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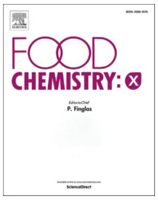

Effects of steam explosion-modified rice bran dietary fiber on volatile flavor compounds retention and release of red date-flavored naan (ethnic specialty food of Xinjiang) during storage

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ABSTRACT

This study explored the effects of steam explosion-modified rice bran dietary fiber (S-RBDF) on red date-flavored naan quality and flavor characteristics. The results revealed that the rheological properties of the dough were improved with the incremental addition of S-RBDF (0–5%). The microstructure revealed that adding an appropriate amount of S-RBDF (1–5%) enabled more starch granules to be embedded in the dough network. Notably, the addition of 5% S-RBDF resulted in naan with an optimum specific volume and texture, which consumers preferred. Additionally, gas chromatography–mass spectrometry analysis showed that adding S-RBDF to naan contributed to the retention and sustained release of pleasant volatile compounds (e.g. red date flavor, etc.), while inhibiting the development of unpleasant volatile compounds by delaying the oxidation and decomposition of lipids and preserving the antioxidant phenolic compounds, thus contributing to flavor maintenance of naan during storage. Overall, these results provided a foundation for developing high-quality flavored naan.

1. Introduction

Naan, a type of food with unique regional characteristics in Xinjiang Province, China, has a history of 2000 years (Zhao, Sun, Zhu, Zhang, & Feng, 2019). Traditional naan is baked in special nang pits using wheat flour as the main ingredient. Xinjiang, which is located in the middle of the Eurasian continent, has a dry climate and receives scarce precipitation, resulting in the formation of a vast desert area. Nang, as a food that is convenient to carry, has low water content, and can be stored easily, is well suited to these local climatic conditions. Thus, it has become an indispensable staple food for people living in Xinjiang (Huang et al., 2020). Recently, with the improvement of living standards and changes in consumption concepts, the flavor of naan has become a significant factor influencing consumer choices (Lal, Singh, Sharma, Singh, & Kumar, 2021).

Exogenous flavoring agents have been widely added to food matrices to impart specific odors to foods (Li, Gao, Guo, Wang, & Yang, 2022). Because most flavors are low-molecular-mass volatile compounds, direct handling and control during processing and storage are difficult due to susceptibility to volatilization and degradation (Premjit et al., 2022). In the baking industry, encapsulation techniques have been used to address these challenges. Fadel, Hassan, Ibraheim, Mageed, and Saad (2019) assessed the impact of using cinnamon essential oil (EO) encapsulated in maltodextrin (CO-MD) as an exogenous flavor on the flavor quality and

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stability of biscuits. Kavitake, Kalahasti, Devi, Ravi, and Shetty (2020) encapsulated vanilla and cardamom in galactan-flavored emulsions for muffin products. These studies have found that although encapsulation techniques can bind flavor compounds well, specific stimulating triggers are required to release the bound flavor compounds. Meanwhile, by the time the switch turns on, the release of these compounds may become uncontrollable and more prone to violent release (English, Okagu, Stephens, Goertzen, & Udenigwe, 2023). Additionally, these encapsulation techniques face other problems, such as a complex preparation process and high cost. These characteristics limit its large-scale application in flavored naan products.

The adsorption technique is an emerging method that could increase shelf-life of flavor substances and protect them from environmental damage (Duppeti, Manjabhatta, & Kempaiah, 2023; Xu et al., 2022). The advantages of the adsorption method include simple operation, high efficiency, and low cost. Increasing studies demonstrate that dietary fiber (DF) has high adsorption capacities for cholesterol, bile acid, glucose, and polycyclic aromatic hydrocarbons (Zheng et al., 2021). However, the application of DF as a flavor adsorbent in baked goods such as naan has not been reported. Rice bran (RB), a by-product of rice milling, is an excellent source of DF. Most extracted rice bran dietary fiber (RBDF) is insoluble, because it consists of cellulose, hemicellulose, and lignin of which only an extremely small proportion is soluble (Liu, Zhang, Yi, Quan, & Lin, 2021).

Our team previously conducted a study on rice bran insoluble dietary fiber (RBIDF) as a host material for flavor compounds and achieved preliminary results (Liu et al., 2023). That is, steam explosion modified-rice bran insoluble dietary fiber (S-RBIDF) had a loosened and unfolded inner structure, which exposed a large number of active binding sites. These binding sites exhibited good adsorption and sustained release ability for red date flavor compounds. In view of this discovery, it was hypothesized that the use of steam explosion-modified rice bran dietary fiber (S-RBDF) as a flavor adsorbent could help maintain the pleasant flavor characteristics of red date-flavored naan during storage. Notably, as a “foreign matter” distinct from the refined wheat flour system, DF would have a strong effect on the dough, such as hindering glutenin aggregation, and disrupting the stability of the gluten network (Li et al., 2023). Therefore, it is important to reasonably control the amount of S-RBDF added to minimize its negative effects on the gluten network structure. This process serves as a crucial foundation for developing high-quality flavored naan products. The aim of this study was to investigate the effects of adding S-RBDF on red date-flavored naan quality and flavor. By analyzing the dough rheology, microstructure, nutrient composition, specific volume, and texture properties of naan, the optimal amount of S-RBDF was determined. Then, GC–MS was used to determine changes in volatile flavor compounds for red date-flavored naan with the addition of S-RBDF during storage and compared it with control samples. These results provided the foundation for high-quality flavored naan.

2. Materials and methods

2.1. Materials

Beijing Huajie Qitai Co., Ltd. (Beijing, China) supplied the RB. S-RBDF was prepared in a laboratory according to the method of Liu et al. (2023). Red date flavor was purchased from Bairui Flavors and Fragrances Co., Ltd. (Hangzhou, China). According to the composition list of red date flavor provided by the merchant, 15 authentic chemical standards were purchased from Shanghai Meixing Chemical Technology Co., Ltd. These authentic standards include citronellol (≥ 99%), benzyl alcohol (≥ 99%), benzaldehyde (≥ 99%), trans-cinnamaldehyde (≥ 99%), citronellate acetate (≥ 99%), isoamyl isovalerate (≥ 99%), methyl maltol (≥ 99%), ethyl maltol (≥ 99%), engenol (≥ 99%), etc. Internal standard (IS) (4-methyl-2-pentanol) and C_7-C_{30} n-alkane authentic standard were purchased from Sigma-Aldrich Chemical Co., Ltd. (Shanghai, China).

2.2. Dough and red date-flavored naan preparation

The dough formulation consisted of 500 g wheat flour, 35 g corn oil, 4 g salt, 2.5 g yeast, 2 g red date flavor, 250 g tap water, and different concentrations of S-RBDF (1, 3%, 5%, 7% and 9% on wheat flour weight basis, *w*/w). The dough formulated with 0% S-RBDF was used as the control. The dough was proofed for 1 h. Afterwards, one batch of dough was used for analysis and another batch was utilized to make red date-flavored naan. The dough was shaped into a medium-thin round naan with a thick edge and adorned with special patterns. Baking was carried out in an oven for 20 min. Then, the naan was cooled to room temperature in order to take measurements.

