rice, forbidden rice, imperial rice, prized rice and king’s rice in different regions globally. *Chak hao ambi* meaning “delicious black rice”, is the term for black rice in Manipur. Black rice is also known as *kala bati* in Odisha and *Kala dhan* in Chhattisgarh. *Kal* signifies dark, whereas *bati* denotes rice (Sompong *et al*., 2011) [23].

The total production of black rice in India is mentioned in Fig 1 (Krishi Jagran, 2021). China represented 39% of black rice consumption, followed by India at 30%, Indonesia at 10%, Bangladesh at 9%, Thailand at 5%, Burma at 4% and the Philippines at 3%.

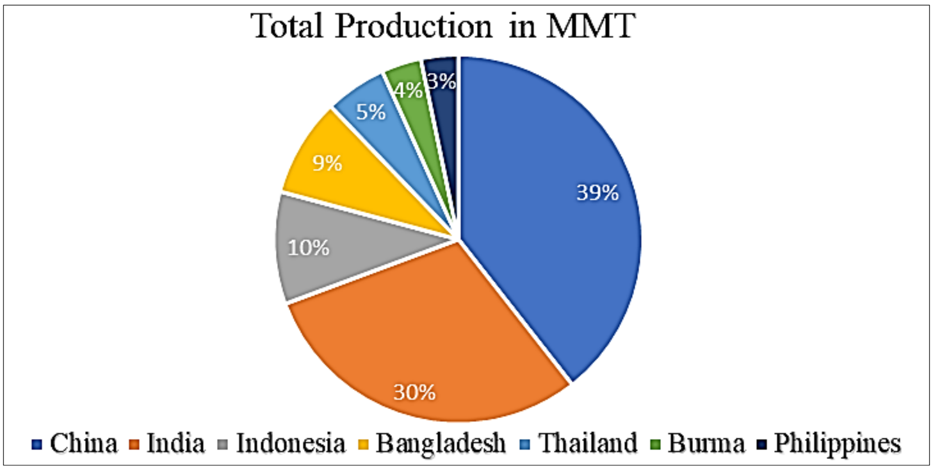

Fig 1: Black rice producing countries

The regions of Manipur, Odisha, West Bengal, Uttar Pradesh, Jharkhand, Maharashtra and a few others are major producers of black rice, which are indigenous to North-East India (Kumar *et al*., 2023) [11]

Table 1: Nutritional value of black rice

Sr. No.	Particulars	Quantity per 100 g
1.	Fat	3.33 g
2.	Protein	8.89 g
3.	Carbohydrates	75.50 g
4.	Fiber	4.70 g
5.	Iron	3.50 g
6.	Calories	355.50 kcal

(Saha *et al*., 2022) [20]

Table 2: Nutritional Superiority of Black Rice over other Types of Rice (100 g Cooked Rice)

Compositions	Polished white rice (g)	Brown rice (g)	Red rice (g)	Black rice (g)
Protein	6.8	7.9	7.0	8.5
Iron	1.2	2.2	5.5	3.5
Fiber	0.6	2.8	2.0	4.7

(Banerjee *et al*., 2019) [3]

As observed from Table 1 and Table 2, black rice is superior to brown rice due to its higher protein and fibre content. Additionally, black rice is rich in antioxidants, which possess a variety of additional medicinal properties. Black rice contains approximately six times as many antioxidants as brown rice. Pigmented rice, such as black rice, contain a greater quantity of phenolic compounds than other rice varieties (Das *et al*., 2014; Thanuja *et al*., 2018) [5, 26]. Black rice contains the highest concentration of total anthocyanins (327.60 mg 100 g^{-1}) among all the coloured cereals that were examined (Thompson *et al*., 1994) [27]. Anthocyanin's hypoglycaemic, anti-inflammatory, anti-cancer and antioxidant properties render it a functional component that contributes to the prevent ion of disorders (Hamid *et al*., 2010) [6].

In a period of swiftly urbanizing cities, changing standards of living, convenience and most importantly, a health-conscious public morning cereal has become more significant snack. People are also beginning to select ready to ear and convenient foods. Rice, wheat and pulses comprises the majority of India's staple foods, despite the substantial disparities discovered in daily caloric requirements and ingestion among various populations. As a result, these items may be indispensable when preparing RTE meals for Indians. Additionally, the gelatinization, dextrinization and caramelization of cereal carbohydrates, which impart their flavour and crispiness, are critical procedure of RTE meals (Pardeshi and Chattopadhyay, 2014) [17].

Rice is a popular choice for puffing due to its nutritional value, texture, and flavour. A whole grain product, puffed rice is produced by milling, parboiling, and pregelatinizing rice. Before being pulverized, the grains are typically hydrothermally preconditioned. After being treated with saline water to achieve the desired moisture level, the milled grains are used for puffing and roasting method. Its delicacy, elegance and characteristics associated with its cellular formations are the primary reasons for its value (Hoke). Puffed rice is also known as murmura, mumra, murra, muri, puri, borugulu, mandakki, kellepuri, churmuri and several other names. It is an inexpensive breakfast cereal and refreshment that is extensively consumed on a global scale. Puffed rice is also incorporated as breakfast cereals and refreshment meals in numerous regions of the globe. It serves as an ingredient in the popular Indian Chaat dish like bhel puri. However, it is also distributed as prasad in temples and gurudwaras (Tigari and Ramesh, 2020) [28].

2. Materials and Methods

The present research, "Process Optimization of Hot Air Puffing of Black Rice" was conducted at the Department of Food Grains and Seeds Processing Technology of Post Graduate Institute of Post-Harvest Technology and

Management, Killa-Roha, Dist. Raigad, (18°25'35.16312" N, 73°10'45.77484" E) during the year 2024-2025.

2.1 Sample preparation

Preliminary trials were conducted with black rice to determine the suitability for its puffing in a semi-automated continuous hot air puffing system. The paddy was pre-processed following existing techniques and methodology (Figure 2) being followed in commercial puffed rice factories in Maharashtra, as mentioned by Katkar *et al*., (2022) [8].

