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Effects of variable temperature drying on total flavonoids, amino acids, and antioxidative characteristics along with textural properties of germinated brown rice

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Abstract

Germinated brown rice (GBR) is a kind of nutritional whole cereal food but faces an issue of long-term storage due to its high moisture content. In this study, the variable temperature (VT) drying condition for GBR was established by drying at 50°C for 60 min, followed by further drying at 70°C for 130 min. The results showed a lower percentage of fissured grains of GBR in the VT drying group (27%) than that dried at 70°C (35%) and 90°C (78%). The contents of total flavonoid, γ-aminobutyric acid (GABA), and antioxidant capacities *in vitro* of GBR in the VT drying group were higher than those of GBR in 90 and 110°C drying groups. The texture, color, and flavor of GBR were effectively maintained by the VT drying method compared with those of GBR dried under a higher constant temperature. This study provided reference data for the GBR drying process.

Keywords: germinated brown rice; variable temperature drying; fissuring; flavor; texture.

Practical Application: There are several dry processing methods, such as microwave drying, but it has not been widely used in rice processing due to temperature control, heating uniformity, equipment investment, and other issues. Suitable variable temperature drying method can effectively maintain the nutritional and edible quality of germinated brown rice.

1 INTRODUCTION

Germination is an effective and simple way to improve the nutrition and edible quality of brown rice. Specifically, germinated brown rice (GBR) contains an abundant functional component, such as γ-aminobutyric acid (GABA). Studies have shown that regular intake of GBR exhibits some beneficial effects, including anti-obesity (Lim *et al*., 2016), anti-diabetes (Lee *et al*., 2019; Nguyen *et al*., 2021), and anti-cancer (Li *et al*., 2019). However, GBR faces an issue of storage due to its high moisture content. The moisture content of GBR should be less than 14% wet basis (w.b.) for the purpose of long-term storage (Jittanit *et al*., 2010).

The most common method for extending the shelf life of GBR is drying. Hot air drying is the most commonly used drying method in the food processing industry due to its facility and low cost (Shang *et al*., 2018). However, high temperature and/or long drying period inevitably cause quality degradation such as fissuring, browning, and degradation of nutrition and flavor (Mussi *et al*., 2015; Sun *et al*., 2015). Low-temperature air drying was proposed as an efficient drying method to inhibit falling off in GBR quality, but it is a time-consuming process, which may cause food safety problems.

Variable temperature (VT) drying is a promising method for its shorter drying time, maintenance of nutrition, and lower fissure rate (Maldaner *et al*., 2021; Nosrati *et al*., 2021). Aquerreta *et al*. (2007) reported that the percentage of fissured kernels was drastically reduced using a two- or three-step hot drying process in comparison with those of the one-step drying method. The pre-germinated rough rice was processed using a three-stage drying method (fluidized bed drying, FBD) to obtain a higher yield, lower fissure rate, and better color (Tumpanuvatr et al., 2017). Sootjarit *et al*. (2011) found that the three-stage VT drying processing significantly reduced the fissured kernels and increased GABA content and antioxidant activity of GBR compared with those of GBR processed using the single-stage hot drying method under 50°C. A recent study also investigated the effect of drying approaches in conjunction with VT and tempering on the physicochemical quality of rice (Wang *et al*., 2023). Although VT drying has been widely investigated, the quality of GBR is varied under different temperatures procedure. Therefore, it is still necessary to comprehensively evaluate the quality of GBR, such as chemical components, color, texture, and flavor after VT drying processing.

2 MATERIALS AND METHODS

2.1 Materials and reagents

The brown rice (*japonica rice*) was provided by Yingfeng Wudou Ecological Agriculture Co., Ltd. (Shanghai, China). The hydroxyl-free radical assay kit (A018-1-1) was purchased from Nanjing Jiancheng Bioengineering Institute (Nanjing, China). The amino acid mixture standard solution (Type B, 016-08641) was purchased from Wako Pure Chemical Industries, Ltd. (Wako, Japan). All the other chemicals used in this study were of analytical grade and were obtained from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

2.2 Preparation of GBR

GBR was prepared by the method of Zhu *et al*. (2022). Briefly, the brown rice was sterilized in 0.1% sodium hypochlorite for 30

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s and washed with ultrapure water several times. Then, brown rice grains were soaked in ultrapure water at 29°C for 13 h and germinated in a thermostat incubator at 29°C for 24 h in darkness. The brown rice was kept moist during the germination process.

2.3 Drying process and condition

The GBR samples were evenly spread out on a tray and placed in an electric thermostatic drying oven under different oven temperatures (50, 70, 90, and 110°C, respectively). Single-stage hot air drying at about 50°C is a common condition used for the drying process of GBR (Moongngarm & Saetung, 2010; Sootjarit *et al.*, 2011); therefore, 50°C was selected as the control in this study. The VT drying temperature and time procedure were manually set up as follows: 50°C/30 min (first stage)+70°C/140 min (second stage), 50°C/60 min (first stage)+70°C/130 min (second stage), and 50°C/90 min (first stage)+70°C/110 min (second stage) according to our pre-experiment and previous studies (Sootjarit *et al.*, 2011; Tumpanuvatr *et al.*, 2018), and the temperature variation during processing was ±1°C. The drying process was terminated when the moisture content of GBR reached 14% (w.b.). The GBR processed under VT drying conditions that exhibited lowest fissuring rate was chosen, grinded, and sieved through an 80-mesh sieve for nutrition components and antioxidative activities analysis.

