



Research article

Utilization of alternative resistant starch-rich flours in sourdough bread development

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Abstract

Importance of the work: Sourdough bread provides a suitable matrix for incorporating functional ingredients such as resistant starch (RS), which can enhance the nutritional profile of bakery products.

Objectives: To develop consumer-acceptable sourdough bread enriched with RS-rich flours and to evaluate its physicochemical and sensory properties.

Materials and Methods: Six alternative RS-rich flours—red bean, black bean, white bean, cashew nut, oat and green banana—were used as partial substitution for wheat flour at levels of 0–20% (weight per weight). Evaluation was based on the chemical composition, functional properties, bread quality and consumer acceptance.

Results: RS-rich flour substitution significantly affected sourdough bread quality. The white bean flour at 20% provided the highest protein and dietary fiber contents but reduced loaf volume. The black bean flour at 10% produced the firmest crumb, while green banana flour at 15% had the highest RS retention. Consumer testing indicated that the red bean flour at 15% achieved the highest overall liking, particularly for taste and aroma. Just-About-Right analysis supported the selected substitution levels and identified attributes requiring minor adjustment.

Main finding: The RS-rich flours improved sourdough bread nutrition by increasing RS, protein or fiber, while maintaining acceptable sensory quality.

Introduction

Bread is one of the most widely consumed bakery products globally and serves as a key nutritional source for many populations, with its convenience and versatility contributing

to the continuous expansion of the bakery industry. In Thailand, the bakery market reached a value of THB 42,023 million in 2022, representing a growth rate of 10.8%, driven by major companies such as Farmhouse, Le Pan, S&P and CPRAM (Institute of Food, 2022). However, conventional bread is produced primarily from refined wheat flour, which

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contains mainly rapidly digestible carbohydrates. Excessive consumption of refined carbohydrate-rich products has been associated with an increased risk of chronic diseases, including obesity, type 2 diabetes, cardiovascular disease and certain cancers (Ludwig, 2002; Willett et al., 2002; Reynolds et al., 2019).

Sourdough bread has gained increasing attention as a healthier alternative to conventional yeast-leavened bread due to its natural fermentation process involving lactic acid bacteria and yeasts, which improves mineral bioavailability, reduces antinutritional factors, enhances digestibility and produces organic acids that may contribute to a lower postprandial glycemic response (Catzeddu, 2011). Therefore, sourdough fermentation provides a suitable technological platform for developing functional bakery products with improved nutritional and sensory quality.

Among functional ingredients, resistant starch (RS) has been recognized for its physiological properties similar to dietary fiber as RS escapes digestion in the small intestine and is fermented by colonic microbiota, leading to the production of short-chain fatty acids that promote gut health, improve insulin sensitivity and reduce the risk of metabolic disorders (Englyst et al., 1992; Raigond et al., 2015). RS intake has been reported to derive mainly from cereal-based products, such as bread and pasta, highlighting bakery products as promising vehicles for RS enrichment (Murphy et al., 2008). However, the RS content of conventional wheat flour is relatively low compared with RS-rich sources such as legumes and green banana flour (Raigond et al., 2015; Jyothsna and Hymavathi, 2017), limiting its potential contribution to functional and health-oriented bakery products.

Incorporating flours naturally rich in RS into sourdough formulations may enhance nutritional quality while maintaining acceptable technological and sensory properties. Several alternative flours, such as legume flour and green banana flour, contain higher levels of protein, dietary fiber and RS than refined wheat flour (Ovando-Martínez et al., 2009; Hoover et al., 2010; Raigond et al., 2015). Nevertheless, their incorporation into bread systems may affect the dough structure, loaf volume, crumb texture, color, aroma, flavor and consumer acceptability due to gluten dilution, differences in water absorption, starch behavior and the presence of characteristic flavors. Therefore, the successful use of RS-rich flours in sourdough bread requires not only nutritional improvement but also the maintenance of acceptable physicochemical and sensory qualities.

Although other studies have investigated the use of alternative flours or RS sources in bakery products, limited

information is available on the comparative effects of different RS-rich flours in sourdough bread, particularly when considering consumer acceptance, Just-About-Right (JAR) responses, physicochemical quality and processing compatibility. In addition, few studies have compared conventional oven baking with microwave-assisted oven baking for RS-enriched sourdough bread in terms of product quality and energy-related advantages. This knowledge gap limits the practical application of RS-rich flours for developing functional sourdough products that are both nutritionally improved and acceptable to consumers.

Therefore, it was hypothesized in the current study that partial substitution of wheat flour with selected RS-rich flours could improve the nutritional quality of sourdough bread, particularly RS, protein and dietary fiber contents, while maintaining acceptable sensory and physicochemical properties when used at suitable substitution levels. The novelty of this study lies in the comparative evaluation of six RS-rich alternatives—red bean, black bean, white bean, cashew nut, oat and green banana flours—at different substitution levels, combined with consumer acceptance, JAR analysis, physicochemical characterization and processing comparison between conventional oven baking and microwave-assisted oven baking. The objectives of this study were to develop consumer-acceptable sourdough bread enriched with RS-rich flours and to evaluate the effects of flour type, substitution level and baking process on the physicochemical, sensory and nutritional properties of the final products.

Materials and Methods

Raw materials and quality characterization

Raw materials

The main raw materials used were: commercial wheat flour (Spacecraft brand; Thai Wheat Industry Co., Ltd.; Thailand); whole wheat flour (Imperial; KCG Corporation; Thailand); oat flour, black bean flour, red bean flour and white bean flour (B-Natural; Bangyai Supply; Thailand); cashew nut flour (18 KCALBAKE; Thailand); banana flour (Kankaew Farm Co., Ltd.; Thailand); salt (Kanghan, Pattani; Thailand); filtered chlorine-free water; and a naturally fermented sourdough starter.

The sourdough starter was prepared using commercial wheat flour (Spacecraft brand) and filtered water at a 1:1 ratio (weight per weight). The mixture was fermented under natural

conditions in sterilized containers. During fermentation, lactic acid was produced by the activity of yeasts and lactic acid bacteria, contributing to the inhibition of undesirable microorganisms.

Proximate analysis

The chemical composition of each flour was analyzed in triplicate. The moisture content was determined using the method of Association of Official Analytical Chemists (2012) based on hot-air oven drying at $105 \pm 2^\circ\text{C}$. The ash content was measured following Association of Official Analytical Chemists (2012) based on dry ashing at 550°C . Total nitrogen was quantified using the Kjeldahl method (Association of Official Analytical Chemists, 2012) with a Kjeltec analyzer (Foss; Sweden) and converted to protein using a factor of 6.25. The fat content was determined according to the method of Association of Official Analytical Chemists (2012) with an automatic Soxhlet extractor. Crude fiber was analyzed using a Fibertec system (Foss; Sweden) and acid and alkali digestion. The carbohydrate content was calculated based on differences.