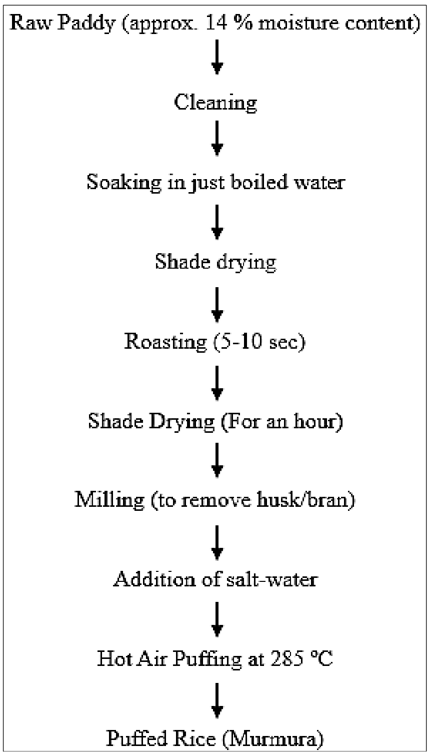

Fig 2: Flowchart of Sample preparation for Rice Puffing

2.2 Selection of process parameter

Depending on the needs of the various cereal grains and millets, the puffing machine can be adjusted to varied puffing temperature (ambient to 350 ºC) and feed rates (up to 10,000 g/h). In order to find the ideal process condition with respect to the response parameters like final moisture content (FMC,% db), expansion ratio (ER), puffing percentage (PP,%) and colour change (ΔE). Process parameters like puffing temperature (PT) and feed rate (FR) and soaking time (ST) were varied from 250 to 320 ºC, 2000 to 8000 g/h and 8 h to 30 h respectively.

2.3 Optimization

A three-factor and five-level Central Composite Rotatable Design (CCRD) was used for experimentation. To produce the highest quality HTST air-puffed black rice, the relative effects of the process variables (A: Soaking Time, h; B: Puffing Temperature, °C and C: Feed Rate, g/h) on the responses were investigated, and the continuous hot air puffing process was optimized. Here -1.6812, −1, 0, +1, +1.6812 represent low, medium, and high levels, respectively. In accordance, 20 runs as shown in Table 3 were conducted under identical environmental conditions. The results of experiments were analysed by response surface methodology using the statistical software Design Expert 2024 (StatEase, 2024).

The pre-processed black rice samples were prepared, and an experiment on HTST hot air puffing of black rice was conducted in CCRD with three variables *viz*., A: Soaking Time (ST, h), B: Puffing Temperature (PT, ºC) and C: Feed Rate (FR, g/h). Table 3 represents the actual and coded values of puffing variables of black rice.

Table 3: Experimental plan with actual and coded value of variables

Coded			Actual		
A	**B**	**C**	**A**	**B**	**C**
Center Point					
0	0	0	19	285	5000
0	0	0	19	285	5000
0	0	0	19	285	5000
0	0	0	19	285	5000
0	0	0	19	285	5000
0	0	0	19	285	5000
Box point					
-1	-1	-1	12.50	265	3200
-1	-1	+1	12.50	265	6800
-1	+1	-1	12.50	305	3200
-1	+1	+1	12.50	305	6800
+1	-1	-1	25.50	265	3200
+1	-1	+1	25.50	265	6800
+1	+1	-1	25.50	305	3200
+1	+1	+1	25.50	305	6800
Star point					
-1.6812	0	0	8	285	5000
+1.6812	0	0	30	285	5000
0	-1.6812	0	19	250	5000
0	+1.6812	0	19	320	5000
0	0	-1.6812	19	285	2000
0	0	-1.6812	19	285	8000

Each set of above experiment was conducted at interval of 6 months from 0 month to 18 months aging interval of paddy.

2.4 Evaluation of response parameter

Under the experimental design, the levels and combinations of treatments are described along with the process parameters such as Soaking Time (ST, h), Puffing Temperature (PT, ºC) and Feed Rate (FR, g/h) for puffing grains based on the puffed grain qualities such as final moisture content (FMC,% db), expansion ratio (ER), puffing percentage (PP,%) and colour change (ΔE).

2.4.1 Moisture content (% db)

The moisture content of the sample was determined by using hot air oven (0 to 300 °C). The weighed samples were subjected to remove moisture at 130 ± 2 °C for 90 min.

The moisture content was determined using the hot air oven method by using the following relationship (Sharad *et al*., 2024) [22].

$$\text{Moisture content} = \frac{\text{Initial weight (g)} - \text{Final weight (g)}}{\text{Initial weight (g)}} \times 100 \quad \ldots (1)$$

2.4.2 Expansion ratio (ER) measurement

Expansion ratio is the ratio of volume of final product after puffing to the volume of raw product before puffing. It is the physical quality attribute, which is desired to be maximum, when puffed. Maximum expansion ratio indicates good quality of puffing. Expansion ratio is determined by taking initial volume of sample fed (V_1) and expanded volume of puffed sample (V_2) (Katkar, 2022) [8]. The expansion ratio was calculated as,

$$\text{Expansion Ratio (ER)} = \frac{V2}{V1} \times 100 \quad \dots (2)$$

where,
V_1 - Initial volume of sample fed
V_2 - Expanded volume of puffed sample

2.4.3 Puffing Percentage (PP) measurement

The puffing percentage was calculated for puffed rice. The puffing percentage was calculated by following formula (Katkar, 2022) [8].

$$\text{Puffing Percentage (PP)} = \frac{\text{Puffed product (Np)}}{\text{Total product in feed sample (Nt)}} \times 100 \quad \dots (3)$$

where,
Np=Total puffed product
Nt =Total number of grains in the sample

2.4.4 Colour change (ΔE)

The colour of the grain samples at different state of processing were determined by CIE colour scales L*, a* and b* using Hunter Lab digital colorimeter. Where L* indicates the degree of lightness or darkness of the sample extended from 0 (black) to 100 (white), a* indicates degree of redness (+ a) to greenness (- a) whereas b* indicates the degree of yellowness (+ b) to blueness (- b), respectively.

$$\Delta E = \sqrt{((L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2)} \quad \dots. (4)$$

Where:
L_1 and L_2 are the lightness values of the two colours.
a_1 and a_2 are the a* (red-green) values of the two colours.
b_1 and b_2 are the b* (yellow-blue) values of the two colours. (Ahmad *et al*., 2014) [1].