2.4 Moisture content analysis

The moisture content was determined using the oven drying method (AOAC, 934.01, 1934).

2.5 Fissuring rate evaluation

The fissuring rate of GBR was evaluated according to the Tumpanuvatr *et al.*'s (2018) method. Briefly, 100 grains of rice were randomly selected, one or more cracks on the kernels were considered as fissure, and the percentage of fissured kernels to the total amount of grains was presented as the fissuring rate.

2.6 Determination of total flavonoid contents

A weight of 2 g of GBR powder was taken out, to which 10 mL of ethanol (50%, v/v) was added for ultrasonic extraction (280 W, 45°C, 40 min). This mixture was then centrifuged at 4000 rpm/min for 10 min to obtain the supernatant. Further, a volume of 2 mL of aluminum chloride (0.1 mol/L) was added into 5 mL of the supernatant and was allowed to react for 8 min before adding 3 mL potassium acetate solution (1 mol/L) to the previous mixture. Later, the absorbance was determined at 420 nm after 30 min reaction at room temperature. The total flavonoid content was expressed as milligrams of rutin equivalents per 100 g on a dry weight (DW) basis.

2.7 Free amino acid determination

The determination of free amino acid was performed as mentioned by Guan *et al.* (2019) with slight modification. Briefly, 1 mL of HCl (0.1 mol/L) was added to the GBR powder (0.1 g) and pulverized with a tissue lyzer (Model Sceintz-48, Xinzhi Biological Technology Co., Ltd., China) at 60 Hz for 5 min. A volume of 400 μL of the supernatant was then taken out after centrifugation at 12000 rpm for 10 min. Further, 10% trichloroacetic acid (m/v, 400 μL) was added, mixed, and incubated at 4°C for 1 h. Further, centrifugation was carried out at 12000 rpm for 30 min, and 400 μL of supernatant was pipetted out. After that, 8 mol/L NaOH (11.5 μL) was added and then centrifuged at 12000 rpm for 30 min. The obtained supernatant (100 μL) was filtered through a 0.45 μm filter membrane, and 30 μL of the sample was injected into an automatic amino acid analyzer (Model L-8900, Hitachi, Japan) with a Na-cation-exchange column (3 μm, 4.6 mm×60 mm). Each test had a retention time of 90 min. The absorbance at 570 nm was measured after amino acids were post-column derivatized with ninhydrin. On a DW basis, the results were presented as milligrams per 100 g (DW).

2.8 Antioxidative activity in vitro analysis

GBR powder (0.5 g) was ultrasonically extracted with anhydrous ethanol (5 mL) at room temperature for 30 min and then centrifuged at 4000 rpm for 10 min to obtain the supernatant for the following detection. 1,1-Diphenyl-2-picrylhydrazyl (DPPH) solution (0.1 mmol/L) was prepared. The reaction solution was incubated at room temperature for 30 min, followed by the measurement of absorbance at 520 nm, and then calculated using the following equation:

$$\text{DPPH radical scavenging capacity (\%)} = \left(1 - \frac{A_i - A_j}{A_c}\right) \times 100$$

where A_i=absorbance of the sample (0.5 mL) and DPPH solution (2 mL); A_j=absorbance of the sample (0.5 mL) and anhydrous ethanol (2 mL); and A_c=absorbance of anhydrous ethanol (0.5 mL) and DPPH solution (2 mL).

The hydroxyl radical inhibiting activity was measured based on the principle of Fenton's method and was carried out according to the Guan *et al.*'s (2019) method. The results were performed using the following equation:

$$\text{Hydroxyl radical inhibiting activity (\%)} = \left(1 - \frac{A_s}{A_c}\right) \times 100$$

where A_s and A_c are the sample and the control absorbances, respectively.

2.9 Texture profile analysis (TPA)

A weight of 10 g of GBR was added to 12 mL of ultrapure water and was cooked for 40 min. The textural properties of cooked GBR were analyzed using a TA-XT Plus Texture analyzer with a P/50 probe (Stable Micro Systems Ltd., UK). Random six rice grains were taken out and placed symmetrically on the platform for texture measurement. The probe was allowed to descend at a speed of 10 mm/s, with test and post-test speeds of 0.5 and 5 mm/s, respectively. The compression ratio was set to 75%, and the trigger point was set to 10 g. Force-time curves were used to depict GBR's hardness, adhesiveness, springiness, and viscosity.

2.10 Color determination

The GBR powder (2.0 g) was weighed, placed in a plastic bag, and evenly paved about 2 mm. The color values of L^* (lightness), a^* (redness), and b^* (yellowness) were determined using a spectrophotometer (Model Ci62L+RTL, X-Rite Ltd., USA).

2.11 Flavor determination

Flavor determination was carried out as the method of Zhu *et al.* (2022). Briefly, 5.0 g of GBR powder was weighed, placed into a headspace extraction bottle, and sealed. The flavor components' characteristics of the GBR were analyzed via an electronic nose (Model Super Nose, Isenso, USA), which contained an array of 14 different metal oxide sensors. The operation conditions were as follows: equilibrium time, 30 min; cleaning time, 60 s; flow rate, 0.6 L/min; and sampling time, 60 s.