2.3. Dynamic rheological analysis of the dough

The dynamic rheological property of the dough was measured using a KNX2110 rheometer (Malvern Instrument, Malvern, UK) according to the method of Zhang et al. (2022). The frequency was swept from 0.1 to 10 Hz with a strain value of 0.1%, and the elastic modulus (G′) and viscous modulus (G″) were analyzed.

2.4. Microstructure analysis of the dough

The microstructure of the dough (2000× magnification) was observed using a cryo-scanning electron microscope (cryo-SEM) (JSM6301F, JEOL, Tokyo, Japan) equipped with a cryotransport device.

2.5. Nutrient composition and energy value analysis of red date-flavored naan

The total dietary fiber (TDF), moisture, protein, ash, and fat content of naan was determined according to the method of AOAC (2012). The calculation of available carbohydrate content was based on the weight difference (without TDF content). The energy value was determined according to the method of FAO Food and Nutrition (2003).

2.6. Specific volume analysis of red date-flavored naan

The specific volume of naan was calculated according to the method of AACC (2010).

2.7. Texture profile analysis of red date-flavored naan

The textural characteristics of naan were analyzed by employing a texture analyzer (TA.XT. Plus, Stable Micro Systems Ltd., Surrey, UK). The naan was cut into 15-mm-thick uniform pieces, and the two central pieces were then compressed to 40% of their initial height at a rate of 1.7 mm/s. Hardness (g), chewiness, springiness and cohesiveness were subsequently evaluated.

2.8. Volatile flavor compound analysis of red date-flavored naan

The naan samples were stored at 4 °C for 0, 7, 14, 21, and 28 days. Subsequently, their volatile flavor compounds were determined using HS–SPME/GC–MS (TSQ 9000, Thermo Fisher Scientific, Waltham, MA, USA) according to the method of Liu et al. (2023) and Zhao et al. (2021). Add 5 g of samples to a headspace vial, along with 10 μL of IS. The SPME fiber (DVB/CAR/PDMS, 50/30 μm) was exposed to the headspace of the vial for 30 min and then desorbed. The volatile compounds were separated using an HP-INNOWax capillary column (60 m × 0.25 mm × 0.5 μm). Supplementary Table S1 shows additional instrument measurement parameters. The volatile flavor compounds were identified by comparing their mass spectra (MS) and the retention times with those of standard compounds. The volatile flavor compounds without authentic standards were preliminarily identified by searching NIST 14 mass spectroscopic library. Match fractions <80% were used as the cutoff values, and the retention index (RI) was calculated according to the Kovats' method based on retention time of C_7-C_{30} standard alkanes. The key volatile flavor compounds detected in naan were quantified using the external standard method. Calibration curves for the 15 volatile flavor compounds were established using the external standard method, and subsequently, this method was verified. The linearity of compounds was determined by evaluating the regression curve. The limits of detection (LODs) and limits of quantification (LOQs) of the method were determined by 3 times and 10 times signal-to-noise ratio (SNR), respectively. Precision was measured using relative standard deviations (RSDs). The relevant methodological parameters are given in Supplementary Table S2. These curves displayed good linearity over the selected concentration range with linear regression correlation coefficients better than 0.99. The ranges of LODs and LOQs were 0.117–1.14 μg/kg and 0.39–3.8 μg/kg, respectively, with RSDs ranging from 1.47% to 7.43%. All parameters meet the requirements of quantitative analysis. The other volatile flavor compounds were semi-quantitated based on the peak area relative to the area of the IS.

2.9. Statistical analysis

All experiments were repeated three times. Results were expressed as mean ± standard deviation. The statistical analysis and one-way analysis of ANOVA followed by the Duncan's test were performed using the SPSS 23.0 software. Differences were regarded as significant at $p < 0.05$.

3. Results and discussion

3.1. Effects of adding S-RBDF on the dynamic rheological properties of the dough

As shown in Fig. 1, the storage modulus (G') of all the dough samples was always higher than the loss modulus (G") in the whole frequency range, which indicated that the dough had the characteristics of gel or solid (Huang et al., 2020). Compared with the control, adding 1%, 3%, and 5% S-RBDF to the dough increased both G′ and G″. Notably, dough that had 5% S-RBDF had the highest G′ and G″, which showed a stronger gluten network with better viscoelasticity. These results were attributed to S-RBDF containing soluble dietary fiber (SDF), which formed crosslinks between the starch chains (Prasadi & Joye, 2023). The crosslinked starch structure interacted with gluten by forming a network structure that was more compact, which contributed to enhanced viscoelasticity and a stronger gluten network. Meanwhile, this also meant that adding S-RBDF could modulate the capacity of protein and starch to absorb water, and selecting appropriate amount affected dough internal molecules expansion and interaction, and further affects a stable three-dimensional network structure formation. However, when the addition of S-RBDF exceeded 5%, the G′ and G″ of the dough decreased significantly. This showed that excessive S-RBDF negatively affected the three-dimensional gluten network. The results could be attributed to the excessive S-RBDF, which competed with the starch and protein in the dough for water, thereby reducing water availability to gluten and affecting the viscoelasticity of dough (Hu et al., 2022). In addition, excessive S-RBDF not only diluted gluten proteins but also hindered gluten development by creating steric hindrance (Li et al., 2023). Hence, these results indicated that S-RBDF could make a dough with better viscoelasticity and stronger gluten network structure by adding appropriate amount.

3.2. Effects of adding S-RBDF on the microstructure of dough

As shown in Fig. 2, the gluten network of the control group was distributed uniformly; however, the structure appeared relatively loose with poor continuity and some starch was exposed on its surface (Zhang et al., 2022). In comparison, by adding 1%, 3%, and 5% S-RBDF, the continuity of the gluten network structure was significantly improved, and the starch granules were distributed evenly within the matrix. In particular, the dough with 5% S-RBDF formed the most uniform and continuous network structure, in which the starch granules were wrapped tightly within the membrane-like gluten matrix. These results were attributed to S-RBDF containing SDF, which could interact with the gluten through the hydrogen bonds and provide a filler for the network structure, which enhanced the gluten structure (Zhu, Tao, Wang, and Xu, 2023). If, however, the addition of S-RBDF was increased to a level >5%, it caused cracks to form as well as discontinuous structures to appear in the gluten network and exposed a certain number of starch particles. Meanwhile, the graphs of the dough with 9% S-RBDF exhibited some pits. The dilutive effect of excessive S-RBDF on dough caused these differences, which resulted in the collapse of the protein network's structure or starch branched networks (Liu et al., 2023). Furthermore, the competition for free water between excessive S-RBDF and gluten protein to bind to when the dough was being mixed limited the formation of a gluten network structure. Thus, these results indicated that S-RBDF contributed to forming a more uniform and compact gluten