Water absorption capacity

The water absorption capacity (WAC) was determined using flour samples (each 1 g) that were placed in separate 15 mL centrifuge tubes, each mixed with 10 mL distilled water for three 20 s cycles and left at room temperature for 30 min. Then, each sample was centrifuged at $1,000 \times g$ for 15 min at 25°C . The supernatant was decanted, tubes were inverted at a 45° angle for 5 min and weighed. WAC as a percentage was calculated following a modified method of American Association of Cereal Chemists (2000), using Equation 1:

$$\text{WAC} = [(W_2 - W_1) - W_s] / W_s \times 100 \quad (1)$$

where W_1 is the tube weight of a dry sample, W_2 is the tube weight with hydrated sediment and W_s is the sample weight.

Swelling power and solubility

The swelling power was evaluated at 50°C to reflect the early stage of starch hydration prior to gelatinization. At this temperature, starch granules absorb water and swell without extensive structural breakdown, allowing differences among wheat flour and RS-rich flours to be detected. Although measurements at higher temperatures could provide additional insight, this approach was selected to focus on the hydration behavior relevant to dough development during sourdough

fermentation.

Swelling power and solubility as a percentage were determined using a modified method of Daramola and Osanyinlusi (2006). Each flour sample (0.1 g) was suspended in 10 mL distilled water and heated at 50°C with shaking at 180 revolutions per minute (rpm) for 30 min. Then the sample was centrifuged at 1,500 rpm for 20 min. The supernatant was dried at 105°C to determine solubility and the sediment was weighed to calculate based on Equations 2–3:

$$\text{Swelling power} = \frac{\text{Weight of starch sediment}}{\text{Initial dry starch weight}} \quad (2)$$

$$\text{Solubility (\%)} = \frac{\text{Dried supernatant weight}}{\text{Initial dry starch weight}} \times 100 \quad (3)$$

Resistant and non-resistant starch

The resistant and non-resistant starch contents were quantified following Hefni et al. (2021). Duplicate flour samples (100 mg) were incubated overnight in sodium malate buffer (100 mmol/L, pH 6.0) containing pancreatic α -amylase and amyloglucosidase. The starch fractions were analyzed using method 32-40.01 (American Association of Cereal Chemists, 2000) and method 2002.02 (Association of Official Analytical Chemists, 2012), with a K-RSTAR enzymatic kit (Megazyme; Ireland).

Product formulation

Consumer acceptance and the effects of varying the substitution levels of the RS-rich flours on the sensory quality of sourdough bread were evaluated using a nine-point hedonic scale. The effects specifically included changes in appearance, aroma, texture, taste and overall liking, as influenced by the different levels of RS substitution.

The study was carried out in two phases. In the first phase, a randomized complete block design (RCBD) was used to determine the optimal level of RS in sourdough bread at substitution levels of 0%, 5%, 10%, 15% or 20%. This phase focused on evaluating the RS-rich flours as partial substitutes for bread flour based on consumer acceptance and sensory attributes.

In the second phase, the impact was examined of microwave-assisted processing in combination with conventional baking on sourdough bread quality. Sensory evaluation was conducted using 30 consumers based on the nine-point hedonic scale and the Just-About-Right (JAR) test. A standard sourdough formulation was used for all trials. This study was approved by

the Kasetsart University Ethics Committee, Bangkok, Thailand (KUREC; Approval No. KUREC-HSR68/068).

Sourdough bread formulations

The basic sourdough formulation was adapted from Grant Bakes (2023) and consisted of bread flour (310.5 g), whole wheat flour (27 g), water (240 mL), sourdough starter (75 g) and salt (7.5 g). RS-rich flours were incorporated by replacing bread flour at 5%, 10%, 15% or 20%, based on the total flour weight of the formulation, while the amount of whole wheat flour was kept constant at 27 g. The amounts of RS-rich flour added were 16.86 g, 33.75 g, 50.60 g and 67.50 g for the 5%, 10%, 15% and 20% substitution levels, respectively. The formulation details are shown in Table 3. Each RS-rich flour was evaluated separately at the four substitution levels. Thus, the preliminary sensory screening contained 24 substituted formulations in total, consisting of six flour sources and four substitution levels; in addition, there was one control formulation

Sourdough bread preparation

Levain was prepared by refreshing the starter and fermenting it for 4–5 hr until it had doubled in volume. The dough was mixed and fermented at 27°C for 5 hr with stretch-and-fold applied every hour. After bulk fermentation, the dough was pre-shaped, rested for 20 min and final-shaped before cold retardation at 4°C for 14 hr. Baking was carried out in a Dutch oven at 250°C for 21 min with the lid on, followed by 5 min at 230°C without the lid. The baked bread was cooled at room temperature prior to evaluation.

Consumer panel and recruitment

The preliminary consumer acceptance test was conducted using 30 untrained consumers to screen the most acceptable substitution level of each resistant starch-rich flour. The number of consumers was considered appropriate for the product development stage, as other sensory studies have suggested that 30–50 consumers were sufficient for detecting significant differences in acceptability among product formulations (Hough et al., 2006; Meilgaard et al., 2007).

In total, 30 untrained consumers were recruited from Kasetsart University, Bangkok, Thailand. Eligible participants were aged at least 18 yr, regular consumers of bread and willing to evaluate the sourdough bread samples. Individuals were excluded if they had known allergies or dietary restrictions related to wheat, legumes, oat, banana, cashew nut or other ingredients used in the formulations. Prior to evaluation,

all participants were informed about the study procedure and provided written, informed consent. The study protocol was approved by the Kasetsart University Research Ethics Committee (Approval number: KUREC-HSR68/068).

Consumer acceptance was evaluated using a nine-point hedonic scale for appearance, crumb color, aroma, taste, sourness, saltiness, texture, softness, chewiness and overall liking. The Just-About-Right (JAR) test was also used to assess key sensory attributes requiring adjustment. *Consumer acceptance test and sample presentation*

Consumer acceptance testing was conducted to determine the optimal substitution level of each RS-rich flour in sourdough bread. The evaluation was performed in six separate sessions according to the flour type: black bean, red bean, cashew nut, green banana, oat or white bean flour. In each session, consumers evaluated five samples consisting of one control sample and four sourdough bread samples substituted with the corresponding RS-rich flour at 5%, 10%, 15% and 20% based on the total flour weight of the formulation. Therefore, each consumer evaluated only five samples per session rather than all 25 formulations at once, to minimize sensory fatigue and carry-over effects. Thus, the evaluation was divided into six sessions according to flour type.

All samples were coded with three-digit random numbers and served in randomized order following a RCBD, where consumers served as blocks. Samples were presented as approximately 2 cm × 2 cm pieces containing both crust and crumbs in x3 lidded plastic cups. Drinking water was provided for palate cleansing between samples. Consumers evaluated liking using the nine-point hedonic scale for appearance, crumb color, aroma, taste, sourness, saltiness, texture, softness, chewiness and overall liking. In addition, a Just-About-Right (JAR) test was conducted for selected key attributes (crumb color, sourness, saltiness, softness and chewiness) to identify attributes requiring adjustment and to support the selection of the optimal substitution level.