2.12 Statistical analysis

All analyses were performed in triplicates. The figures were drawn using Origin 2021 (Origin Lab Co., USA) software. The statistical significance of the data was determined using the one-way analysis of variance (ANOVA) method (IBM SPSS Statistics 25, IBM Co., USA), followed by the least significant difference (LSD) multiple comparison test. A statistically significant difference was defined as $P<0.05$. The results were presented as the mean±standard deviation (SD).

3 RESULTS AND DISCUSSION

3.1 Effect of drying temperatures on the drying time and fissuring rate of GBR

The obtained drying time of the moisture content when GBR reached 14% under different temperatures was 300 min at 50°C, 150 min at 70°C, 60 min at 90°C, and 45 min at 110°C (Table 1). The percentage of fissured grains became progressively more severe as the drying temperature increased. Specifically, the percentage of fissured grains processed at 110°C (87%) increased by 3 times and 1.5 times compared with those of GBR processed at 50°C (22%) and 70°C (35%) (Table 1). A similar trend was observed in a previous study where rough rice was processed at 53, 60, and 80°C, respectively, as a result of which, the treatment at 80°C led to the highest percentage of fissured grains (69%) (Iguaz *et al.*, 2006). However, another previous study showed that the hot air drying at 150°C (41%) had a significantly lower percentage of fissured kernels than those of GBR processed at 130°C (65%) (Srisang *et al.*, 2011). Fissuring is not a desirable characteristic for rice manufacturers as it negatively impacts the cooking properties. Improper drying process of GBR usually increases the percentage of fissured grains due to a larger moisture gradient and higher pressure inside the kernel (Müller *et al.*, 2022), which degrades the taste, flavor, and texture of GBR. Decreasing the percentage of fissured grains in the drying process is very important for maintaining GBR quality. Therefore, it is necessary to establish optimal hot drying conditions for different categories of rice due to the difference in starch structure in order to decrease the fissuring rate.

Table 1. Drying time and percentage of fissured grain at different drying temperatures*.

Conditions	Total time (min)	Fissured grain (%)
50°C	300	$22±3^{e}$
70°C	150	$35±0^{c}$
90°C	60	$78±1^{b}$
110°C	45	$87±2^{a}$
50°C/30 min+70°C/140 min	170	$32±2^{c}$
50°C/60 min+70°C/130 min	190	$27±1^{d}$
50°C/90 min+70°C/110 min	200	$27±1^{d}$

"Total time": the drying time required for the moisture content of GBR reaching 14% under different conditions; *different letters behind data indicate statistical significance in differences among groups ($P<0.05$). Data are described as the mean±SD.

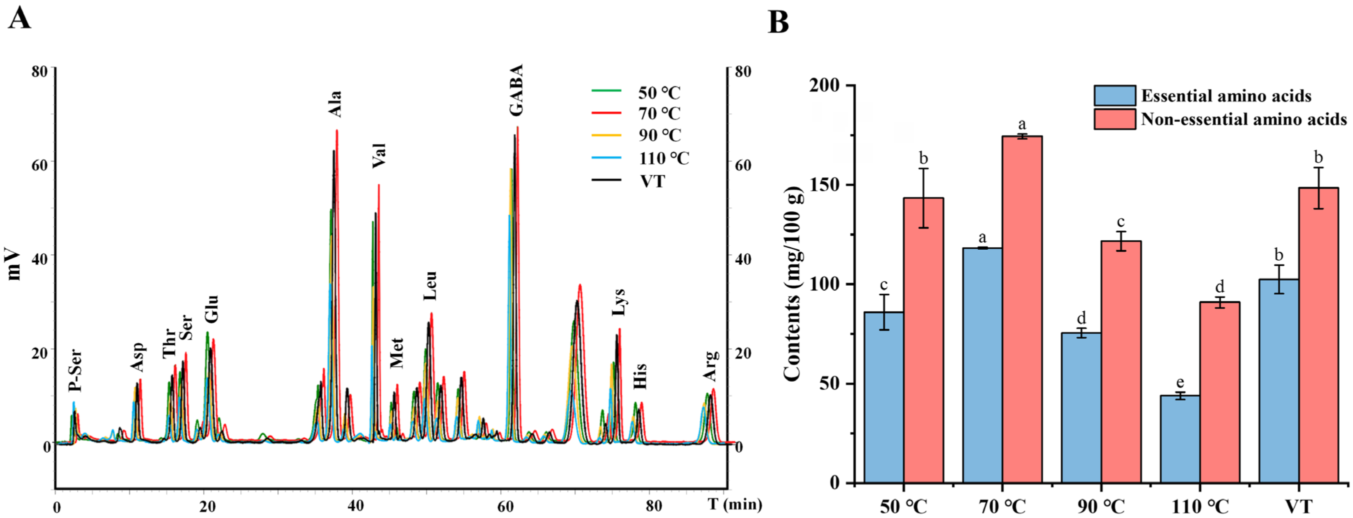
The study has shown that the percentage of the fissured kernel of the reference GBR dried in the shade was approximately 25% (Srisang *et al.*, 2011). In this study, the percentage of fissured grains under VT processing conditions was lower than those of GBR under constant temperature drying conditions (70, 90, and 110°C) (Table 1). Temperatures of 50 and 70°C were chosen as variable drying temperatures based on drying time and percentage of fissured grains. The percentage of fissured grains under variable drying conditions of 50°C/60 min+70°C/130 min (27%) and 50°C/90 min+70°C/110 min (27%) was significantly lower than that of GBR under drying condition of 50°C/30 min+70°C/140 min (32%) ($P<0.05$). Considering the processing efficiency, drying at 50°C for 60 min followed by drying at 70°C for 130 min was selected as the optimal condition of VT drying. It was shown that the fissuring rate of GBR processed under the suitable VT processing condition was significantly lower than that of GBR drying with a one-step procedure at high temperatures in this study.