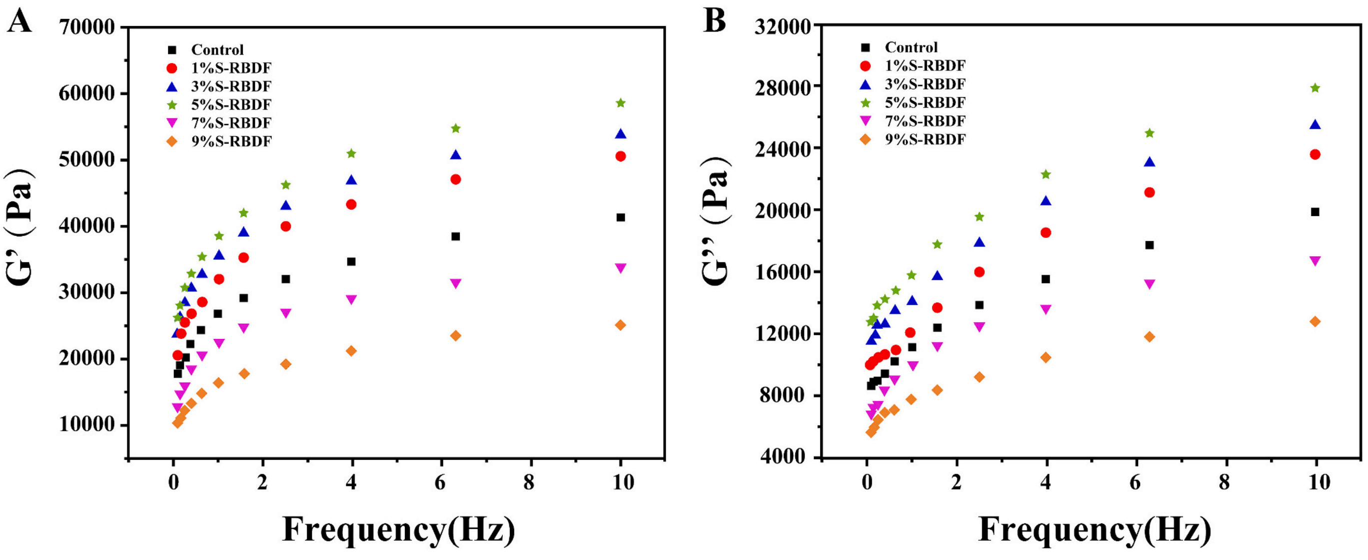

Fig. 1. Effects of different levels of S-RBDF on the (A) G′ and (B) G″ of dough.

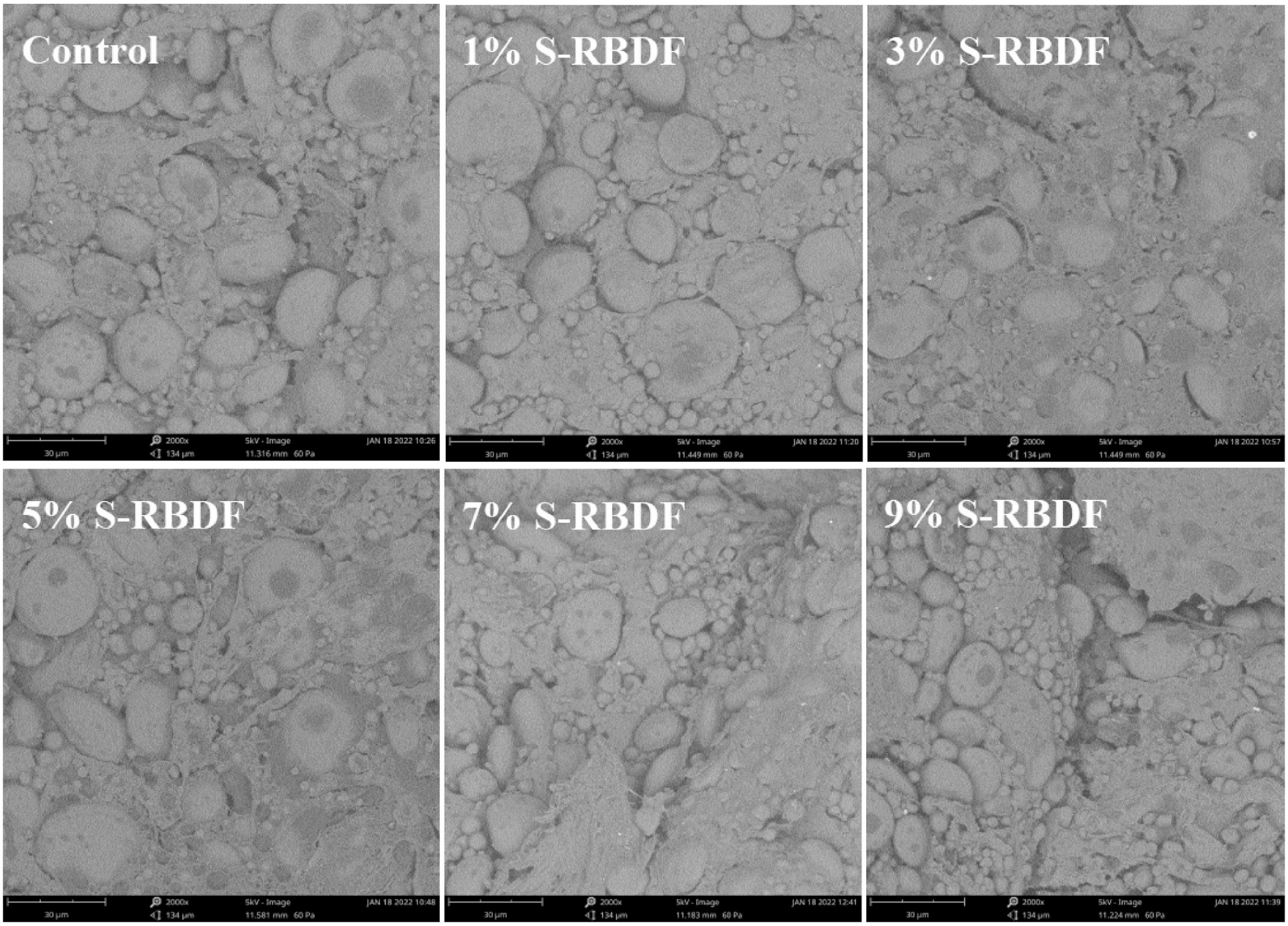

Fig. 2. Effects of different levels of S-RBDF on the microstructure of dough (2000 ×).

network by adding appropriate amount.