Baking process comparison

The impact of microwave-assisted processing combined with conventional oven baking was evaluated in the second phase of the study. Conventional oven baking was used as the standard process for comparison. In the standard process, the sourdough bread samples were baked in an electric oven at 250°C for 21 min, followed by 230°C for 5 min. For the combined microwave–oven process, first, the dough was heated using a microwave oven at 450 W for 10 min, followed by baking in an electric oven at 200°C for 7 min and then

200°C for an additional 8 min. The resulting products from the two baking processes were compared based on consumer acceptance, using the nine-point hedonic scale and JAR test and estimated energy consumption.

Quality of sourdough bread

Proximate composition

The chemical composition of the sourdough bread samples made from the various RS-rich flour was analyzed in triplicate. The moisture content was determined using the method described in Association of Official Analytical Chemists (2012) based on hot-air oven drying at $105 \pm 2^\circ\text{C}$. The ash content was measured following Association of Official Analytical Chemists (2012) based on dry ashing at 550°C . Total nitrogen was quantified using the Kjeldahl method (Association of Official Analytical Chemists, 2012) using a Kjeltec analyzer (Foss; Sweden) and converted to protein using a factor of 6.25. The fat content was analyzed using method 920.39 (Association of Official Analytical Chemists, 2012) with an automatic Soxhlet extractor (E-816, Buchi, Switzerland). The crude fiber content was determined using a Fibertec system (Foss, Sweden) based on acid and alkali digestion. Carbohydrates were calculated based on differences.

Physical qualities

Color analysis

The color of the bread crumb and crust was quantified in the CIE Lab* color space using a spectrophotometer (CM-3500d; Konica Minolta; Japan). Crumb samples were prepared by cutting into cubes (20 mm each side). For crust color analysis, the crust was carefully separated and cut into square pieces (50 mm each side). Measurements were performed on five randomly selected pieces for each sample to ensure representative data.

Texture profile analysis

Texture properties were measured using a texture analyzer (TA.XT Plus; Stable Micro Systems; UK). Central crumb cubes (20 mm each side) were compressed using a 50 mm cylinder probe at 2 mm/s and 60% deformation. For each bread sample, 15 replicates were analyzed for hardness, springiness, cohesiveness, gumminess and chewiness.

Specific volume

The bread samples were weighed after cooling and the loaf

volume was determined using the sesame seed displacement method. Three replicates were used and the specific volume was calculated following Julianti et al. (2017).

Water activity

The water activity (a_w) of the crust and crumb was measured using an AquaLab meter (3TE; Meter Group; USA). Three replicates were analyzed.

Resistant and Non-Resistant Starch Analysis

The resistant and non-resistant starch contents were analyzed following Hefni et al. (2021). Duplicate flour samples (100 mg each) were incubated overnight in sodium malate buffer (100 mmol /L, pH 6.0) containing pancreatic α -amylase and amyloglucosidase. Starch fractions were quantified using the 32-40.01 method (American Association of Cereal Chemists, 2000) and the 2002.02 method (Association of Official Analytical Chemists, 2012) with a K-RSTAR enzymatic kit (Megazyme; Ireland).

Data analysis

Data were analyzed using analysis of variance (ANOVA) and mean comparisons were carried out using Duncan's multiple range test (DMRT) at the 95% confidence level. All measurements were conducted in triplicate.

Sensory evaluation data were analyzed using ANOVA followed by DMRT at the 95% confidence level. Statistical analyses were performed using the SPSS software (Version 20; IBM Corp.; USA).

The effects of the baking process were compared based on the hedonic scores of the sourdough breads produced using conventional oven baking and combined microwave-oven baking for each formulation using paired-samples t tests. Statistical significance was set at $p < 0.05$.

Results and Discussion

Chemical composition and functional properties of raw materials

Table 1 summarizes the chemical composition of the wheat flour and alternative RS-rich flours. There were distinct compositional differences among the flour types, particularly in the protein, dietary fiber and resistant starch contents, which are critical factors influencing sourdough fermentation and

Table 1 Chemical composition of wheat flour and substituted resistant starch-rich flours.

Quality parameters	Moisture (% dry basis)	Ash (% dry basis)	Fat (% dry basis)	Fiber (% dry basis)	Protein (% dry basis)	Carbohydrate (% basis)	Resistant starch (g/100 g)
Whole wheat	14.11±0.04 ^a	1.30±0.02 ^f	0.56±0.01 ^d	2.31±0.53 ^c	14.87±0.09 ^e	66.60±0.10 ^c	6.95±0.76 ^d
Bread flour	11.19±0.04 ^c	0.58±0.01 ^g	0.38±0.06 ^d	0.58±0.10 ^f	16.41±0.52 ^d	70.85±0.52 ^b	3.59±0.19 ^d
Black bean	10.87±0.02 ^d	2.93±0.04 ^b	1.18±0.02 ^c	5.69±0.60 ^b	27.94±0.82 ^b	51.67±0.80 ^g	30.69±0.32 ^b
Red bean	9.12±0.00 ^f	3.59±0.06 ^a	1.49±0.09 ^c	5.22±0.36 ^b	24.55±0.42 ^c	56.04±0.47 ^c	32.22±0.75 ^b
Cashew nut	5.75±0.07 ^h	2.56±0.02 ^c	34.58±0.96 ^a	1.17±0.04 ^e	39.24±0.59 ^a	16.70±1.52 ^b	1.99±0.75 ^e
Green banana	11.28±0.06 ^b	2.00±0.04 ^d	0.18±0.08 ^d	1.71±0.17 ^d	0.00±0.00 ^f	84.83±0.16 ^a	60.17±1.00 ^a
Oat	8.24±0.02 ^g	1.56±0.02 ^c	8.00±0.09 ^b	1.65±0.37 ^d	16.19±0.33 ^d	64.20±0.59 ^d	0.34±0.07 ^f
White bean	9.38±0.02 ^e	3.63±0.03 ^a	1.50±0.01 ^c	6.74±0.15 ^a	24.65±0.22 ^c	54.11±0.40 ^f	33.90±1.81 ^b

Mean ± SD values in each column followed by different lowercase superscript letters are significantly ($p < 0.05$) different.

bread quality (Arendt and Zannini, 2013; Deora et al., 2015; Raigond et al., 2015). The legume flours (red, white and black beans) were characterized by high protein (24.55–27.94%) and dietary fiber (5.22–6.74%) contents, which are known to enhance dough buffering capacity, provide fermentable nitrogen sources for lactic acid bacteria and strengthen the dough matrix structure in sourdough fermentation (Arendt and Zannini, 2013; Deora et al., 2015).

The green banana flour had the highest resistant starch content (60.17 g/100 g), consistent with the predominance of RS type II with a B-type crystalline structure that resists enzymatic digestion (Ovando-Martínez et al., 2009; Huang et al., 2022). This high RS level is expected to contribute to reduced glycemic response and increased dietary fiber functionality in sourdough bread.

The cashew nut flour contained extremely high fat and protein contents, which may enhance crumb softness and flavor development but contributed to negligible RS. The oat flour had a moderate protein content but minimal RS, indicating limited functionality for glycemic modulation.

The functional properties relevant to dough hydration and fermentation are summarized in Table 2. Although swelling power and water absorption were measured below the gelatinization temperature, these properties play a critical role in determining dough rheology and gas retention in sourdough systems (Doehlert et al., 2010; Arendt and Zannini, 2013; Deora et al., 2015).