3.2 Effect of drying temperatures on the amino acid contents of GBR

The chromatogram and the change trends of essential and non-essential amino acids are shown in Figures 1A and B, and all specific amino acids are listed in Table 2. The analysis showed that the content of most of the amino acids (except cysteine and ornithine) in GBR dried at 70°C were higher than those of GBR dried at 50, 90, and 110 °C ($P < 0.05$). The contents of amino acids in GBR under VT drying condition were lower than those of GBR dried at 70°C but higher than the other three GBR drying (50, 90, and 110°C) groups ($P<0.05$). These results may suggest that VT drying may be an alternative method for GBR to maintain protein quality.

The changes in the content of free amino acids under different temperatures may be due to (1) interactions between amino acids causing new links; (2) degradation reactions involving lateral chains of the proteins; (3) rearrangements of amino acids with -SH and -SS groups; (4) thermal denaturation; (5) interactions with lipids, which can decrease the availability of sulfur-containing amino acids; and (6) carbohydrate-protein interactions (Maillard reaction) (Mesías *et al.*, 2016; Pompei *et al.*, 1988).

GABA, an attractive and predominant amino acid in GBR, exhibited the same change trends with other amino acids. The increase of GABA content in GBR is related to the promotion of glutamate metabolism. Appropriate temperature is conducive to the activation of glutamic acid decarboxylase, thus promoting the enrichment of GABA. Similarly, Tumpanuvatr *et al*. (2018) showed that the application of two-stage drying including FBD at 60°C for 10 min in the first stage followed by FBD at 100°C in the second stage together with a tempering step between drying stages displayed the highest GABA content in GBR sample. However, Sootjarit *et al*. (2011) found that the single-stage drying by FBD at 120°C produced the highest GABA content of GBR compared with other conditions applied in their study. This phenomenon suggested that the accumulation of GABA in response to high temperatures could be a stress response. The mechanism relating to the influence of different temperatures on GBR content change requires further investigation.



*Different letters on the bars indicate statistical significance in differences among groups ($P<0.05$). Data are described as the mean±SD. The bars show the mean values with SDs.

Figure 1. Effect of drying temperatures on the amino acid contents of GBR. (A) Chromatogram of amino acids. (B) Contents of essential and non-essential amino acids. VT: variable temperature (50°C/60 min+70°C/130 min)*.

Table 2. Amino acid contents of GBR at different drying temperatures (mg/100 g)*.

Amino acids	50°C	70°C	90°C	110°C	VT
Aspartic acid	5.44±0.63^{c}	9.58±0.48^{a}	8.01±0.16^{b}	5.63±0.40^{c}	9.39±0.65^{a}
Threonine	8.69±0.99^{c}	12.04±0.16^{a}	7.59±0.22^{d}	4.30±0.18^{e}	10.07±0.66^{b}
Serine	9.09±0.98^{c}	12.50±0.11^{a}	8.76±0.32^{c}	6.59±0.23^{d}	10.88±0.71^{b}
Glutamic acid	28.56±2.85^{a}	29.14±0.30^{a}	21.39±0.58^{c}	18.96±0.57^{c}	25.47±1.81^{b}
Glycine	7.43±0.80^{b}	10.37±0.08^{a}	6.19±0.50^{c}	3.36±0.30^{d}	8.32±0.51^{b}
Alanine	26.42±2.92^{c}	38.42±0.33^{a}	26.93±0.97^{c}	19.99±0.56^{d}	34.11±2.26^{b}
Valine	15.98±1.58^{b}	19.82±0.09^{a}	12.58±0.41^{c}	7.58±0.24^{d}	16.76±1.15^{b}
Cysteine	0.81±0.09^{a}	0.35±0.19^{b}	0.00±0.00^{c}	0.09±0.16^{c}	0.55±0.03^{b}
Methionine	5.53±0.48^{c}	8.03±0.49^{a}	4.44±0.27^{d}	2.52±0.14^{e}	6.77±0.53^{b}
Isoleucine	9.42±1.07^{b}	11.38±0.07^{a}	6.72±0.16^{c}	3.60±0.14^{d}	9.89±0.70^{b}
Leucine	18.24±1.96^{c}	27.09±0.19^{a}	16.77±0.53^{c}	8.76±0.36^{d}	23.67±1.64^{b}
Tyrosine	15.10±1.66^{b}	17.84±0.14^{a}	11.52±0.26^{c}	6.39±0.25^{d}	14.87±1.03^{b}
Phenylalanine	12.39±1.19^{c}	17.92±0.17^{a}	11.70±0.11^{c}	6.37±0.57^{d}	15.86±1.10^{b}
Ornithine	3.96±0.38^{a}	3.61±0.10^{b}	2.20±0.08^{c}	0.81±0.02^{d}	2.45±0.13^{c}
Lysine	10.68±1.20^{c}	16.53±0.41^{a}	11.75±0.47^{c}	7.82±0.29^{d}	14.66±1.06^{b}
Histidine	8.81±1.02^{a}	9.30±0.35^{a}	6.37±0.29^{c}	4.84±0.17^{d}	7.47±0.54^{b}
Arginine	17.32±2.02^{b}	21.03±0.31^{a}	16.75±0.81^{b}	14.12±0.50^{c}	18.26±1.45^{b}
Proline	10.60±0.56^{b}	12.85±0.11^{a}	7.32±0.60^{c}	4.34±0.35^{d}	9.73±0.96^{b}
Tryptophan	5.01±0.52^{ab}	5.41±0.06^{a}	3.94±0.16^{c}	2.94±0.11^{d}	4.70±0.42^{b}
AspNH2	4.69±0.54^{a}	5.07±0.17^{a}	3.43±0.20^{b}	3.51±0.11^{b}	3.91±0.32^{b}
GluNH2	5.08±0.59^{a}	4.33±0.40^{b}	2.83±0.11^{cd}	2.29±0.03^{d}	2.94±0.27^{c}
GABA	27.75±3.21^{c}	35.95±0.30^{a}	32.28±1.13^{b}	25.89±0.97^{c}	33.28±2.18^{ab}
Σ	279.52±22.05^{bc}	329.21±1.58^{a}	223.05±6.72^{c}	154.36±4.49^{d}	283.00±16.07^{b}