3.3. *Effects of adding S-RBDF on the nutritional composition of red date-flavored naan*

As shown in Table 1, as the levels of S-RBDF increased, the moisture content increased in the red date-flavored naan. This increase was caused mainly by the greater number of hydroxyl groups present in the fiber structure of S-RBDF, which allowed for the interaction of more water through hydrogen bonding. A slight increase in ash content was observed with increased S-RBDF levels. Furthermore, as the levels of S-RBDF increased, fat and protein content decreased because the initial fat and protein content between S-RBDF and wheat flour were different. Wang et al. (2023) reported that reducing the fat content could inhibit the oxidative rancidity of baked products during long-term storage, thus extending its shelf-life. Unlike fat and protein, as the levels of S-RBDF increased, the TDF content also increased. The European Regulation for Nutrition and Health Claims on Foods has specified that to be a "source of dietary fiber," a product must have 3 g or more of DF per 100 g (Council of European Union, 2007). Therefore, naan with the addition of 3% to 9% S-RBDF could be labeled as a "source of dietary fiber." More importantly, because of the dilution effect induced by S-RBDF, adding S-RBDF to naan caused the available carbohydrates to be significantly lower than that in the control ($p < 0.05$), which ultimately led to a reduction in energy values.

3.4. *Effects of adding S-RBDF on the specific volume and texture profile of red date-flavored naan*

Among the various physical attributes of naan, specific volume and

Table 1
Effects of different levels of S-RBDF on the nutritional composition of red date-flavored naan.

Parameters	Control	1% S-RBDF	3% S-RBDF	5% S-RBDF	7% S-RBDF	9% S-RBDF
Moisture (%)	30.12 ± 0.16^{a}	30.48 ± 0.37^{a}	30.95 ± 0.07^{a}	31.98 ± 0.46^{b}	32.11 ± 0.25^{b}	33.30 ± 0.12^{c}
Protein (%)	14.22 ± 0.46^{a}	14.04 ± 0.15^{a}	13.51 ± 0.28^{ab}	12.84 ± 0.35^{b}	11.71 ± 0.21^{c}	10.69 ± 0.11^{d}
Fat (%)	7.54 ± 0.05^{a}	7.31 ± 0.11^{ab}	7.09 ± 0.12^{ab}	6.88 ± 0.02^{abc}	6.45 ± 0.05^{bc}	6.02 ± 0.14^{c}
TDF (%)	1.32 ± 0.03^{a}	2.69 ± 0.01^{b}	2.99 ± 0.07^{b}	3.24 ± 0.06^{b}	4.75 ± 0.09^{c}	5.57 ± 0.14^{d}
Ash (%)	0.61 ± 0.01^{a}	0.63 ± 0.03^{a}	0.68 ± 0.05^{a}	0.79 ± 0.02^{b}	0.90 ± 0.22^{c}	0.96 ± 0.09^{c}
Available carbohydrate (%)	46.19 ± 0.34^{a}	44.85 ± 0.11^{b}	44.78 ± 0.26^{b}	44.27 ± 0.25^{bc}	44.08 ± 0.32^{bc}	43.46 ± 0.23^{c}
Energy value (kJ/100 g)	1316.51 ± 5.54^{a}	1293.12 ± 6.26^{b}	1277.18 ± 4.13^{b}	1251.35 ± 4.98^{c}	1225.08 ± 5.21^{d}	1187.85 ± 4.23^{e}

Data are the mean ± standard deviation of three independent experiments ($n = 3$). Different superscript letters denote that the mean values within a row are significantly different ($p < 0.05$ according to a Duncan's test).

texture properties were considered as indicators for consumer acceptance. As shown in Table 2, the specific volume of naan was closely associated with the amount of S-RBDF added. The specific volume of naan first increased from 2.35 mL/g (the control group) to 2.41 (naan with 1%, S-RBDF), 2.52 (3% S-RBDF), and 2.65 mL/g (5% S-RBDF). This phenomenon can be attributed to the reinforcement of the gluten network structure of nang through the addition of aan ppropriate amount of S-RBDF (Xu, Li, Zhao, Wang, & Wang, 2021). As discussed in Sections 3.1 and 3.2, the rheological properties and microstructure of the dough previously confirmed this finding, which ultimately resulted in higher specific volume. The specific volume, however, was negatively affected by the excessive addition of S-RBDF (>5%). These results could be attributed to the chemical and mechanical effects of excessive S-RBDF on the gluten network structure (Sun, Ma, Zhong, & Liang, 2022). Physical damage occurred when the dough expanded, and excessive DF caused the foam structure of the dough to be stripped, resulting in thinner cell walls that easily broke. This weakened the gluten matrix and reduced the volume of naan. In addition, excessive DF diluted the gluten, which limited the interactions among water, fat, DF, and the gluten network. These changes caused the gluten polymer network position to collapse, reduced carbon dioxide (CO_2) gas retention, and decreased the specific volume of naan (Zhou et al., 2021).

Previous studies have shown a significant impact of specific volume on the hardness of naan, indicating that these factors are negatively correlated (Gu et al., 2022). In other words, a smaller specific volume leads to a denser and firmer naan. The lowest hardness of nang was observed when 5% S-RBDF was added, which may be attributed to its high specific volume. The "chewiness," defined as the level of difficulty in masticating food before swallowing, parameters presented a similar change with the hardness values—that is, a relatively lower S-RBDF (1%, 3%, and 5%) markedly decreased the naan chewiness, whereas a higher S-RBDF (7% and 9%) obviously increased the chewiness. Springiness reflects the elasticity of naan, and cohesiveness reflects the resistance of its internal structure. As the addition of S-RBDF increased from 0% to 5%, the springiness and cohesiveness of naan gradually improved, which was attributed to the proper formation of the gluten network and an increase in specific volume (Davy, Kirkman, Scarlett, & Vuong, 2022). Furthermore, the S-RBDF demonstrated excellent water retention, which enhanced starch gelatinization during baking. This improved the springiness and cohesiveness of dough by strengthening the interaction between gluten proteins and gelatinized starch, ultimately affecting their mechanical properties (Kiumarsi et al., 2019). When adding 7–9% S-RBDF, however, the springiness and cohesiveness of the naan significantly decreased ($p < 0.05$), which may have been caused by the diluted gluten content (Li et al., 2023). As mentioned earlier, when excessive S-RBDF was added to naan, the intermolecular interaction between gluten proteins for network formation was disrupted, resulting in reduced elasticity and fragile naan. To sum up, the addition of 5% S-RBDF resulted in naan with an optimum specific volume and texture, which consumers preferred.