The oat flour had the highest swelling power, indicating a greater proportion of amorphous starch regions capable of readily binding water (Doehlert et al., 2010). In contrast, the legume flours and green banana flour had high water absorption capacities (225–253%), which contributed to enhanced dough hydration and extensibility, thereby supporting gas retention during sourdough fermentation (Arendt and Zannini, 2013).

Table 2 Functional properties of wheat flour and substituted resistant starch-rich flours related to sourdough behavior

Quality parameter	Swelling (%)	Solubility (%)	Absorption (%)
Whole wheat	4.35±0.06 ^d	9.81±0.21 ^c	177.54±1.65 ^c
Bread flour	3.96±0.16 ^c	6.86±0.40 ^{cd}	214.09±0.72 ^b
Black bean	4.27±0.07 ^d	24.40±2.86 ^a	161.43±1.31 ^d
Red bean	4.80±0.05 ^{bc}	22.47±3.09 ^{ab}	253.24±1.91 ^a
Cashew nut	4.15±0.24 ^{de}	18.49±2.44 ^{ab}	153.8±1.07 ^d
Green banana	4.65±0.05 ^c	9.12±1.72 ^c	225.57±0.61 ^b
Oat	6.22±0.10 ^a	3.56±0.13 ^d	242.21±1.34 ^a
White bean	4.96±0.24 ^b	20.74±3.46 ^{ab}	250.46±1.54 ^a

Mean ± SD values in each column followed by different lowercase superscript letters are significantly ($p < 0.05$) different.

Water availability is essential for both lactic acid bacteria metabolism and gluten network development (Katina et al., 2005; Poutanen et al., 2009; Arendt and Zannini, 2013). Consequently, flours with higher water absorption capacity promote fermentation activity and structural development of the dough, ultimately influencing loaf volume and crumb structure.

Based on their combined chemical composition and functional behavior, the green banana flour and legume flours (red, white and black beans) were the most suitable raw materials for wheat flour substitution in sourdough, owing to their high RS, dietary fiber and protein contents, as well as their favorable hydration properties.

Sensory screening and selection of optimal substitution levels

Table 3 presents the basic sourdough formulations and the substitution scheme used for preliminary sensory screening. In each formulation, RS-rich flour was used to partially replace

Table 3 Sourdough bread formulations used for preliminary sensory screening of resistant starch (RS)-rich flour substitution levels.

Raw material	Amount of bread flour replaced with RS-rich flour (g)				
	Control	5%	10%	15%	20%
Starter (g)	75.00	75.00	75.00	75.00	75.00
Water (ml)	240.00	240.00	240.00	240.00	240.00
Salt (g)	7.50	7.50	7.50	7.50	7.50
Bread flour (g)	310.50	293.64	276.75	259.90	243.00
Whole wheat flour (g)	27.00	27.00	27.00	27.00	27.00
Red bean flour (g)	-	16.86	33.75	50.60	67.50
White bean flour (g)	-	16.86	33.75	50.60	67.50
Black bean flour (g)	-	16.86	33.75	50.60	67.50
Cashew nut flour (g)	-	16.86	33.75	50.60	67.50
Oat flour (g)	-	16.86	33.75	50.60	67.50
Green banana flour (g)	-	16.86	33.75	50.60	67.50

Sourdough bread recipe adapted from Grant Bakes (2023).

bread flour at 5%, 10%, 15% and 20%, while the amounts of starter, water, salt and whole wheat flour were kept constant. Each RS-rich flour was evaluated separately at the same substitution levels to compare consumer acceptance and to identify the most suitable level for further analysis.

Preliminary sensory screening was conducted using a nine-point hedonic scale to evaluate consumer acceptance of the sourdough breads substituted with six RS-rich flours at levels of 5%, 10%, 15% or 20%. Consumers evaluated 10 sensory attributes (overall appearance, crumb color, overall aroma, overall taste, sourness, saltiness, overall texture, softness, chewiness and overall liking). Because the screening involved

24 substituted formulations, Fig. 1 presents the overall liking scores as a summary indicator for selecting suitable substitution levels, while the key trends in individual sensory attributes are described in the text. Detailed hedonic scores for individual sensory attributes are provided in Supplementary Tables S1–S6.

Overall liking was used as the primary criterion for selecting suitable substitution levels, together with attribute liking scores and JAR responses. The black bean flour had the strongest decline in consumer acceptance as the substitution level increased, with decreases in appearance, crumb color, aroma, taste, texture, softness, chewiness and overall liking. This indicated that black bean flour had a stronger sensory impact than the other RS-rich flours, particularly at the 15% and 20% substitution levels. In contrast, the red bean and green banana flours maintained moderate acceptance up to 15%, while the oat and white bean flours had acceptable scores even at 20% substitution. The cashew nut flour at 15% had relatively favorable aroma and texture scores, supporting its selection for further product development. Therefore, the selected substitution levels were 10% for black bean, 15% for red bean, cashew nut and green banana and 20% for oat and white bean.

Consumer acceptance of sourdough bread containing black bean flour decreased significantly with increasing substitution levels, reaching its lowest score at 20% substitution. This decline was attributed primarily to the intensified beany aroma resulting from higher concentrations of volatile compounds, particularly aldehydes and ketones, which are commonly associated with undesirable flavors in legume-based bakery

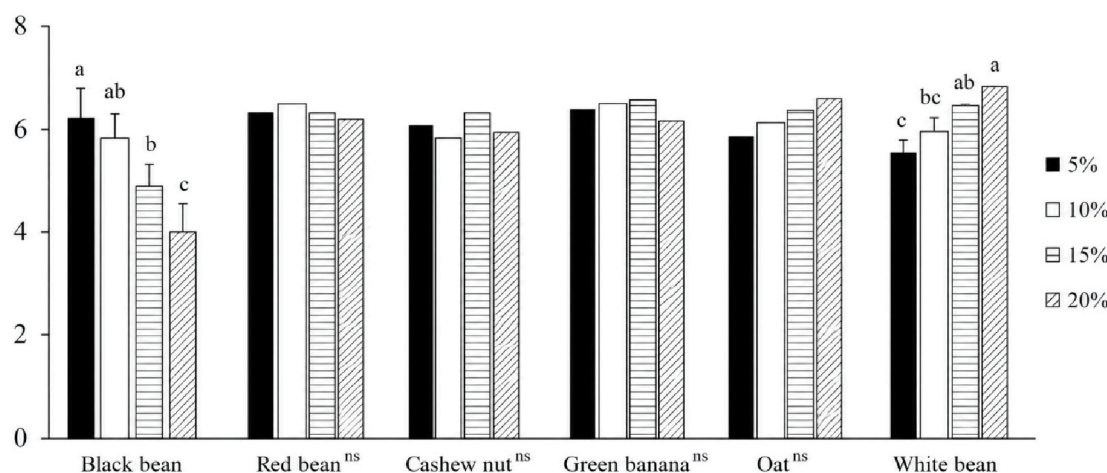


Fig. 1 Overall liking scores (mean $\pm$ SD, $n = 30$) from preliminary sensory screening of sourdough breads formulated with six resistant starch (RS)-rich flours at substitution levels of 5–20%. Overall liking was used as summary criterion for selecting suitable substitution levels, together with individual attribute liking scores and JAR responses. Different lowercase letters above bars denote significant differences among means within each flour type. ns = not significant.

products (Mohan et al., 2020).