VT: variable temperature (50°C/60 min+70°C/130 min); *different letters behind data indicate statistical significance in differences among groups ($P<0.05$). Data are described as the mean±SD.

3.3 Effect of drying temperatures on the total flavonoid contents of GBR

The total flavonoid contents of GBR are shown in Figure 2A. It showed that the total flavonoid contents of the GBR significantly decreased with the increasing drying temperatures within the range from 50 to 110°C ($P<0.05$), which indicated that the total flavonoids were probably decomposed. The reason why higher temperature leads to a decrease in the total flavonoid content is the reaction of hydrolysis (Liao *et al.*, 2020), oxidation (Irakli *et al.*, 2018), and degradation of flavonoids (Buchner *et al.*, 2006). The total flavonoid content of the GBR in the VT drying group was significantly different from that of the GBR drying at constant temperature ($P<0.05$) and was observed to be 142.70 mg/100 g, which was significantly lower by 13.09% when compared to GBR drying at 50°C and higher than GBR drying at 70, 90, and 110°C ($P<0.05$). These results further showed that VT drying processing is conducive to maintaining some components that are thermally unstable in GBR.

3.4 Effect of drying temperatures on the antioxidant capacity in vitro of GBR

The *in vitro* antioxidant capacities of GBR processed under different drying temperatures are shown in Figure 2B. With the increase in drying temperature, DPPH radical scavenging and hydroxyl radical inhibiting rates of GBR processed under constant drying temperature exhibited decreasing trends, while those of GBR processed under VT drying conditions were significantly higher than those of GBR processed at 90 and 110°C drying groups ($P<0.05$). There was no significant difference observed in the hydroxyl radical inhibiting activity of GBR processed under VT drying conditions as well as 50 and 70°C drying groups.

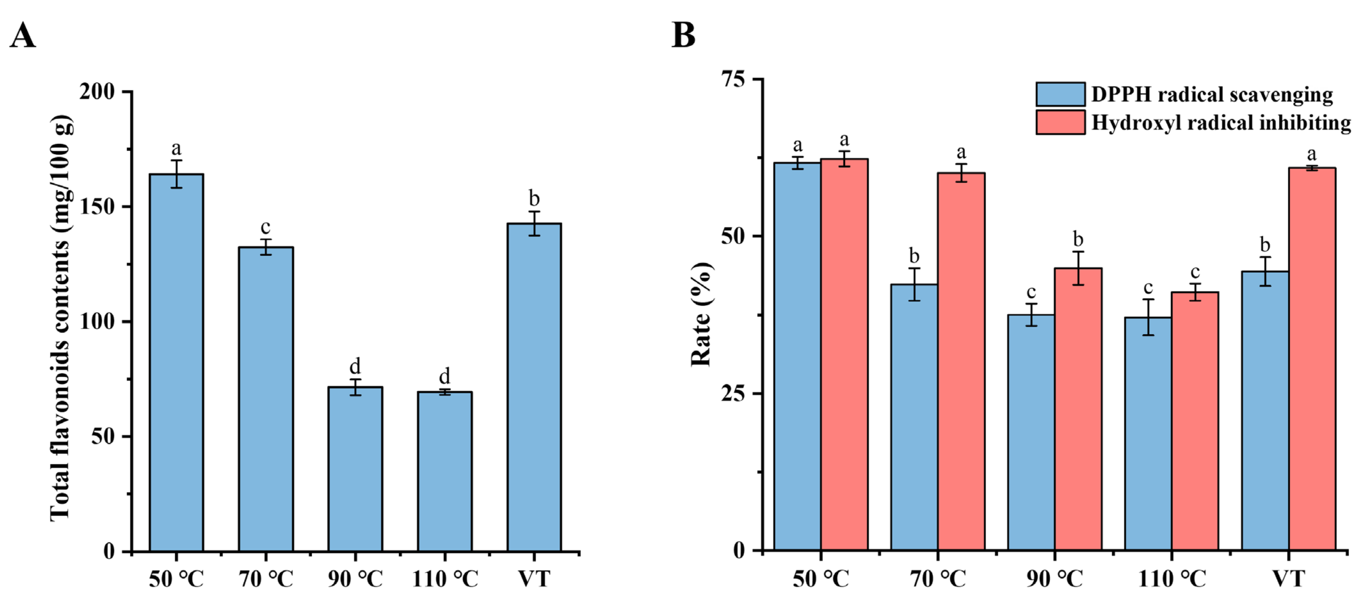
The change trends of *in vitro* antioxidant capacities of GBR processed under different drying temperatures were consistent with those of total flavonoids. Some previous studies also showed a positive correlation between *in vitro* antioxidant capacity and total flavonoid contents as it is one of the main contributors to the antioxidative activity in plant-origin food, including GBR (Goufo & Trindade, 2017; Muzolf-Panek & Stuper-Szablewska, 2021).