2.5 Statistical analysis and optimization

Data analysis and optimization regression analysis and analysis of variance (ANOVA) were conducted for fitting the models to examine the statistical significance of the model terms. The adequacy of developed models was determined using F values, lack-of fit test, R2 (coefficient of determination) and Coefficient of variation (CV), adequate precision ratio (APR) as outlined by Lee *et al*., (2000). For better adequacy of the model the difference between predicted and adjusted R2 should be less than 0.2 whereas the adequate precision ratio should be greater than 4. Coefficient of variation (CV) indicates the relative dispersion of the experimental points from the prediction of the model and it should be less than 10%. The lack of fit is a measure of the failure of a model to represent data in the experimental domain at which points were not included in the regression or variations in the models cannot be accounted for by random error. If there is a significant lack of fit, as indicated by a low probability value, the response predictor is discarded. The R_2 is defined as the ratio of the explained variation to the total variation and is a measure of the degree of fit. Response surfaces and contour plots were generated with the help of commercial statistical package, Design Expert-version 11 (Stat Ease). The numerical and graphical optimization was also performed by the same software.

3. Results and Discussion

3.1 Observations of 0 month, 6 months and 12 months age puffed black rice

Table 4: The responses details obtained for Optimization of process parameters for hot air puffing of black rice after 0 and 6 months of aging

Sr. No.	Soaking Time (ST, h)	Puffing Temperature (PT, °C)	Feed rate (FR, g/h)	0 Month		6 Months		12 Months	
				Expansion Ratio (ER)	Puffing Percentage (PP,%)	Expansion Ratio (ER)	Puffing Percentage (PP,%)	Expansion Ratio (ER)	Puffing Percentage (PP,%)
1	19	285	5000	1.3	3.77	1.46	5.24	1.96	66.77
2	19	285	5000	1.3	2.45	1.42	9.41	1.91	65.3
3	19	285	5000	1.4	2.83	1.46	8.96	2.17	69.9
4	19	285	5000	1.4	4.15	1.33	9.53	2.09	69.09
5	19	285	5000	1.3	2.55	1.42	8.51	1.91	65.2
6	19	285	5000	1.4	3.75	1.33	7.93	2.04	68.9
7	13	265	3200	1.4	1.04	1.46	2.3	1.74	39.8
8	13	265	6800	1.4	1.91	1.54	3.46	1.83	50.91
9	13	305	3200	1.6	2.47	1.71	3.33	1.69	51.45
10	13	305	6800	1.4	2.67	1.67	4.4	1.8	55.56
11	26	265	3200	1.14	2.97	1.56	5.79	1.35	26.82
12	26	265	6800	1.4	3.99	1.25	7.15	1.66	22
13	26	305	3200	1.6	2.89	1.72	7.7	1.84	63.95
14	26	305	6800	1.4	2.83	1.56	8.52	1.79	53.27
15	8	285	5000	1.4	0	1.33	0	1.84	0
16	30	285	5000	1.5	1.68	1.96	5.97	1.91	69.29
17	19	250	5000	1.69	1.76	1.38	7.89	2.16	10.97
18	19	320	5000	1.2	2.85	1.88	6.54	2.15	75.4
19	19	285	2000	1.17	4.87	1.67	5.13	1.57	69.6
20	19	285	8000	1.3	3.37	1.88	2.92	2.12	68.3

The observations that were made throughout the process of optimizing the hot air puffing of black rice which was stored for less than one month, six months and twelve months are presented in Table 4. It was determined that the values of puffing percentage and expansion ratio that were obtained during this experiment was very low; hence, the data was not acquired for any further optimization.

3.2 Observations and result of 18 months age puffed black rice

Table 5: The responses details obtained for Optimization of process parameters for hot air puffing of black rice after 18 months of aging

Sr. No.	Soaking time (ST, h)	Puffing temperature (PT, °C)	Feed rate (FR, g/h)	18 Months			
				Expansion Ratio (ER)	Puffing Percentage (PP,%)	Moisture content (MC,%db)	Colour change (ΔE)
1	19	285	5000	2.68	89	3.90	13.641
2	19	285	5000	2.59	87.5	3.70	17.145
3	19	285	5000	2.63	86.2	4.10	11.790
4	19	285	5000	2.49	86.1	3.79	16.021
5	19	285	5000	2.69	86.7	4.50	11.006
6	19	285	5000	2.64	87.4	4.18	14.770
7	13	265	3200	2.08	82	5.20	25.603
8	13	265	6800	1.67	50	4.40	24.647
9	13	305	3200	2.34	81.6	4.80	8.7787
10	13	305	6800	2.23	87	4.00	22.733
11	26	265	3200	1.93	63	5.30	17.648
12	26	265	6800	2.44	45	4.40	25.161
13	26	305	3200	1.88	40	4.60	28.949
14	26	305	6800	1.97	22.8	3.78	27.746
15	8	285	5000	1.74	0	6.50	36.430
16	30	285	5000	2.03	42.1	6.00	32.888
17	19	250	5000	1.88	20.8	4.40	9.2565
18	19	320	5000	2.54	83	5.30	17.275
19	19	285	2000	2.64	82	5.10	19.878
20	19	285	8000	2.12	68.3	2.8	12.713

The observations that were made throughout the process of optimizing the puffing of black rice which was stored for 18 months are presented in Table 5. These observations were used for further optimization and results are given below.

3.2.1 Effect of Soaking time (h), Puffing temperature (ºC) and Feed rate (g/h) on moisture content (MC,% db) during hot air puffing of black rice

Here we can observe that from the figure 3 and figure 4, as soaking time goes on increasing from 8 h to 30 h it results in increase in moisture content. On the other hand, in case of puffing temperature, as it goes on increasing from 250 ºC to 310 ºC, moisture content starts decreasing. The feed rate has minimal effect on moisture content.