3.5. *Changes in the volatile flavor compounds of red date-flavored naan during storage*

The change in flavor of red date-flavored naan during storage is a key indicator for evaluating its quality and for determining consumer acceptance. 56 volatile flavor compounds were identified in all red date-flavored naan samples. According to the flavor source of red date-flavored naan, all volatile flavor compounds were divided into two groups. One group consisted of exogenous flavor compounds derived from red date flavor (Table 3), while the other group consisted of endogenous flavor compounds derived from naan matrix (Supplementary Table S3). In the control naan and the naan with 5% S-RBDF, 12 and 15 red date flavor compounds were detected, respectively (Table 3). As the storage period increased, the concentrations of all red date flavor compounds decreased in both the control naan and the naan with 5% S-RBDF as a result of the volatilization effect. However, the concentrations of red date flavor compounds in the naan with 5% S-RBDF was significantly higher than that in the control naan during storage ($p < 0.05$). The highest concentration among the identified alcohols was found in benzyl alcohol, which contributed to the sweet and roasted odor characteristics. The concentration of benzyl alcohol significantly decreased from 21.30 μg/kg to 9.31 μg/kg in the control naan after 28 days ($p < 0.05$), whereas in the naan with 5% S-RBDF, this value significantly decreased from 29.55 μg/kg to 15.47 μg/kg ($p < 0.05$). The highest concentration among the identified aldehydes was found in trans-cinnamaldehyde, which contributed to the cinnamon and fruity odor characteristics. The concentration of trans-cinnamaldehyde significantly decreased from 10.59 μg/kg to 1.47 μg/kg in the control naan after 28 days ($p < 0.05$), and in the naan with 5% S-RBDF, this value also decreased significantly from 18.46 μg/kg to 6.24 μg/kg ($p < 0.05$). The highest concentration among the identified phenols was found in ethyl maltol, which contributed to the caramel odor characteristics. The concentration of ethyl maltol significantly decreased from 35.50 μg/kg to 6.33 μg/kg after 28 days ($p < 0.05$), whereas in the naan with 5% S-RBDF, this value also significantly decreased from 93.08 μg/kg to 36.81 μg/kg ($p < 0.05$). The highest concentration was found among the identified ketones and esters in methylcyclopentanol ketone and dimethyl phthalate, which contributed to the sweet caramel, fruity, and wine-like odor characteristics. Furthermore, after 28 days of storage, the concentrations of these two compounds were significantly higher in the naan with 5% S-RBDF than in the control naan ($p < 0.05$). These findings suggested that adding S-RBDF to naan could contribute to the retention and sustained release of red date flavor compounds. This result was mainly attributed to the fact that S-RBDF has an unfolded structure and a large specific surface area, exposing more internal active binding sites, which contribute to the adsorption of flavor compounds and inhibits their diffusion in the interlayer space (Liu et al., 2023). Fig. 3A shows a heatmap of 15 red date flavor compounds in both the control naan and the naan with 5% S-RBDF at different storage times. The analysis indicated that the concentrations of red date flavor compounds decreased gradually in both the control naan and the naan with 5% S-RBDF during storage. All naan samples were clustered into four groups: (1) 5% SR-N-0 d; (2) 5% SR-N-7 d and 5% SR-N-14 d; (3) control-N-21 d and control-N-28 d; and (4) control-N-0 d, control-N-7 d, control-N-14 d, 5% SR-N-

Table 2
Effects of different levels of S-RBDF on the specific volume and texture profile of red date-flavored naan.

Parameters	Control	1% S-RBDF	3% S-RBDF	5% S-RBDF	7% S-RBDF	9% S-RBDF
Specific volume (mL/g)	2.35 ± 0.04^{a}	2.41 ± 0.03^{a}	2.52 ± 0.01^{b}	2.65 ± 0.11^{c}	2.22 ± 0.01^{d}	2.09 ± 0.05^{e}
Hardness (g)	1781.20 ± 51.28^{a}	1602.68 ± 47.84^{b}	1431.78 ± 63.84^{c}	1223.41 ± 55.15^{d}	1827.70 ± 29.20^{a}	1997.26 ± 45.36^{e}
Chewiness	555.96 ± 20.02^{a}	484.73 ± 44.23^{b}	409.76 ± 26.47^{c}	385.35 ± 18.69^{c}	579.64 ± 41.38^{a}	687.10 ± 46.06^{d}
Springiness	0.86 ± 0.04^{a}	0.88 ± 0.03^{a}	0.95 ± 0.04^{b}	1.01 ± 0.01^{c}	0.80 ± 0.01^{d}	0.73 ± 0.02^{e}
Cohesiveness	0.59 ± 0.02^{a}	0.61 ± 0.01^{ab}	0.63 ± 0.01^{b}	0.68 ± 0.01^{c}	0.54 ± 0.01^{d}	0.52 ± 0.01^{d}

Data are the mean ± standard deviation of three independent experiments (n = 3). Different superscript letters indicate significant difference among mean values within a row ($p < 0.05$ according to Duncan's test).

Table 3
The exogenous flavor compounds (derived from red date flavor) in the naan with 5% S-RBDF during storage compared with the control naan.