3.5 Effect of drying temperatures on the textural properties of GBR

The textural properties of cooked rice represent the edible quality of GBR. The textural curves of GBR processed at different drying temperatures are shown in Figure 3. The textural properties showed that the hardness and viscosity of GBR were gradually decreased, while the adhesiveness was increased with the increase in drying temperature (Table 3). Notably, the hardness, adhesiveness, springiness, and viscosity of GBR in the VT processed group were close to those of GBR in 50 and 70°C drying groups, which suggested the advantages of a suitable VT drying process (Table 3). The percentage of fissured grains increased under high drying temperature conditions. It is known that fissuring kernels make it easier for water to migrate from the outer to the inner layer during the cooking process and help amylose to leach and dissolve, which results in a decrease in hardness (Maldaner *et al.*, 2021; Odunmbaku *et al.*, 2018).

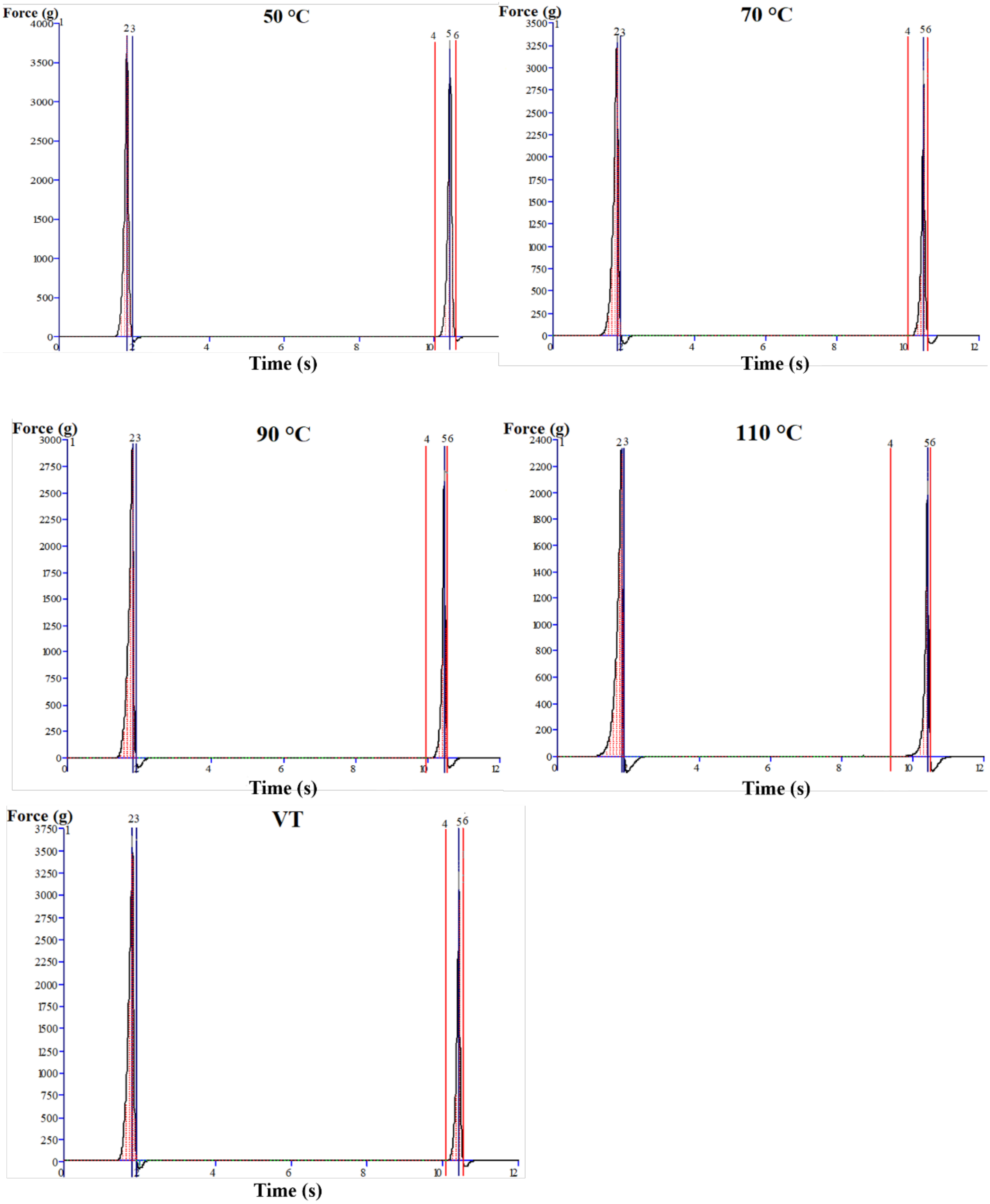
3.6 Effect of drying temperatures on the color of GBR