The R^2 value, obtained using a least squares method, was determined to be 0.8008, indicating a strong fit of the model to the data. The model F-value of 21.44 indicates statistical significance ($P<0.01$). The large F-value for lack of fit suggests that the established model is adequate for predicting the response. The model adequacy, assessed with a predicted R^2 of 0.6382, aligns reasonably with the Adjusted R^2 of 0.7634. This shows that the lack of fit is not substantial, this approach is applicable for exploring the design.

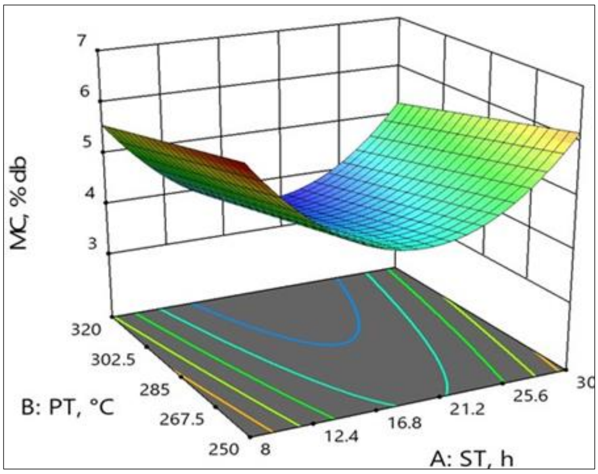

Fig 3: Contour and Surface response graph showing the effect of Soaking time (ST) and Puffing Temperature (PT) on Final Moisture Content (MC,% db) for puffing of black rice

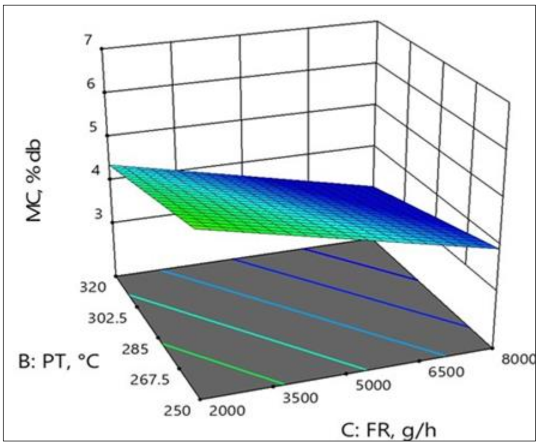

Fig 4: Contour and Surface response graph showing the effect of Puffing temperature (PT) and Feed rate (FR) on Final Moisture Content (MC,% db) for puffing of black rice

The F-values demonstrated that Soaking time² exerted the greatest influence, followed by feed rate and puffing temperature. The regression equation describing the effects of the process variables on expansion ratio in terms of actual levels of variables is given as;

MC,% db = 9.40398 - 0.01308 x PT - 0.000227 x FR + 0.000111 x ST² …. (7)

3.2.2 Effect of Soaking time (h), Puffing temperature (ºC) and Feed rate (g/h) on expansion ratio (ER)

As observed from the figure 5 and figure 6 expansion ratio increases as there is increase in soaking time from 8 h to 30 h and puffing temperature from 250 ºC to 310 ºC till an optimum level. After reaching to an optimum level expansion ratio starts decreasing as there is further increase in soaking time and puffing temperature. It can be due to faster heat transmission from higher temperatures causes the water inside the grain to evaporate more quickly, increasing the expansion force. The graph shows that as the puffing temperature increases, the expansion ratio achieves its optimal value before starting to decrease because warming thermally breaks down the protein and starch, compressing the porous structure instead of expanding it. Feed rate also has marginally similar effect on expansion ratio like soaking time and puffing percentage. Similar observations were recorded by Babar and Pardeshi (2017) [2], Rahman *et al*., (2019) [19] as well as Sharad *et al*., (2024) [22] and Pardeshi and Chattopadhyay (2010) [16]. Also while studying corn and barnyard millet (*Echinochloa frumentacea*), Rahman *et al*, (2019) [19], Sharad *et al*., (2024) [22] and Swapna (2017). Came to similar conclusions.

The R^2 value, computed using a least squares method, was determined to be 0.8596, indicating a strong model fit to the data. The model's F-value of 17.14 indicates statistical significance ($P<0.01$). The F-value indicating lack of fit was not significant for the derived model. The equation demonstrates that the created model was suitable for forecasting the reaction. This model is applicable to predict the design space.

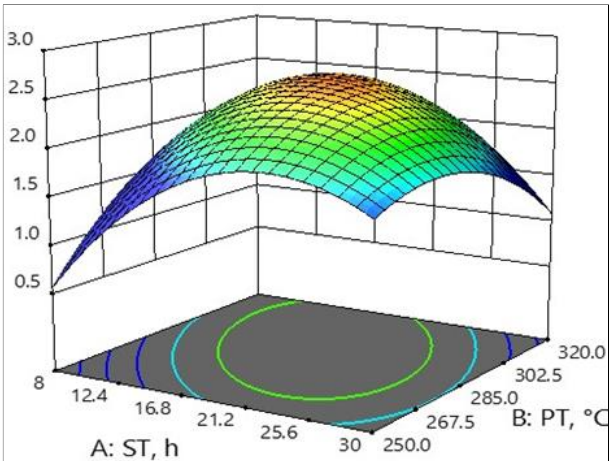

Fig 5: Contour and Surface response graph showing the effect of Puffing Temperature (PT) and Soaking time (ST) on Expansion Ratio (ER) for puffing of black rice