No.	Volatile compound	Odor description	Identification methods	Concentration (ug/kg)									
				Control					Naan with 5% S-RBDF				
				0 day	7 days	14 days	21 days	28 days	0 day	7 days	14 days	21 days	28 days
	Alcohols												
1	Citronellol	Rose, sweet, green	Std, MS, RI	1.03 ± 0.02^{a}	0.86 ± 0.01^{b}	0.51 ± 0.02^{c}	$0.37 \pm 0.01^{c,d}$	0.29 ± 0.01^{d}	1.90 ± 0.02^{e}	1.34 ± 0.01^{f}	1.07 ± 0.01^{a}	0.82 ± 0.02^{b}	0.70 ± 0.04^{b}
2	Benzyl alcohol	Sweet, roasted	Std, MS, RI	21.30 ± 0.04^{a}	18.21 ± 0.04^{b}	15.53 ± 0.11^{c}	12.46 ± 0.21^{d}	9.31 ± 0.02^{e}	29.55 ± 0.18^{f}	23.68 ± 0.05^{g}	20.84 ± 0.01^{a}	17.95 ± 0.33^{b}	15.47 ± 0.06^{c}
	Aldehydes												
3	Benzaldehyde	Almond	Std, MS, RI	2.80 ± 0.02^{a}	2.27 ± 0.06^{b}	1.86 ± 0.01^{c}	1.50 ± 0.04^{d}	1.16 ± 0.08^{e}	3.77 ± 0.02^{f}	3.23 ± 0.01^{g}	2.79 ± 0.02^{a}	2.42 ± 0.04^{b}	2.40 ± 0.02^{b}
4	Trans-cinnamaldehyde	Cinnamon, fruity	Std, MS, RI	10.59 ± 0.09^{a}	8.38 ± 0.01^{b}	6.05 ± 0.01^{c}	3.38 ± 0.02^{d}	1.47 ± 0.10^{e}	18.46 ± 0.01^{f}	13.11 ± 0.02^{g}	10.26 ± 0.14^{a}	8.74 ± 0.09^{b}	6.24 ± 0.03^{c}
	Ketones												
5	β-damarone	Honey, floral	Std, MS, RI	1.26 ± 0.06^{a}	0.95 ± 0.03^{b}	0.67 ± 0.01^{c}	0.40 ± 0.07^{d}	0.37 ± 0.01^{d}	2.86 ± 0.06^{e}	2.38 ± 0.07^{f}	2.10 ± 0.24^{g}	1.54 ± 0.01^{h}	1.22 ± 0.20^{a}
6	Methylcyclopentanol ketone	Maple, sweet caramel	Std, MS, RI	8.93 ± 0.01^{a}	7.05 ± 0.01^{b}	5.28 ± 0.18^{c}	3.60 ± 0.05^{d}	2.71 ± 0.10^{e}	21.00 ± 0.51^{f}	18.20 ± 0.09^{g}	14.77 ± 0.03^{h}	11.35 ± 0.81^{i}	8.70 ± 0.18^{a}
7	β-lonone	Floral, violet, fruity	Std, MS, RI	1.16 ± 0.28^{a}	0.79 ± 0.01^{b}	0.67 ± 0.04^{b}	0.36 ± 0.02^{c}	0.15 ± 0.04^{d}	2.37 ± 0.26^{e}	2.12 ± 0.03^{f}	1.58 ± 0.14^{g}	1.10 ± 0.03^{a}	0.69 ± 0.05^{b}
	Esters												
8	Benzyl butyrate	Jasmine	Std, MS, RI	1.35 ± 0.01^{a}	1.09 ± 0.02^{b}	0.81 ± 0.01^{c}	0.61 ± 0.03^{d}	0.41 ± 0.03^{e}	2.20 ± 0.02^{f}	1.86 ± 0.02^{g}	1.53 ± 0.10^{h}	1.32 ± 0.04^{a}	$1.26 \pm 0.02^{a,b}$
9	Dimethyl phthalate	Sweet, fruity, wine	Std, MS, RI	2.93 ± 0.02^{a}	2.34 ± 0.01^{b}	2.06 ± 0.01^{c}	1.60 ± 0.01^{d}	1.21 ± 0.02^{e}	3.87 ± 0.03^{f}	3.27 ± 0.44^{g}	3.02 ± 0.06^{a}	2.73 ± 0.30^{h}	2.49 ± 0.01^{b}
10	2-hydroxypropyl acetate	Honey, oil	Std, MS, RI	ND	ND	ND	ND	ND	4.42 ± 0.05^{a}	4.34 ± 0.05^{a}	3.60 ± 0.08^{b}	2.90 ± 0.04^{c}	2.76 ± 0.01^{c}
11	Citronellate acetate	Herbal	Std, MS, RI	ND	ND	ND	ND	ND	1.77 ± 0.09^{a}	1.31 ± 0.03^{b}	1.02 ± 0.03^{c}	0.67 ± 0.01^{d}	0.34 ± 0.04^{e}
12	Isoamyl isovalerate	Apple, pineapple	Std, MS, RI	1.58 ± 0.01^{a}	1.13 ± 0.04^{b}	0.81 ± 0.01^{c}	0.53 ± 0.02^{d}	0.24 ± 0.07^{e}	2.30 ± 0.01^{f}	2.00 ± 0.01^{g}	1.84 ± 0.01^{h}	$1.75 \pm 0.02^{a,h}$	1.57 ± 0.06^{a}
	Phenols												
13	Methyl maltol	Sweet caramel	Std, MS, RI	1.22 ± 0.01^{a}	1.07 ± 0.05^{a}	0.83 ± 0.02^{b}	0.69 ± 0.01^{b}	0.40 ± 0.04^{c}	1.56 ± 0.01^{d}	1.31 ± 0.03^{a}	1.11 ± 0.02^{a}	0.85 ± 0.08^{b}	0.73 ± 0.07^{b}
14	Ethyl maltol	Caramel	Std, MS, RI	35.50 ± 0.94^{a}	24.01 ± 0.34^{b}	18.67 ± 0.09^{c}	12.20 ± 0.36^{d}	6.33 ± 0.11^{e}	93.08 ± 0.87^{f}	80.14 ± 0.28^{g}	67.84 ± 0.41^{h}	48.09 ± 0.07^{i}	36.81 ± 0.57^{a}
15	Engenol	Smoky, smoked meat	Std, MS, RI	ND	ND	ND	ND	ND	0.97 ± 0.04^{a}	0.79 ± 0.01^{b}	0.60 ± 0.04^{c}	0.43 ± 0.07^{d}	0.26 ± 0.01^{e}

ND: indicates not detected.
Identification methods: RI: retention index; MS: mass spectra data; Std: confirmed by authentic standards. Odor descriptions were obtained from the literature (He et al., 2023; Liu et al., 2023). Values are mean ± standard deviation (n = 3). Values in the same row with different superscripts denote significant differences ($p < 0.05$).

21 d, and 5% SR-N-28 d. The heatmap colors of groups (1) and (2) were predominantly white and red, which indicated a high concentration of flavor compounds. The heatmap colors of groups (3) and (4) were predominantly blue, which indicated a low concentration of flavor compounds. Additionally, the naan with 5% S-RBDF on days 21 and 28 and the control naan on days 0, 7, and 14 were clustered together. These results also indicated that adding S-RBDF to naan contributed to the retention and sustained release of red date flavor compounds.

The endogenous nature of rice bran, microbial metabolism, the caramelization process under drying conditions, oxidation of lipids, and rearrangement of carbohydrates through the Maillard reaction all contributed to the presence of endogenous flavor compounds derived from naan matrix. As shown in Supplementary Table S3, 35 endogenous flavor compounds were detected in the control naan and 41 in the naan with 5% S-RBDF. The hydrocarbons, including straight-chain and cyclic alkanes, were recognized as endogenous to RB, which originated from the decarboxylation of long-chain fatty acids (Gao et al., 2021). However, most alkenes had a high flavor threshold and did not significantly affect the overall flavor profile. Alcohols resulted from ester decomposition and aldehyde reduction. As the storage period increased, the concentrations of alcohols decreased in both the control naan and the naan with 5% S-RBDF. After 28 days of storage, the concentrations of alcohols in the naan with 5% S-RBDF were significantly higher than those in the control naan ($p < 0.05$). There was a higher abundance in 1-hexanol, 3-methyl-1-butanol, and phenylethyl alcohol, which contributed to the malty, fruity, floral, and brandy odor characteristics (Qin et al., 2023). Esters typically formed as a result of the combination of low-grade saturated fatty acids and alcohols, and three esters were detected, namely, ethyl acetate, ethyl hexanoate, and ethyl propanoate. Among them, ethyl acetate had the highest concentration, which was a