The values of L^*, a^*, and b^* of GBR processed under different drying conditions were given as input into the database from the website (https://www.colortell.com/labto) to obtain the chromaticity of GBR. As a result, it was observed that



VT: variable temperature (50°C/60 min+70°C/130 min); *different letters on the bars mean statistical significance in differences among groups ($P<0.05$). Data are described as the mean±SD. The bars show the mean values with SDs.

Figure 2. Effect of drying temperatures on the total flavonoid contents and antioxidant capacity of GBR. (A) Total flavonoid contents of GBR. (B) DPPH radical scavenging and hydroxyl radical inhibiting activities*.



VT: variable temperature (50°C/60 min+70°C/130 min).

Figure 3. Textural curves of GBR under different drying temperatures.

Table 3. Texture properties of GBR at different drying temperatures*.

Groups	50°C	70°C	90°C	110°C	VT
Hardness (g)	3671.95±962.15^{a}	3192.33±517.08^{ab}	3093.35±253.68^{ab}	2519.93±195.54^{b}	3429.98±594.21^{ab}
Adhesiveness (g·s)	8.58±0.16^{d}	19.57±7.03^{c}	22.81±4.47^{b}	32.02±3.58^{a}	19.31±3.09^{c}
Springiness (mm)	4.18±0.34^{a}	4.28±0.45^{a}	3.42±0.17^{b}	3.67±0.66^{ab}	4.21±0.19^{a}
Viscosity (g)	1.74±0.18^{a}	1.72±0.05^{a}	1.62±0.11^{a}	1.58±0.07^{a}	1.70±0.01^{a}

VT: variable temperature (50°C/60 min+70°C/130 min); *different letters behind data indicate statistical significance in differences among groups ($P<0.05$). Data are described as the mean±SD.

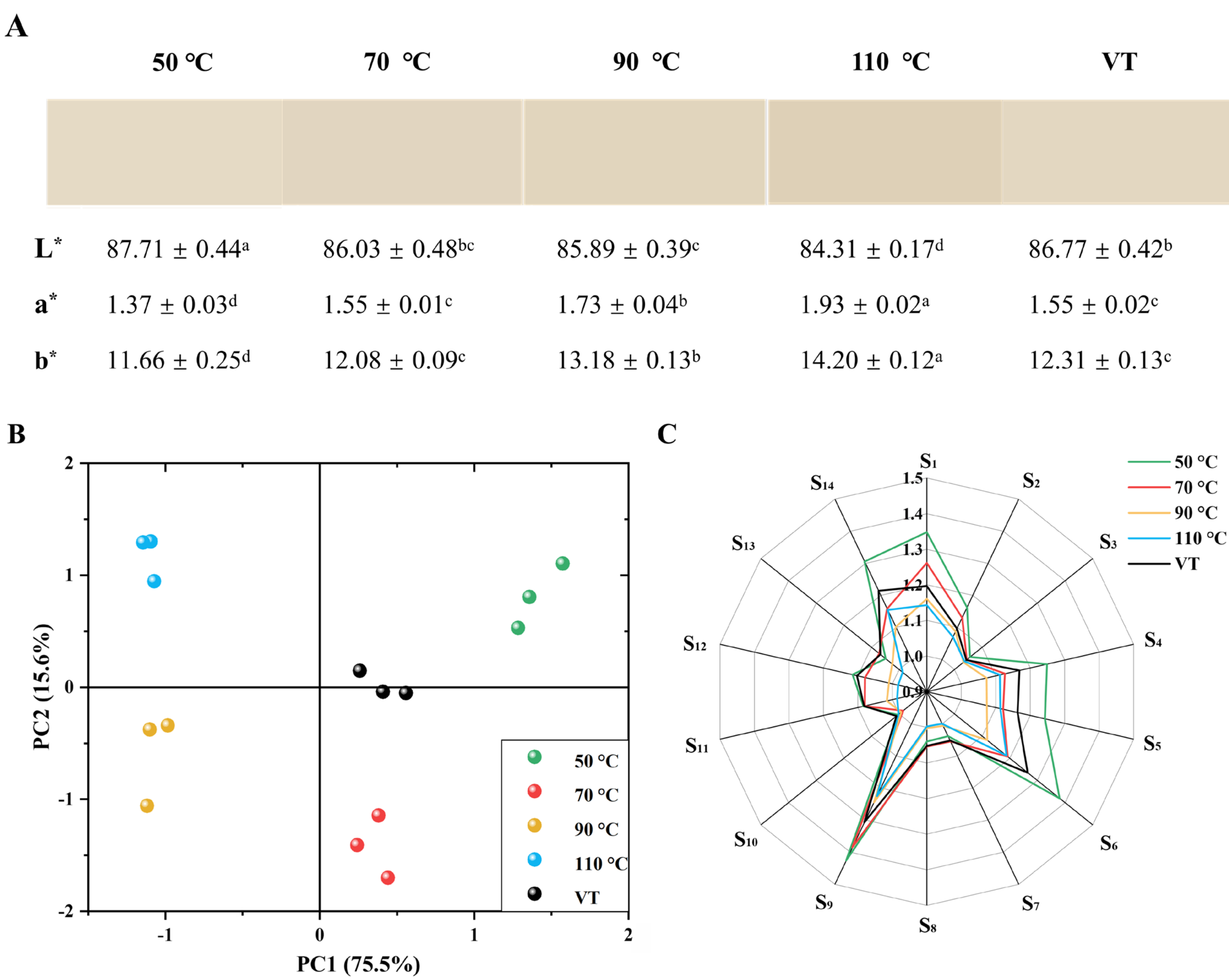
drying temperatures had a significant impact on GBR color (Figure 4A): the L* of GBR obviously decreased, and the a* as well as b* increased with the increasing of drying temperatures ($P<0.05$), while the L*, a*, and b* values of GBR in the VT drying group were close to those of GBR in the 50 and 70°C drying group, which indicated that high-temperature drying resulted in the darker color of GBR compared with low temperature. Similar results were also found in other drying conditions, including regular hot air oven drying, FBD, and microwave heating (Kim *et al.*, 2014; Sootjarit *et al.*, 2011). The formation of some Maillard reaction products, which are produced by the heat applied during the drying process of rice, may explain the color changes under different drying temperatures (Rordprapat *et al.*, 2005). In addition to the drying temperature, the drying method also affected the color of brown rice. Hot air-assisted radiofrequency treatment and drum drying reduce the L* value and increase the a* and b* values (Liao *et al.*, 2020; Qi *et al.*, 2019).