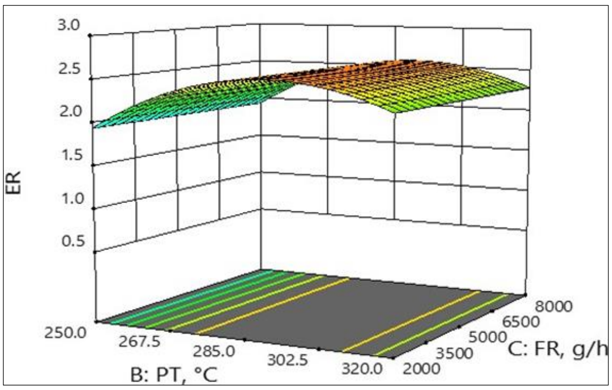

Fig 6: Contour and Surface response graph showing the effect of Puffing Temperature (PT) and Feed Rate (FR) on Expansion Ratio (ER) for puffing of black rice

The F values suggested that soaking time² was the most influential factor, whereas PT² had a minor effect on ER. The quadratic term puffing temperature exhibited minimal efficacy over ER. The regression equation describing the effects of the process variables on expansion ratio in terms of actual levels of variables is given as;

ER = -25.5335 + 0.191174 x PT + 0.000674 x ST x PT + 1.02006 x ST x FR - 0.00506 x ST - 0.00035 x PT …(8)

3.2.3 Effect of Soaking time (h), Puffing temperature (°C) and Feed rate (g/h) on Puffing percentage (%) of puffed black rice

From the figure 7 and figure 8 given below we can conclude that increase in soaking time from 8 h to 30 h and puffing temperature from 250 °C to 310 °C leads to increase in puffing percentage till an optimum level. There is an optimum zone near 18 h to 22 h soaking time and 285 °C. After reaching to an optimum level puffing percentage start decreasing. Feed rate has marginal effect on puffing percentage as there is a minor rise in puffing percentage after increase in soaking time and puffing percentage.

The R^2 value was calculated using the least squares approach and found to be 0.9866, signifying a robust fit of the model to the data. The model's F-value of 11.24 denotes statistical significance ($P<0.01$). The quadratic term is substantial. The F-value for lack of fit was significant, suggesting that the developed model was insufficient for predicting the response. The significant lack of fit renders this model inappropriate for exploring the design space. The F values suggested that soaking time² was the most influential factor, followed by puffing temperature², which had a minor effect on ER.

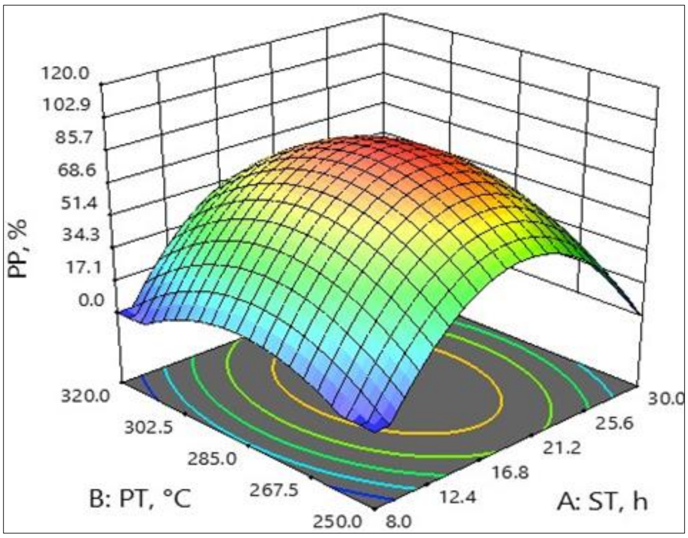

Fig 7: Contour and Surface response graph showing the effect of Puffing Temperature (PT) and Soaking time (ST) on Puffing Percentage (PP) for puffing of black rice

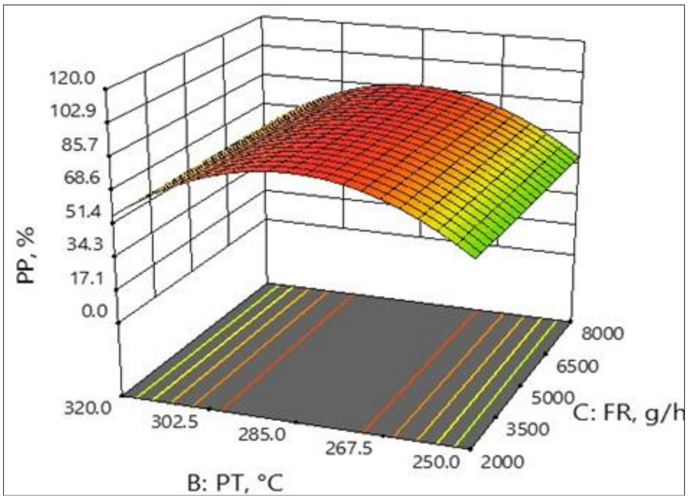

Fig 8: Contour and Surface response graph showing the effect of Puffing Temperature (PT) and Soaking time (ST) on puffing percentage (PP) for puffing of black rice

The puffing of grains depends on the right balance between moisture (from soaking) and heat (from puffing temperature). Up to a certain point, more soaking and higher temperature improve puffing by enhancing steam generation and starch expansion. However, beyond the optimum, excessive moisture or heat causes structural damage, crust formation, or premature moisture loss, resulting in a decline in puffing efficiency. Comparable findings were reported by Niravkumar (2011) [14] and by Katkar *et al*., (2024) [9] while observing trend of puffing percentage during puffing of rice.

3.2.4 Impact of Soaking time (h), Puffing temperature (ºC) and Feed rate (g/h) on colour change (ΔE) during hot air puffing of black rice

From the graph given below in figure 9 and figure 10 it is observed that the colour change value (ΔE) decreases as soaking time and puffing temperature increases from 8 h to 30 h and 250 ºC to 310 ºC respectively. It reaches to an optimum level where it is minimum. After reaching to the optimum level, it starts increasing with the further increase in soaking time and puffing temperature. Jog reported similar results while examining barnyard millet, while Katkar *et al*., (2024) [9] and Pal *et al*., (2019) [15] reported similar results when monitoring rice.