In contrast, the red bean flour had a more stable acceptance profile at similar levels. This difference may have been related to differences in flavor-active compounds and off-flavor precursors between the red bean and black bean flours (Kinsella, 1979; Yang et al., 2018), resulting in a milder ‘beany’ perception and improved flavor integration within the acidic sourdough matrix.

Furthermore, the white bean bread at 20% received the highest overall liking score (6.7), likely due to its mild flavor profile and lower concentrations of off-flavor precursors. For the red bean, cashew nut, oat and green banana flours, the liking scores remained stable across substitution levels, suggesting no major sensory drawbacks.

In addition to hedonic evaluation, the JAR test was conducted to identify sensory attributes requiring formulation adjustment and to support the selection of suitable substitution levels, as shown in Table 4. Five key attributes (crumb color, sourness, saltiness, softness, chewiness) were evaluated using a three-point JAR scale. Consumer responses were expressed as the percentages of “too little”, “just-about-right” and “too much”. The net score was calculated as the percentage of “too much” minus the percentage of “too little”. A net score ranging from −20 to +20 was considered acceptable, indicating that the attribute intensity was close to the ideal level. A net score below −20 indicated that the attribute intensity should be increased, whereas a score above +20 indicated that the attribute intensity should be reduced. The JAR results were interpreted together with the overall liking scores and individual sensory attribute scores to determine the optimal substitution level for each RS-

rich flour.

The JAR results supported the selection of the optimal substitution levels obtained from the hedonic test. The black bean flour was selected at 10% because higher substitution levels resulted in a marked decline in overall liking and required multiple sensory adjustments. The red bean, cashew nut and green banana flours were selected at 15%, as these formulations maintained acceptable overall liking and had favorable texture-related JAR responses. The oat and white bean flours were selected at 20%, representing the highest substitution levels that maintained consumer acceptance. In particular, the white bean flour at 20% had JAR responses of at least 70% for crumb color, sourness, saltiness and softness, although chewiness may require further texture optimization. Based on these results, the JAR analysis provided practical guidance for balancing sensory acceptability with nutritional enhancement in RS-enriched sourdough bread.

The optimal substitution level of each RS-rich flour was selected based on the combined results of the nine-point hedonic test and the JAR analysis. Overall liking was used as the primary criterion, while individual sensory attributes were also considered for overall appearance, crumb color, overall aroma, overall taste, sourness, saltiness, overall texture, softness and chewiness. In addition, the JAR responses and net scores were used to identify whether key attributes required adjustment. The selected level represented the highest substitution level that maintained consumer acceptability and did not show severe imbalance in key sensory attributes.

Based on these criteria, the optimal substitution levels were determined as: 10% black bean flour, 15% red bean flour,

Table 4 Just-about-right responses and net scores in parentheses of selected resistant starch (RS)-rich sourdough bread formulations.

Flour source	Selected level (%)	Crumb color	Sourness	Saltiness	Softness	Chewiness	Main interpretation
Black bean	10	60.0 (-6.6)	46.7 (-20.0)	56.7 (+43.3)	46.7 (+13.3)	60.0 (-26.7)	Saltiness should be reduced and chewiness should be improved
Red bean	15	43.3 (+50.0)	46.7 (+46.7)	66.7 (-20.0)	86.7 (-6.7)	63.3 (-3.3)	Color intensity and sourness should be reduced
Cashew nut	15	70.0 (-16.7)	40.0 (+20.0)	70.0 (-10.0)	73.3 (-6.7)	80.0 (+13.3)	Texture was acceptable; sourness should be monitored
Green banana	15	56.7 (+30.0)	60.0 (+33.4)	66.7 (-20.0)	86.7 (-6.7)	70.0 (-3.4)	Color intensity and sourness should be reduced
Oat	20	90.0 (-10.0)	66.7 (+13.3)	73.3 (-13.3)	80.0 (+6.6)	70.0 (-16.6)	Most attributes were perceived as acceptable
White bean	20	73.3 (-13.4)	70.0 (+23.3)	86.6 (-13.3)	70.0 (-16.7)	56.8 (+16.7)	Flavor balance was acceptable; chewiness may need improvement

Net score =percentage of “too much” minus percentage of “too little”. A Net score between −20 and +20 indicates acceptable intensity, whereas values below −20 indicate that the attribute should be increased. Values above +20 indicate that the attribute should be reduced.

15% cashew nut flour, 15% green banana flour, 20% oat flour and 20% white bean flour. These selected levels were used for subsequent physicochemical analysis and final product development.

In the study, conventional oven baking was used as the standard process for comparison. The conventional baking process was carried out using an electric oven with a power rating of 2,000 W at 250°C for 21 min, followed by 230°C for 5 min. For the combined microwave-oven process, the sourdough bread was first baked in an electric oven at 200°C for 7 min, then heated in a microwave oven at 450 W for 10 min and finally baked in an electric oven at 200°C for an additional 8 min. The combined process was applied to reduce baking time and energy consumption while maintaining consumer acceptability.

The estimated energy consumption of the conventional oven process was 0.866 kWh, whereas the combined microwave-oven process consumed 0.575 kWh. Therefore, the combined process reduced energy consumption by approximately 0.291 kWh, corresponding to a 33.6% reduction compared to conventional oven baking. Using the Thailand electricity emission factor of 0.548 kg CO₂e/kWh, the estimated carbon footprint decreased from 0.474 kg CO₂e for conventional oven baking to 0.315 kg CO₂e for the combined microwave-oven process.

The direct comparison of overall liking scores between the two baking processes is shown in Table 5. The overall liking scores of the control, black bean, red bean and white bean breads were not significantly different between conventional

Table 5 Comparison of overall liking scores between conventional oven baking and combined microwave-oven baking.

Formulation	Conventional oven baking	Microwave-oven baking	Difference	<i>p</i> value
Control	7.6±1.3	7.1±1.1	-0.5	0.117
Black bean 10%	7.0±0.9	7.0±0.9	0.0	1.000
Red bean 15%	7.3±1.0	7.3±1.0	-0.03	0.712
Cashew nut 15%	7.6±1.1	6.7±1.0	-1.0	<0.001
Green banana 15%	7.1±0.7	6.6±1.0	-0.5	<0.001
Oat 20%	7.2±0.8	6.9±1.0	-0.3	0.009
White bean 20%	7.0±1.2	6.6±0.7	-0.4	0.173

values presented as mean ± SD (*n* = 30).

Difference = microwave-oven baking minus conventional oven baking.

p values based on paired-samples *t* test.

oven baking and combined microwave-oven baking, indicating that the combined process could maintain consumer acceptance for these formulations. However, the cashew nut, green banana and oat breads had significantly lower overall liking scores when processed using the combined microwave-oven method. Although significant differences were observed in these formulations, their overall liking scores remained within the acceptable range, suggesting that the combined process may still be applicable with formulation-specific optimization.