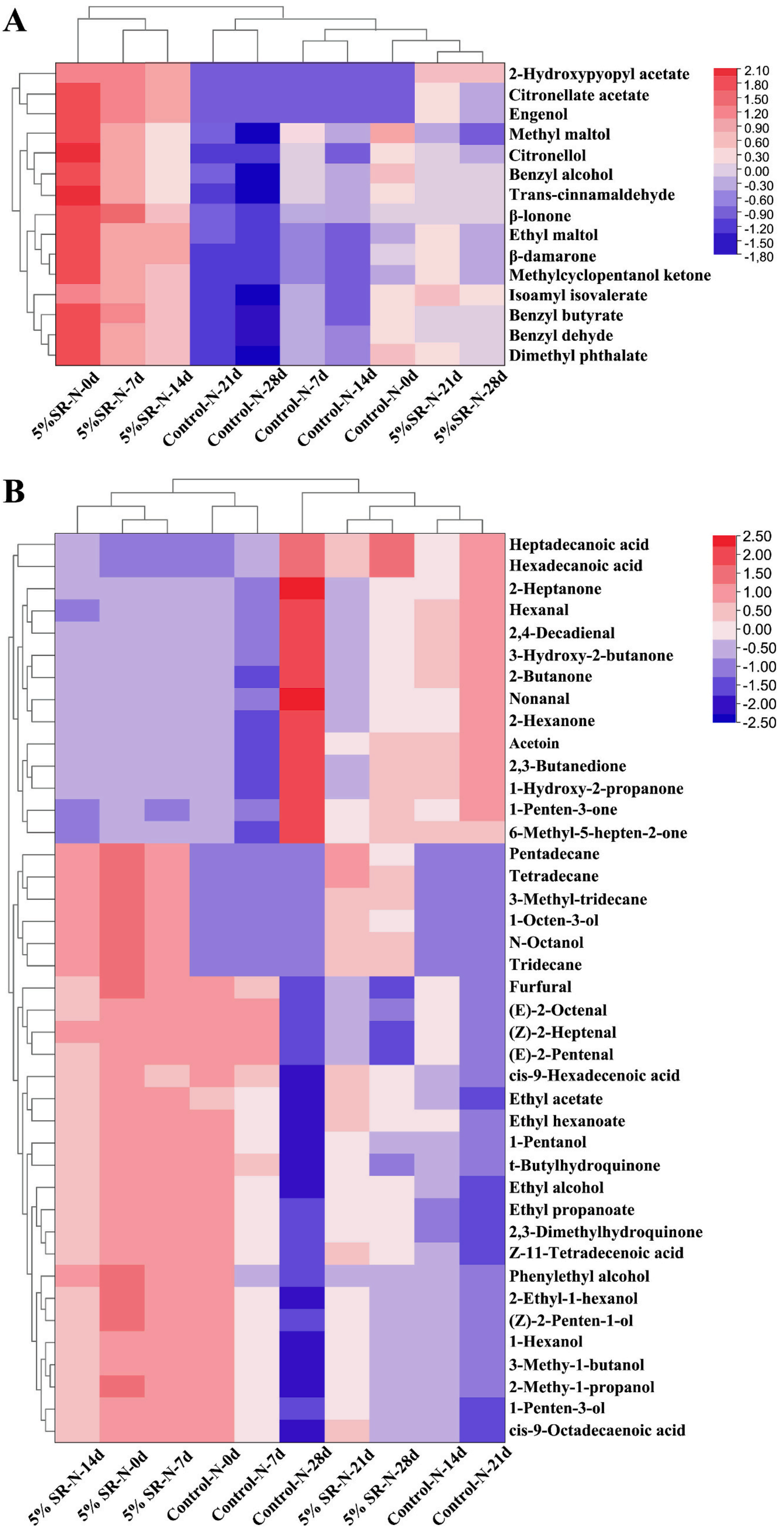

Fig. 3. Heatmap of (A) the exogenous flavor compounds (derived from red date flavor) and (B) the endogenous flavor compounds (derived from naan matrix) in the naan with 5% S-RBDF during storage compared with the control naan. Control-N-0 d, Control-N-7 d, Control-N-14 d, Control-N-21 d, and Control-N-28 d represent the control naan stored for 0, 7, 14, 21, and 28 days, respectively; 5% SR-N-0 d, 5% SR-N-7 d, 5% SR-N-14 d, 5% SR-N-21 d, and 5% SR-N-28 d represent the naan with 5% S-RBDF stored for 0, 7, 14, 21, and 28 days, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

typical volatile compound with a vinous and fruity odors. According to other studies, higher concentrations of ethanol and acetic acid were also accompanied by a higher concentration of ethyl acetate (Fang et al., 2023). Herein, a complete linear relationship was also observed among these compounds. As the storage period increased, the concentrations of esters decreased in both the control naan and the naan with 5% S-RBDF. Additionally, the concentrations of esters were higher in the naan with 5% S-RBDF than in the control naan after 28 days of storage. High levels of alcohols and esters were perceived positively in a sensory analysis of wheat-based baked foods (Liu, Gu, Shi, & Chen, 2024). These results indicated that the addition of S-RBDF was conducive to the retention and sustained release of alcohols and esters in stored naan, which contributed to its pleasant flavor. Aldehydes were produced primarily through the decomposition of lipids (Zhou, She, Zhu, & Zhou, 2022). Hexanal, nonanal, and 2,4-decadienal are oxidation products of linoleic acid, which are considered to be early markers of food oxidation (Jia et al., 2022). From days 0 to 7, the concentrations of hexanal, nonanal, and 2,4-decadienal in the control naan decreased as the storage period increased, and then increased significantly until the end of the storage period ($p < 0.05$). From days 0 to 14, the concentrations of hexanal, nonanal, and 2,4-decadienal in the naan with 5% S-RBDF decreased, but thereafter they showed a significant increase until the end of the storage period ($p < 0.05$). During the early storage stage, the significant decrease in the concentrations of hexanal, nonanal, and 2,4-decadienal could be attributed to their high volatility and unstable properties. As the storage time increased, however, the degree of lipid oxidization increased, resulting in higher levels of lipid oxidation products. Most important, the increased concentrations of hexanal, nonanal, and 2,4-decadienal in the naan with 5% S-RBDF were significantly lower than that in the control naan ($p < 0.05$) after 28 days of storage. Additionally, the concentrations of unsaturated aldehydes in both the control naan and the naan with 5% S-RBDF decreased, which could be attributed to their further autoxidation or decomposition (Zhang, Guan, Zhang, Dai, & Hao, 2018). These results indicated that the addition of S-RBDF inhibited the development of aldehydes caused by lipid oxidation in stored naan, thereby slowing down flavor deterioration. Ketones are believed to be formed through the oxidative degradation of fatty acids or Maillard reactions. The concentrations of ketones in the control naan decreased during the first 7 days of storage, but thereafter, they exhibited a significant increase from days 14 to 28. In the naan with 5% S-RBDF, however, the concentrations of ketones reached their lowest level after 14 days of storage and then increased from days 21 to 28. Jensen, Oestdal, Skibsted, Larsen, and Thybo (2011) also reported similar results that the ketones produced during baking in wheat and whole-wheat bread decreased during the first two weeks of storage. Between the second and third weeks of storage, the ketone concentration increased, because of lipid oxidation and further reactions with proteins and amino acids. Additionally, after 28 days of storage, the increased levels of ketones in the naan with 5% S-RBDF were significantly lower than that in the control naan ($p < 0.05$). These results indicated that the addition of S-RBDF to naan inhibited ketone development caused by lipid oxidation during the late storage period, which slowed down flavor deterioration. Acids also accounted for a large portion of the flavor compounds in stored naan. The concentrations of unsaturated fatty acids, such as *Z*-11-tetradecenoic acid and *cis*-9-octadecaenoic acid, exhibited a decline over the storage period in both the control naan and the naan with 5% S-RBDF. These unsaturated fatty acids can be cleaved to different aldehydes and ketones depending on the oxidized lipids (Liu et al., 2020). The concentrations of saturated fatty acids increased in both the control naan and the naan with 5% S-RBDF during storage. It has been reported that saturated fatty acids can be formed through the degradation of triglycerides (Novotni et al., 2018). Additionally, after 28 days of storage, the changes in unsaturated fatty acid concentrations of the naan with 5% S-RBDF were lower than those of the control naan. These results indicated that the addition of S-RBDF to naan reduced the degradation of unsaturated fatty acids to some extent during storage. The concentrations of 2,3-dimethylhydroquinone and *t*-butylhydroquinone decreased in both the control naan and the naan with 5% S-RBDF during storage. Significantly, these phenols compounds can be used as antioxidants for lipid peroxidation (Gu et al., 2021). After 28 days of storage, the concentrations of phenols in the naan with 5% S-RBDF were significantly higher than that in the control naan ($p < 0.05$). These results indicated that the addition of S-RBDF to naan was helpful for retaining antioxidant phenol compounds, which resulted in lower concentrations of lipid-oxidation-derived volatile compounds and thus slowed down the deterioration of stored naan flavor. Fig. 3B shows a heatmap of 41 endogenous flavor compounds in both the control naan and the naan with 5% S-RBDF at different storage time. All naan samples were clustered into four groups: (1) 5% SR-N-0 d, 5% SR-N-7 d and 5% SR-N-14 d; (2) control-N-0 d and control-N-7 d; (3) 5% SR-N-21 d, 5% SR-N-28 d, control-N-14 d, and control-N-21 d; and (4) control-N-28 d. The heatmap colors for alcohols, phenols, unsaturated fatty acids, esters, and hydrocarbons in groups (1) and (2) were mainly white and red, indicating a high concentration of flavor compounds. The heatmap colors for aldehydes and ketones in groups (1) and (2) were mainly blue, indicating a low concentration of flavor compounds. The heatmap colors for these volatile flavor compounds in groups (3) and (4), however, were opposite to those in groups (1) and (2). These results indicated that the addition of S-RBDF to naan contributed to the retention and sustained release of pleasant flavor compounds (e.g. alcohols, esters, phenols, etc.), while inhibiting the development of unpleasant flavor compounds by delaying the oxidation and decomposition of lipids and preserving the antioxidant phenolic compounds, thus contributing to flavor maintenance of naan during storage.