The R^2 value was computed using a least squares method and determined to be 0.7664, indicating a strong fit of the model to the data. The model F-value of 27.88 indicates that the model is significant ($P<0.01$). The F-value indicating lack of fit was not significant for the derived model. The equation demonstrates that the created model was suitable for forecasting the reaction. This model can facilitate navigation inside the design space.

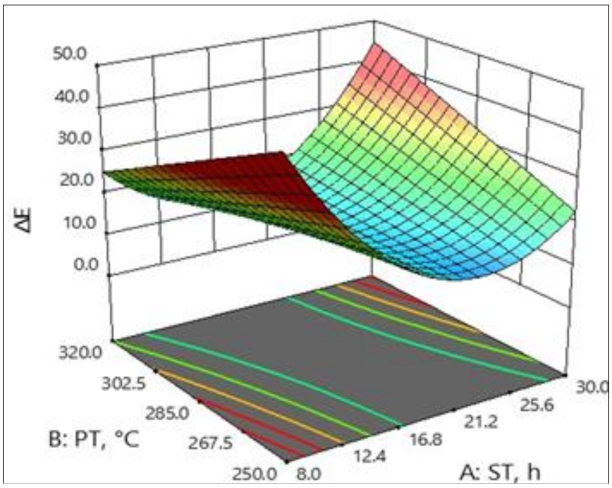

Fig 9: Contour and Surface response graph showing the effect of Puffing Temperature (PT) and soaking time (ST) on colour change (Δ E) for puffing of black rice

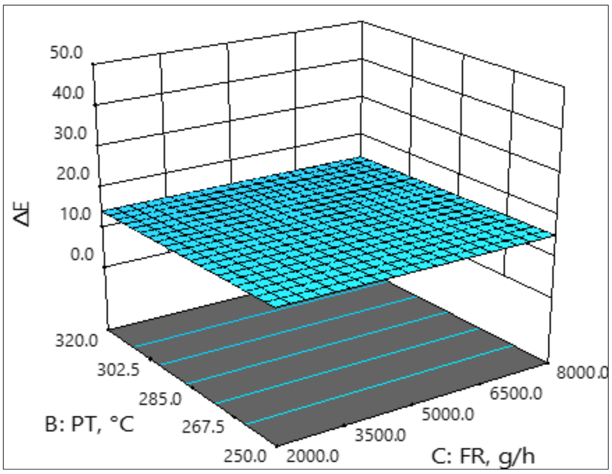

Fig 10: Contour and Surface response graph showing the effect of Puffing Temperature (PT) and Feed Rate (FR) on colour change (Δ E) for puffing of black rice

The F values suggested that soaking time² was the most influential factor, followed by AB, which was moderately effective compared to ΔE. The regression equation describing the effects of the process variables on expansion ratio in terms of actual levels of variables is given as;

$\Delta E = 34.0037 - 0.006767 \times ST \times PT + 0.057342 \times ST$ … (9)

3.2.5 Optimization of hot air puffing process for black rice

To get the optimum outcome, the hot air puffing process parameters were optimized both numerically and graphically. The software generated optimum conditions of independent variables with the predicted values of responses. The best condition for hot air puffing of black rice was determined to be Solution No. 1, which had the highest desire rating that is 0.909 (Table no 8).

The optimum values of process variables obtained by numerical optimization were found at soaking time of 19 h, puffing temperature of 290 ºC and feed rate of 6800 g/h. The superimposed contours of all responses for puffing temperature and feed rate and their intersection zone for minimum final moisture content, maximum expansion ratio, maximum puffing percentage minimum colour change indicated the ranges of variables which could be considered as the optimum range for best product quality. The range of optimum values of process variables obtained from the superimposed contours is as given in Figure 11 and 12 and Table 6. Software generated optimum conditions of independent variables with the predicted values of responses for hot air puffing of black rice

Table 6: The predicted responses for heated air puffing of black rice grain were generated by the software, which also generated the optimal conditions for independent variables

Number	ST, h	PT, °C	FR, g/h	MC,% db	ER	PP,%	ΔE	Desirability	
1	19.816	288.57	6799.998	3.70	2.576	87.691	14.842	0.909	Selected
2	19.879	288.622	6799.93	3.70	2.577	87.658	14.857	0.909	

The data was analyzed using the response surface approach, and it was found that the optimal parameters for puffing black rice were and 19.82 ~ 20 hours for the soaking time, 6800 g/h for the feed rate, and 288.57 ~ 290 °C for the puffing temperature, resulting in 87.691% puffing percentage (PP,%), 2.576 expansion ratio (ER), 3.7% final moisture content (FMC,% db), and 14.842 color change (ΔE) to be the optimized responses.

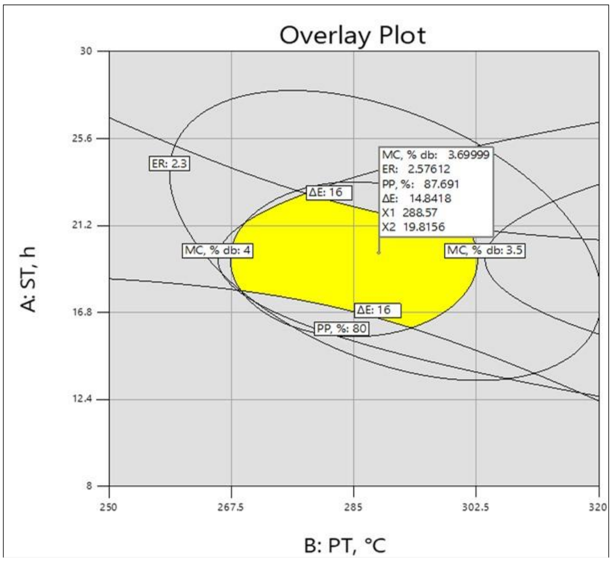

Fig 11: Overlay graph for soaking time (h) and puffing temperature (°C)