As shown in Table 6, the hedonic scores for the oven-baked sourdough breads indicated that the selected RS-rich flour formulations generally maintained consumer acceptance. The cashew nut flour at 15% achieved the highest overall liking score (7.6), suggesting that its mild flavor and relatively high lipid content may have contributed positively to aroma, taste

Table 6 Average hedonic scores for sensory attributes of sourdough bread substituted with resistant starch-rich flour at varying levels processed by baking oven technology.

Attribute	Control	Black bean 10%	Red bean 15%	Cashew nut 15%	Green Banana 15%	Oat 20%	White bean 20%
Appearance							
1. Overall appearance	7.9±0.8 ^a	6.7±1.6 ^b	7.6±1.4 ^a	7.8±1.0 ^a	6.8±1.1 ^b	7.2±1.1 ^{ab}	7.5±0.9 ^a
2. Color preference	8.1±0.9 ^a	7.1±1.1 ^{bc}	7.8±1.2 ^a	8.0±0.8 ^a	6.7±1.1 ^c	7.5±1.0 ^{ab}	7.2±1.3 ^{bc}
Aroma							
3. Overall aroma	7.6±1.6 ^a	6.9±1.3 ^{abc}	7.3±1.3 ^{abc}	7.5±1.3 ^a	6.7±1.4 ^{bc}	7.4±0.9 ^{ab}	6.6±1.4 ^c
Taste							
4. Overall taste	7.7±1.2 ^a	7.2±1.0 ^{abc}	7.2±1.3 ^{abc}	7.5±1.2 ^{ab}	6.9±0.9 ^{bc}	7.2±1.0 ^{abc}	6.7±1.0 ^c
5. Sour taste	7.7±1.3 ^a	6.6±1.5 ^c	7.2±1.5 ^{abc}	7.5±1.5 ^{ab}	6.8±1.1 ^{bc}	7.2±1.1 ^{abc}	6.7±1.2 ^c
6. Saltiness	7.7±1.5 ^a	6.9±1.2 ^{bc}	7.3±1.0 ^{ab}	7.4±1.4 ^{ab}	6.8±1.0 ^{bc}	7.3±0.9 ^{abc}	6.6±0.9 ^c
7. Overall texture	7.9±1.2 ^a	7.2±1.4 ^{bc}	7.4±1.0 ^{abc}	7.8±1.0 ^{ab}	7.1±0.9 ^c	7.2±1.0 ^{bc}	7.1±1.4 ^c
8. Softness	7.7±1.1 ^{ab}	7.1±1.4 ^{ab}	7.3±1.1 ^{ab}	7.8±1.0 ^a	7.3±1.1 ^{ab}	7.5±0.8 ^{ab}	7.1±1.5 ^b
9. Chewiness	7.4±1.3 ^{ab}	6.9±1.8 ^b	7.4±1.3 ^{ab}	7.7±1.5 ^a	7.1±0.8 ^{ab}	7.1±0.9 ^{ab}	7.1±1.1 ^{ab}
10. Overall liking	7.6±1.3 ^{ab}	7.0±0.9 ^{ab}	7.3±1.0 ^{ab}	7.6±1.1 ^a	7.1±0.7 ^{ab}	7.2±0.8 ^{ab}	7.0±1.2 ^b

Mean ± SD values within each row followed by different lowercase superscript letters are significantly (*p* < 0.05) different.

and texture perception. In addition, the red bean flour at 15% and the oat flour at 20% maintained favorable liking scores, indicating that these flours could be incorporated without causing major sensory drawbacks. In contrast, the black bean and white bean formulations had comparatively lower scores in some attributes, which may have been related to flour-specific characteristics such as beany aroma, darker color or changes in crumb texture. Based on these results, the sensory impact of RS-rich flour substitution depended strongly on the flour type rather than the substitution level alone.

As shown in Table 7, the sourdough breads produced using the combined microwave-oven process remained within an acceptable sensory range. The red bean flour at 15% had the highest overall liking score (7.3), indicating good compatibility with the accelerated heating process. Although some formulations, particularly the cashew nut, green banana and white bean breads, had slightly lower scores under the combined process than under the conventional oven baking, most sensory attributes remained acceptable. Based on these results, microwave-assisted oven baking could be used as an alternative processing method for RS-enriched sourdough bread, provided that formulation-specific effects on appearance, taste and texture are considered.

The favorable perception of the cashew nut sourdough may be attributed to its mild flavor profile and inherent fat content, which typically enhances aroma and improves crumb texture (Gómez et al., 2008). Conversely, the lower scores for the black bean bread, particularly regarding appearance and aroma, were

likely due to the persistence of strong, bean-related volatile compounds, which can be less palatable to some consumers.

Quality of sourdough bread

The chemical composition of enriched RS sourdough breads is summarized in Table 8. RS-rich flour substitution significantly modified the nutritional composition of the sourdough bread. The white bean flour at 20% had the highest protein content, while the green banana flour at 15% had the highest resistant starch retention. The cashew nut flour at 15% had the highest fat and dietary fiber contents, which may partly explain its favorable sensory acceptance due to lipid-related effects on flavor and crumb softness. Based on these results, each RS-rich flour contributed differently to the final nutritional profile of sourdough bread.

To effectively compare sourdough breads formulated with the diverse RS-rich flours, each substitution was evaluated based on its specific contribution to the final nutritional matrix. While the aim of including each alternative flour was to enhance the functional carbohydrate profile, the inherent compositional differences of the flours—such as the high protein content in legumes, the lipid-rich nature of cashew nuts and the complex polysaccharides in green banana—resulted in distinct nutritional enhancement.

The protein and dietary fiber contents increased significantly with the incorporation of the RS-rich flours. The legume-based substitution breads, particularly white bean (20%), had the highest protein (19.05%) and fiber (2.88%) contents, consistent with the nutritional density typically provided by pulses (Deora

Table 7 Average hedonic scores for sensory attributes of sourdough bread substituted with resistant starch-rich flour at varying levels processed by baking microwave combined with oven technology.