3.7 Effect of drying temperatures on the flavor of GBR

One of the most important indicators of grain quality is flavor. Different drying processes (especially at different temperatures) usually lead to the change of different aromatic compounds in grains (Sledz *et al.*, 2017).

E-nose analysis is an easier and quicker method for the evaluation of rice aroma quality (Hu et al., 2020). It can detect the comprehensive profile of volatiles by sensor array instead of quantitative analysis of volatiles.

The PCA result showed expected flavor clusters of GBR groups treated with different drying temperatures (Figure 4B). The variance contribution rates of the main factors were 75.5 and 15.6%, respectively, and their accumulative variance contribution rate was 91.1%, which indicated that these two principal components could reflect the information of the total variance. It showed that high drying temperatures (90 and 110°C) and low drying temperatures (50°C, 70°C, and VT) treatment had



L*: lightness; a*: redness; b*: yellowness. Sensors used in electronic nose and the corresponding performance are described below: S_1: ammonia and amines; S_2: sulfur compounds, H_2S; S_3: hydrogen; S_4: ethanol and organic solvent; S_5: alcohols, ketones, aldehydes, and aromatic compounds; S_6: methane and natural gas; S_7: flammable gas; S_8: volatile organic compounds in the environment; S_9: liquefied gas and natural gas; S_{10}: hydrocarbons; S_{11}: hydrocarbons, ethanol, natural gas, and smoke; S_{12}: ethanol and organic solvent; S_{13}: smoke; S_{14}: methane. The minimal detectable concentration is 10 ppt.

Figure 4. Effect of drying temperatures on the color and flavor of GBR. (A) Color changes. (B) PCA analysis of flavor composition. (C) Radar chart of volatile compounds. VT: variable temperature (50°C/60 min+70°C/130 min).

different effects on the flavor of GBR. But there was no significant difference between GBR in the VT drying group and that in the drying group at 70°C.

Furthermore, the maximum response signal of each sensor as a radial vector was exhibited in a radar map (Figure 4C). Overall, the radar chart of GBR in the 70°C and VT drying groups was almost overlapped, indicating the presence of similar volatile compounds in the two samples. The contents of alcohols, ketones, aldehydes, aromatic compounds, and hydrocarbons (reflected by the following sensors: S_4, S_5, S_6, S_{11}, S_{12}, and S_{14}) in the VT group were closer to those found in the lower temperature groups (50 and 70°C). The contents of ammonia, sulfur compounds, hydrocarbons, and ethanol (as measured by sensors S_1, S_2, S_9, and S_{12}) decreased as drying temperatures increased.

Some volatile compounds were lost as a result of heating, but it also aided in the formation of volatile compounds via the Maillard and caramelization reactions (Sacchetti *et al*., 2016).

4 CONCLUSION

This study investigated the effects of different drying temperatures on the fissure rate, contents of total flavonoid contents and amino acids (including GABA), *in vitro* antioxidant capacities, and physical properties such as texture, color, and flavor of GBR. In comparison to constant temperature drying, VT drying could effectively reduce the percentage of fissured grains while maintaining GBR quality. A suitable VT drying process is a straightforward and simple processing technology that can significantly improve the nutritional and edible quality of GBR. This study provided reference data for the GBR VT drying process.

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