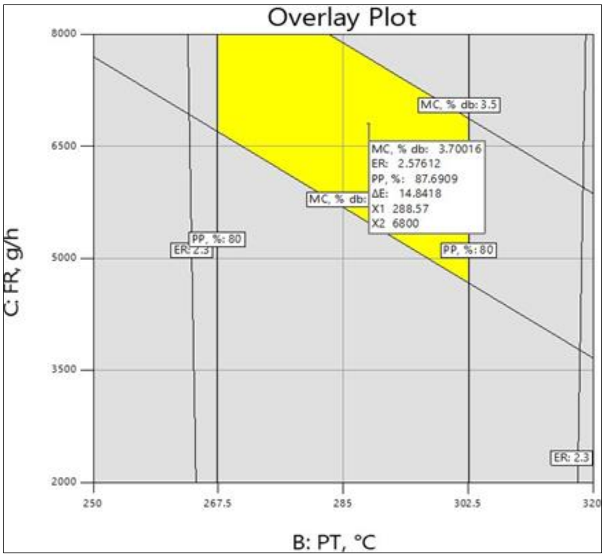

Fig 12: Overlay graph for puffing temperature (°C) and feed rate (g/h)

Table 7: Point of prediction versus actual observation for different variables and responses

Response	Predicted value	Actual value	Variation%	C.V.%	Mean	SD
ST, h	19.82	19.00	4.12320	2.97300	19.41	0.576999
PT, ◦C	288.57	290.00	-0.49554	0.34954	289.29	1.011163
FR, g/h	6799.998	6800	-0.00029	0.00003	6800.00	0.001414
MC,% db	3.70	3.70	0.00000	0.00000	3.70	0.000000
ER	2.58	2.69	-4.26365	3.06153	2.63	0.08061
PP,%	87.69	89.00	-1.49389	1.04771	88.35	0.925603
ΔE	14.84	14.77	0.47393	0.34386	14.81	0.050912

Table 7 indicates that the optimal conditions, characterized by a soaking time of 19 h, puffing temperature of 290 °C and feed rate of 6800 g/h, result in a moisture content of 3.70% db, an expansion ratio of 2.58, puffing percentage of 89.00% and colour change (ΔE) of 14.77.

Table 8: Comparison of results from 12 and 18 months hot air puffed black rice

Sr. No.	Aging months	Soaking time (h)	Puffing temperature (°C)	Feed rate (g/h)	Final moisture content (db,%)	Expansion ratio	Puffing percentage (%)	Colour change (ΔE)
1	12	18.435	290	6800	2.841	2.007	69.543	17.518
2	18	19.816	288.50	6800	3.700	2.576	87.69	14.840

3.3 Effect of aging on Puffing percentage (%) and expansion ratio on hot air puffing of black rice

From the table 8 we can conclude that the majority of puffing quality criteria, the 18-month-old black rice continuously outperformed the 12-month-old black rice. The puffing qualities appear to have been enhanced by the slightly longer soaking time and the extended age period. Despite being puffed at almost the same temperature and feed rate, the 18-month sample did not dry out as much because it maintained more moisture after puffing (3.70% vs. 2.84%). Better texture is frequently associated with this increased residual moisture. The biggest difference is observed in during the puffing is that 18 months black rice expanded more evenly and efficiently during puffing, achieving a much higher expansion ratio (2.576 vs. 2.007) and greater puffing percentage (87.69% vs. 69.54%).This implies that let the grains to age for 18 months may enhance their structural preparedness for puffing.

It can be concluded that from the observations mentioned in Table 4, 5 and 8, when black rice is stored for longer period of time in proper condition, its expansion ratio and puffing percentage increases with its aging period. At the beginning, the expansion ratio was 1.14 and the puffing percentage was 4.87%. Over a time, an ascending inclination was noted. Ultimately, it was found that the expansion ratio and puffing percentage were 2.576 and 87.69% respectively at 18 months age. Comparable findings were reported by Saha and Roy (2022) [20] while investigating about amylose content in rice, as well as by Peng *et al*., (2019) and by Chinnaswamy and Bhattacharya (1983) in their findings.

3.4 Bio-chemical Analysis

The effects of hot air puffing on moisture content, ash, fat, protein, fibre, carbohydrate of the raw and puffed rice are presented in Table 9.

Table 9: Changes in bio-chemical composition of raw and hot air puffed Black rice

Sr. No.	Parameters (% db)	Black rice		
		Raw	Puff	Variation
1	Moisture Content	11.81	3.18	73.049
2	Ash	1.29	0.91	29.721
3	Fat	2.26	1.87	17.242
4	Protein	9.57	7.88	17.636
5	Fiber	5.45	4.31	20.884
6	Carbohydrate	81.43	85.03	4.419

In case of chemical analysis, the ash, fat and protein content 1.17, 2.06 and 9.36 which was observed in raw grains decreases to 0.89, 1.85 and 8.28 respectively after puffing. The reduction in fat content was due to the formation of an amylose-fat complex resulting from the interaction between free fat and amylose. Furthermore, the fat was hydrolysed into fatty acids and monoglycerides at elevated temperature and pressure, which also contributed to the reduction in fat content (Kaur & Singh, 2000).

Explosion puffing did not significantly affect the overall protein content; rather, it resulted in a notable reduction in protein solubility (Ummadi *et al*., 1995). The reduction in ash content results from the loss of high volatile mineral content during puffing at elevated temperatures (Mir *et al*., 2016). The much-increased carbohydrate content in puffed form might be because puffed seeds had more endosperm, which accounts for 94% of the kernel's starch (Kumar *et al*., 2023) [11].

4. Conclusion

Optimization of hot air puffing of black rice done by using various processing parameters like final moisture content (% db), expansion ratio, puffing percentage (%), Colour change (ΔE) with respect to soaking time (h), Puffing temperature (°C) and Feed Rate (g/h). With a capacity of 2000 to 10000 g/h, the system may be adjusted to any puffing temperature between ambient to 350 °C. For hot air puffing of black rice, the ideal values of process variables such as soaking time (ST) 20 h, puffing temperature (PT) 290 °C, feed rate (FR) 6800 g/h, in a single pass while puffed in a hot air puffing machine, were found and the resulting optimized actual quality process parameters were found to be final moisture content (FMC) 3.7% db, expansion ratio (ER) 2.576, puffing percentage (PP) 87.691%, colour change value 14.842 respectively. Aging has a positive impact on puffing of black rice as initially it was observed that the expansion ratio and puffing percentage was 1.14 and 4.87%, respectively at 0 month aging of rice. Over a time, it was found that the expansion ratio and puffing percentage were 2.69 and 89% respectively at 18 months age. Moisture content, ash content, fibre content, protein content and fat content during puffing of black rice decreases and carbohydrate content increases.