Attribute	Control	Black bean 10%	Red bean 15%	Cashew nut 15%	Green Banana 15%	Oat 20%	White bean 20%
Appearance							
1. Overall appearance	7.3±1.1 ^{ab}	6.9±1.3 ^{bc}	7.6±1.3 ^a	6.6±1.1 ^c	6.5±1.1 ^c	7.0±1.2 ^{abc}	6.7±1.2 ^c
2. Color preference	7.6±1.0 ^{ab}	7.1±1.0 ^{bc}	7.8±1.2 ^a	6.8±1.0 ^{cd}	6.3±1.1 ^{de}	7.3±1.2 ^{abc}	6.0±1.1 ^c
Aroma							
3. Overall aroma	7.2±1.3 ^a	7.0±1.1 ^{abc}	7.2±1.3 ^a	6.8±0.9 ^{abc}	6.4±1.5 ^c	7.1±1.2 ^{ab}	6.5±1.1 ^{bc}
Taste							
4. Overall taste	6.8±1.4 ^{ab}	7.3±0.9 ^a	7.3±1.1 ^a	6.1±1.2 ^c	6.5±1.0 ^{bc}	6.9±1.3 ^{ab}	6.6±1.6 ^{abc}
5. Sour taste	6.6±1.4 ^{abc}	6.7±1.3 ^{abc}	7.3±1.4 ^a	6.0±1.3 ^{bc}	6.4±1.3 ^{bc}	6.9±1.3 ^{ab}	6.1±1.4 ^{bc}
6. Saltiness	6.8±1.2 ^{abc}	6.9±1.2 ^{ab}	7.3±1.1 ^a	5.9±1.2 ^d	6.4±1.1 ^{bcd}	6.9±1.1 ^{ab}	6.2±1.0 ^{cd}
7. Overall texture	7.1±1.1 ^{ab}	7.2±1.2 ^{ab}	7.3±1.1 ^a	6.5±1.1 ^c	6.7±1.1 ^{abc}	7.0±1.1 ^{abc}	6.7±0.9 ^{bc}
8. Softness	7.1±1.2 ^a	7.2±1.2 ^a	7.3±1.1 ^a	6.4±1.2 ^b	7.1±1.2 ^a	7.2±1.1 ^a	6.2±1.2 ^b
9. Chewiness	7.2±1.1 ^{ab}	7.0±1.5 ^{abc}	7.4±1.3 ^a	6.7±1.1 ^{bc}	6.7±1.1 ^{bc}	6.9±1.1 ^{abc}	6.4±1.4 ^c
10. Overall liking	7.1±1.1 ^{ab}	7.0±0.9 ^{ab}	7.3±1.0 ^a	6.7±1.0 ^b	6.6±1.0 ^b	6.9±1.0 ^{ab}	6.6±0.7 ^b

Mean ± SD values within each row followed by different lowercase superscript letters are significantly ($p < 0.05$) different.

Table 8 Chemical quality parameters of sourdough bread (control) compared with sourdough bread supplemented with resistant starch (RS)-rich flour.

Quality parameter	Moisture	Protein	Fat	Fiber	Ash	Carbohydrate	Resistant starch (g/100 g dwb)
Control	43.67±0.14 ^d	16.89±0.09 ^e	0.14±0.02 ^d	1.50±0.07 ^d	1.24±0.02 ^e	36.55±0.24 ^b	4.83±0.05 ^d
Black bean 10%	45.08±0.04 ^c	18.33±0.12 ^c	0.75±0.03 ^b	1.39±0.09 ^d	1.33±0.03 ^d	33.12±0.17 ^d	5.16±0.98 ^c
Red bean 15%	43.83±0.14 ^d	18.24±0.15 ^c	0.02±0.01 ^f	1.84±0.15 ^c	1.70±0.01 ^a	34.38±0.18 ^c	5.38±0.14 ^b
Cashew nut 15%	46.49±0.26 ^a	18.83±0.13 ^b	2.07±0.04 ^a	3.55±0.17 ^a	1.52±0.04 ^b	27.54±0.33 ^f	5.15±0.43 ^c
Green Banana 15%	43.16±0.21 ^e	15.22±0.09 ^f	0.07±0.01 ^e	1.90±0.05 ^c	1.44±0.02 ^c	38.22±0.34 ^a	5.46±0.05 ^a
Oat 20%	42.61±0.29 ^f	17.40±0.05 ^d	0.44±0.02 ^c	2.00±0.03 ^c	1.43±0.01 ^c	36.12±0.26 ^b	4.84±0.30 ^d
White bean 20%	45.55±0.30 ^b	19.05±0.09 ^a	0.06±0.01 ^e	2.88±0.02 ^b	1.33±0.03 ^d	31.12±0.24 ^c	5.22±0.25 ^c

dwb = dry weight basis.

Mean ± SD values within each column followed by different lowercase superscript letters are significantly ($p < 0.05$) different.

et al., 2015). Notably, the bread with cashew nut substitution (15%) also had a significant fiber content (3.55%). Although the cashew nut flour itself contained less crude fiber (1.17%) than the legumes (Table 1), its higher fiber value in the bread formulation likely reflected a synergistic effect during the sourdough process (Katina et al., 2005; Poutanen et al., 2009). The acidic environment and prolonged fermentation may have promoted the formation of resistant starch Type III (retrograded starch) (Eerlingen and Delcour, 1995) and the complexation of lipids with starch and proteins, which can be quantified analytically as a part of the dietary fiber fraction (Sajilata et al., 2006). Additionally, the high fat content (2.07%) in the bread with cashew nut substitution contributed positively to the flavor and crumb texture (Aslam et al., 2020).

The RS levels are presented in Table 8. Despite partial degradation during baking due to starch gelatinization, the breads substituted with RS-rich flours—particularly red bean (15%), green banana (15%) and white bean (20%)—retained significantly higher RS contents (5.22–5.46 g/100 g, on a dry weight basis, dwb) compared to the control (4.83 g/100 g, dwb). This remaining RS suggested that RS Type II and III structures in these sources had partial thermal stability under sourdough fermentation and baking conditions (Huang et al., 2022), demonstrating the efficacy of this substitution strategy for producing nutritionally enhanced functional bread.

The color and texture attributes of the sourdough breads are presented in Table 9. The crust and crumb color values varied significantly based on the type of RS-rich flour incorporated. Contrary to initial observations, the black bean bread produced the darkest crust ($L^* = 45.76$), which was significantly lower than in the other formulations. While the green banana and red bean flours also contributed to lower lightness compared to the control, their crust L^* values (61.09 and 58.99, respectively) were not significantly different from each other. The intense

browning in the black bean sourdough was likely due to the high concentration of anthocyanins and phenolic pigments in the seed coat, which underwent thermal degradation and promoted non-enzymatic browning during baking. In contrast, the white bean bread had the highest crumb lightness ($L^* = 73.32$), consistent with its low pigment content and pale starch characteristics.

The texture profile analysis indicated that the sourdough bread containing 10% black bean flour had the highest hardness (24.09 N), significantly exceeding that of the other formulations. Although there were gluten dilution and fiber-starch interactions in all the substituted breads, the pronounced hardness of the black bean sourdough could have been due to the rigid cellular matrix and relatively high amylose content of the black bean components, which promoted the formation of a compact starch-protein network upon cooling. In addition, the polyphenols present in black beans can form complexes with proteins, further restricting gluten extensibility and impairing gas cell expansion more severely than in other legume-based formulations (Mancebo et al., 2015).

The white bean bread (20%) had the lowest loaf volume (1,504 cm³) and specific volume (1.76 cm³/g), likely resulting from intensified competition for water among its high protein (19.05%), starch and fiber contents, which severely limited gluten expansion. In contrast, the oat bread (20%) had a comparatively high specific volume (2.81 cm³/g), supported by its high swelling power and β -glucan content, which enhanced gas entrapment and foam stabilization within the dough matrix (Gallagher et al., 2004).

Overall, the incorporation of RS-rich flours significantly improved the nutritional density of the sourdough bread without compromising sensory acceptability. The RS content in the substituted samples increased by approximately 6.8–13.0% compared to the control (4.83 g/100g, dwb), with the highest

Table 9 Physical quality parameters of sourdough bread (control) compared with sourdough bread supplemented with resistant starch (RS)-rich flour.