Supplementary Fig. S1 shows the differences in varieties and concentrations of volatile flavor compounds between the control naan and the naan with 5% S-RBDF during different storage periods. The exogenous flavor compounds derived from red date flavor are represented in Fig. S1A and S1B, while the endogenous flavor compounds derived from naan matrix are represented in Fig. S1C and S1D. The concentrations of red date flavor compounds were 0.7-fold and 1.8-fold higher in the control naan and the naan with 5% S-RBDF, respectively, compared to the endogenous flavor compounds of both types of naan samples during storage, which indicated that red date flavor compounds played a key role in all nang samples. As shown in Fig. S1A and S1B, the control naan contained 12 red date flavor compounds, whereas the naan with 5% S-RBDF contained 15 compounds, with total concentrations of 323.40 μg/kg and 616.82 μg/kg, respectively. Compared with the control naan, the varieties and concentrations of red date flavor compounds in the naan with 5% S-RBDF showed a significant increase during storage. Phenols and alcohols were the two main red date flavor compounds in both the control naan and the naan with 5% S-RBDF, which accounted for >46% and 20% of red date flavor compounds in the naan samples, respectively. Compared with the control naan, their concentrations in the naan with 5% S-RBDF increased by 2.3-fold and 0.4-fold, respectively. Aldehydes, ketones, and esters accounted for >10%, 13%, and 8% of red date flavor compounds in the naan samples, respectively. Compared with the control naan, their concentrations in the naan with 5% S-RBDF increased by 0.8-fold, 1.7-fold and 2.0-fold, respectively. Furthermore, the number of phenol and ester compounds in the naan with 5% S-RBDF was higher than those in the control naan during storage. Engenol, 2-hydroxypropyl acetate and citronellate acetate were only detected in the naan with 5% S-RBDF. These results indicated that adding S-RBDF to naan could contribute to the retention and sustained release of red date flavor compounds. As shown in Fig. S1C and S1D, the control naan contained 36 endogenous flavor compounds, while the naan with 5% S-RBDF contained 41 compounds, with total concentrations of 190.37 μg/kg and 220.07 μg/kg, respectively. Compared with the control naan, the concentrations and varieties of endogenous flavor compounds in the naan with 5% S-RBDF showed a significant increase during storage. Ketones, aldehydes, and alcohols were the three main endogenous flavor compounds in both the control naan and the naan with 5% S-RBDF, accounting for >27%, 26%, and 21% of endogenous flavor compounds in the naan samples, respectively. Additionally, acids, phenols, and esters accounted for >12%, 5%, and 4% of endogenous flavor compounds in the naan samples, respectively. Compared with the control naan, the concentrations of alcohols, esters, phenols, and acids in the naan with 5% S-RBDF increased by 0.7-fold, 0.5-fold, 0.3-fold and 0.1-fold, respectively. However, the concentrations of aldehydes and ketones in the naan with 5% S-RBDF decreased by 9.86% and 17.14%, respectively. Furthermore, N-octanol, 1-octen-3-ol, and hydrocarbon compounds (tridecane, tetradecane, pentadecane and 3-methyl-tridecane) were only detected in the naan with 5% S-RBDF. These results suggested that the addition of S-RBDF to naan contributed to the retention and sustained release of pleasant flavor compounds (e.g., red date flavor, esters, phenols, etc.), while inhibiting the development of unpleasant flavor compounds by delaying the oxidation and decomposition of lipids and retaining the antioxidant phenolic compounds, thus contributing to flavor maintenance.

4. Conclusion

The application of S-RBDF in red date-flavored naan production had an obvious influence on the quality and flavor characteristics. The addition of appropriate amount of S-RBDF was beneficial for improving the viscoelasticity of the dough. According to cryo-SEM analysis, the dough containing an appropriate amount of S-RBDF exhibited better continuity, with a more compact gluten network structure. Notably, with the addition of 5% S-RBDF, the baked naan had the highest specific volume, lowest hardness, and a texture that was both uniform and soft, which consumers preferred. The analysis of GC–MS indicated that the addition of S-RBDF exhibited a beneficial impact on the flavor of naan. The addition of S-RBDF to naan contributed to the retention and sustained release of pleasant volatile flavor compounds (e.g., red date flavor, etc.), while inhibiting the development of unpleasant volatile compounds by delaying the oxidation and decomposition of lipids and preserving the antioxidant phenolic compounds, thus contributing to flavor maintenance during storage. This study provided a new reference scheme for the industrial-scale processing of high-quality flavored naan.

Ethical guidelines

Ethics approval was not required for this research.

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CRediT authorship contribution statement

Nan Wang: Writing – review & editing, Formal analysis, Data curation. **Dilinuer Ainiwan:** Methodology, Data curation. **Yingxu Liu:** Investigation, Formal analysis. **Jialu He:** Validation, Software. **Tingting Liu:** Resources, Project administration.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101438.

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