References

1. Ahmad MS, Bosco SD, Shah MA, Mir MM. Effect of puffing on physical and antioxidant properties of brown rice. Journal of Food Chemistry. 2014.
2. Babar OA, Pardeshi IL. Study of puffing characteristics of rice-based fryums puffed with whirling bed continuous hot air puffing system. Journal of Ready to Eat Food. 2017;4(2):11-17.
3. Banerjee R, Chakraborty A, Chowdhury S, Ganguly S. Medico-nutritional value and profitability of black rice—the new black gold of Indian agriculture. Science for Agriculture and Allied Sector. 2019;3(6):11-16.
4. Chinnaswamy R, Bhattacharya KR. Studies on expanded rice optimum processing conditions. Journal of Food Science. 1983;48(6):1604-1608.
5. Das KR, Medhabati K, Nongalleima K, Devi HS. The potential of dark purple scented rice—from staple food

to nutraceutical. Current World Environment. 2014;9(3):867-876.
6. Hamid AA, Aiyelaagbe OO, Usman LA, Ameen OM, Lawal A. Antioxidants: Its medicinal and pharmacological applications. African Journal of Pure and Applied Chemistry. 2010;4(8):142-151.
7. Ito VC, Lacerda LG. Black rice (*Oryza sativa* L.): A review of its historical aspects, chemical composition, nutritional and functional properties, and applications and processing technologies. Journal of Food Chemistry. 2019;301:125304.
8. Katkar KC. Studies on evaluation of continuous type hot air puffing system [doctoral dissertation]. Dapoli: Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth; 2022.
9. Katkar KC, Pardeshi IL, Swami SB, Durgawati Sutar PP, Athmaselvi KA, Sontakke PB. Study on high temperature short time (HTST) hot air puffing of rice. Drying Technology. 2024;42(3):563-575.
10. Kaur K, Singh N. Amylose-lipid complex formation during cooking of rice flour. Food Chemistry. 2000;71(4):511-517.
11. Kumar DA, Nirmala B, Reddy DS, Meena A. Profit potential of black rice cultivation in Telangana state. 2023.
12. Maeda H, Yamaguchi T, Omoteno M, Takarad T, Fujita K, Murata K, *et al*. Genetic dissection of black grain rice by the development of a near isogenic line. Journal of Breeding Science. 2014;64(2):134-141.
13. Mir SA, Bosco SJ, Mih MA, Mir MM. Effect of puffing on physical and antioxidant properties of brown rice. Journal of Food Chemistry. 2016;191:139-146.
14. Niravkumar DJ. Technology development for production of ready-to-eat puffed rice using microwave energy [doctoral dissertation]. Anand: Anand Agricultural University; 2011.
15. Pal S, Bagchi TB, Dhali K, Kar A, Sanghamitra P, Sarkar S, *et al*. Evaluation of sensory, physicochemical properties and consumer preference of black rice and their products. Journal of Food Science and Technology. 2019;56(3):1484-1494.
16. Pardeshi IL, Chattopadhyay PK. Hot air puffing kinetics for soy-fortified wheat-based ready-to-eat (RTE) snacks. Food and Bioprocess Technology. 2010;3:415-426.
17. Pardeshi IL, Chattopadhyay PK. Whirling bed hot air puffing kinetics of rice-soy ready-to-eat (RTE) snacks. Journal of Ready to Eat Food. 2014;1(1):1-10.
18. Peng Bo PB, He LuLu HL, Tan Jing TJ, Zheng LiTing ZL, Zhang JieTing ZJ, *et al*. Effects of rice aging on its main nutrients and quality characters. 2019.
19. Rahman HA, Salleh HM, Salim NM. Effect of moisture content and microwave power on puffed yield and expansion volume of Malaysian paddy variety MR297. Malaysian Applied Biology. 2019;48(1):139-143.
20. Saha S, Roy A. Selecting high amylose rice variety for puffing: A correlation between physicochemical parameters and sensory preferences. Measurement of Food. 2022;5:100021.
21. Saha S, Vijayakumar S, Saha S, Mahapatra A, Kumar RM, Sundaram RM. Black rice cultivation in India-prospects and opportunities. Chronicle of Bioresource Management. 2022;6(2):44-48.
22. Sharad JS, Pardeshi IL, Swami SB, Ranveer RC, Kadam JH. Process optimization for hot air puffing of barnyard millet (*Echinochloa frumentacea*). 2024.
23. Sompong R, Siebenhandl-Ehn S, Linsberger-Martin G, Berghofer E. Physicochemical and antioxidative properties of red and black rice varieties from Thailand, China and Sri Lanka. Journal of Food Chemistry. 2011;124(1):132-140.
24. Stat-Ease Inc. Design Expert User’s Guide; Design Expert version 22.0. MN, USA: Stat-Ease Inc.; 2024.
25. Swapna G. Popcorn—a healthy nutritional speciality corn value-added product. International Journal of Food and Nutritional Science. 2017;6(2):1-5.
26. Thanuja B, Parimalavalli R. Role of black rice in health and diseases. International Journal of Health Science and Research. 2018;8:241-248.
27. Thompson LU. Antioxidants and hormone-mediated health benefits of whole grains. Critical Reviews in Food Science & Nutrition. 1994;34(5-6):473-497.
28. Tigari H, Ramesh HC. Working of puffed rice units. Journal of Commerce. 2020;8(2):45-52.
29. Ummadi P, Chenoweth WL, Ng PK. Changes in solubility and distribution of semolina proteins. Journal of Cereal Chemistry. 1995;72(6):564-567.