Quality parameter	Control	Black bean 10%	Red bean 15%	Cashew nut 15%	Green Banana 15%	Oat 20%	White bean 20%
Bread crust							
Color							
L*	49.65±2.37 ^{de}	45.76±0.86 ^e	58.99±0.10 ^b	51.55±0.60 ^{cd}	61.09±2.60 ^{ab}	54.56±4.63 ^c	64.29±0.26 ^a
a*	13.18±0.74 ^a	13.72±0.65 ^a	10.90±0.75 ^{bc}	12.50±1.18 ^{ab}	7.62±1.35 ^d	10.25±1.54 ^c	10.39±0.12 ^c
b*	21.76±0.75 ^b	23.85±1.51 ^b	22.38±2.23 ^b	27.55±0.72 ^a	17.95±2.54 ^c	22.09±3.15 ^b	28.23±0.90 ^a
Bread crumb							
Color							
L*	71.83±0.45 ^b	57.64±0.73 ^f	59.59±0.36 ^e	72.39±0.32 ^b	61.54±0.10 ^d	67.68±0.83 ^c	73.32±0.19 ^a
a*	2.26±0.60 ^b	3.35±0.17 ^b	5.21±0.10 ^a	2.11±0.17 ^d	2.81±0.09 ^c	2.81±0.05 ^c	1.60±0.04 ^c
b*	18.13±1.15 ^a	12.00±0.30 ^c	17.52±1.94 ^a	18.11±0.47 ^a	13.76±0.06 ^b	18.51±0.02 ^a	18.20±0.13 ^a
Texture							
Hardness (N)	13.31±3.68 ^c	24.09±11.65 ^a	18.21±3.46 ^b	13.62±2.05 ^c	17.86±2.43 ^b	13.58±0.97 ^c	19.39±4.60 ^b
Springiness	0.95±0.02 ^{ab}	0.77±0.09 ^d	0.89±0.06 ^c	0.91±0.02 ^{bc}	0.97±0.01 ^a	0.97±0.03 ^a	0.79±0.09 ^d
Cohesiveness	0.67±0.03 ^c	0.63±0.05 ^d	0.64±0.04 ^d	0.69±0.06 ^c	0.81±0.03 ^b	0.86±0.02 ^a	0.61±0.05 ^d
Gumminess	8.87±2.15 ^c	14.72±5.78 ^a	11.65±2.35 ^b	9.41±1.45 ^c	11.77±1.01 ^b	9.48±1.24 ^c	11.79±2.47 ^c
Chewiness	8.37±2.05 ^c	11.49±4.88 ^a	10.27±1.84 ^{abc}	8.59±1.28 ^c	10.65±1.01 ^{ab}	8.45±1.19 ^c	9.33±2.40 ^{bc}
Volume (cm ³)	2,092.33±4.04 ^a	1,834.33±6.03 ^c	1,707±4.58 ^d	1,715.33±4.04 ^d	1,707.33±6.03 ^d	1,849.67±7.09 ^b	1,504±9.54 ^e
Specific volume (cm ³ /g)	4.03±0.01 ^a	2.75±0.01 ^c	2.30±0.01 ^e	2.34±0.01 ^d	2.28±0.01 ^f	2.81±0.01 ^b	1.76±0.01 ^g
a _w	0.85±0.01 ^{bc}	0.85±0.00 ^{cd}	0.86±0.00 ^{ab}	0.84±0.00 ^d	0.86±0.00 ^{bc}	0.87±0.00 ^a	0.86±0.01 ^{bc}

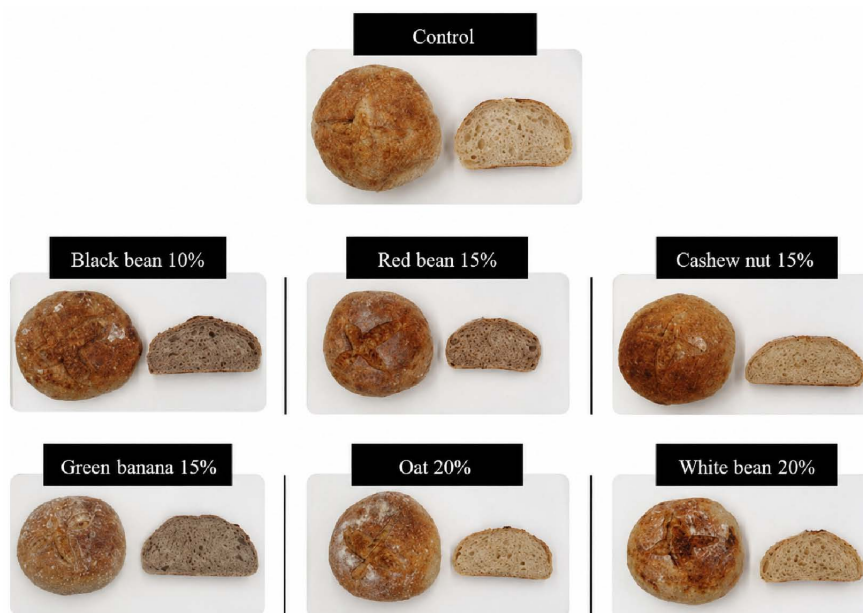
a_w = water activity.

Mean ± SD values within each row followed by different lowercase superscript letters are significantly ($p < 0.05$) different.

retention in the 15% green banana flour formulation (5.46 g/100g, dwb).

While the green banana flour was the most effective for RS enrichment, the legume flours (red, white and black bean)

were superior sources for enhancing both the protein and dietary fiber contents. Specifically, the 20% white bean flour had the highest protein (19.05%) and fiber (2.88%) levels. Furthermore, despite the challenges of gluten dilution, the use

**Fig 2.** Representative sourdough bread samples enriched with different resistant starch (RS)-rich flour sources and substitution levels

of 15% cashew nut flour maintained high consumer acceptance (7.6), comparable to the control, likely due to its lipid-driven textural benefits.

These findings demonstrated that RS-rich flours could successfully fortify sourdough bread, allowing for targeted nutritional enhancement based on the selected flour type. This research has provided a useful framework for the development of functional, energy-efficient bakery products—utilizing combined microwave and oven technology—to meet the growing demand for health-oriented and sustainable food options.

Conclusions

This study demonstrated that RS-rich flours could be used to improve the nutritional quality of sourdough bread while maintaining consumer acceptability when applied at appropriate substitution levels. The optimal substitution levels were 10% black bean flour, 15% red bean flour, cashew nut flour or green banana flour and 20% oat flour or white bean flour. The green banana flour at 15% had the highest RS retention, while the white bean flour at 20% had the highest protein content and improved dietary fiber. Based on the consumer acceptance and JAR results, the red bean, oat and white bean formulations maintained favorable sensory quality, whereas the black bean flour was limited to 10% due to its stronger sensory impact. The combined microwave-oven process reduced the estimated energy consumption compared with conventional oven baking, although some formulations required process-specific optimization. Overall, RS-rich flour selection should be guided by the intended product target, such as RS enhancement, protein enrichment, fiber improvement or maintenance of sensory acceptability.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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