



Original research

Effect of controlled fermented rice bran and its water soluble extract on techno-functional characteristics of wheat bread baked using infrared heating/superheated vapor

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ABSTRACT

Considering the importance of bread in the human daily diet in all over the world, improving the quality characteristics and shelf-life of this staple food using effective fermentation and baking strategies has received considerable attention. In the present study, the effects of controlled rice bran sourdough (RBS) or its water-soluble extract (WSE) in combination with infrared (IR) heating or superheated vapor (SHV) along with hot air (HA) baking methods were investigated on textural and sensorial properties, as well as surface moldiness of the produced wheat loaf breads. According to the results, combined applications of RBS and HA + IR baking process led to the lowest crumb hardness (1.78 N) among the produced samples. The highest specific volume (4.05 cm³/g) was also observed in WSE-added bread baked using the HA + SHV. Moreover, surface moldiness of the RBS added samples was significantly ($P < 0.05$) lower than that of the produced breads using all of the used baking processes. The lowest moldiness was also observed in the RBS-supplemented sample processed using HA + IR method. Overall acceptability of the aforementioned sample was also significantly higher than that of the other samples processed using HA and also HA + IR methods. Accordingly, the combined application of controlled sourdough containing protective starter culture along with the IR baking method may be a useful strategy to enhance technological functionalities and shelf-life of the produced bread.

Keywords: Sourdough; Rice bran; Infrared heating; Superheated vapor; Moldiness.

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1. Introduction

Wheat bread is a staple food all over the world, and therefore, improvement of its quality/shelf-life is an important task from consumer and industrial viewpoints. Considering the importance of fermentation and baking as the main two fundamental steps in the bread-making process, there are strategies such as sourdough (SD) fermentation along with efficient baking technologies to enhance techno-functional properties of wheat bread (Pahlavani et al., 2024; Sadeghi et al., 2023). Recently, application of rice bran (RB) as a potential bio-improver has also received considerable attention in

bakery products due to its positive effects on some techno-functional characteristics of the product. There are also efficient valorization approaches like controlled SD fermentation for application of cereal's bran as food-grade value-added by-products in baking industries (Ebrahimi et al., 2022; Sadeghi et al., 2019a).

Controlled SD fermentation not only can improve the technological functionalities of the produced bread but also enables us to extend mold-free shelf-life of the product by eliminating moldiness. However, fungal growth in bread causes serious problems, while the application of synthetic preservatives may have negative effects on human health due to the development of resistant

Abbreviations: CFU: colony forming units, DY: dough yield, HA: hot air, IR: infrared, LAB: lactic acid bacteria, OA: overall acceptability, RB: rice bran, RBS: rice bran sourdough, SD: sourdough, SHV: superheated vapor, WSE: water soluble extract.

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fungus species. In contrast, biological preservatives such as lactic acid bacteria (LAB) are effective and safe with potential health-promoting activities. In addition to their role in creating flavor in fermented foods, these beneficial bacteria secrete various antimicrobial metabolites to reduce the possible risk of pathogenic agents that have also received significant attention (Sadeghi et al., 2019b).

Application of controlled SD fermented with selected antifungal LAB is common in bread processing due to its promising effects on product quality and shelf-life. The effect of different controlled fermented SDs such as sprouted clover seeds (Zarali et al., 2024), amaranth (Shayesteh Kia et al., 2024), quinoa (Rouhi et al., 2023), sprouted mung bean (Aryashad et al., 2023; Ziaee rizi et al., 2024), oat (Hajinia et al., 2021), acorn (Purabdolah et al., 2020), wheat germ (Ebrahimi et al., 2021), RB (Sadeghi et al., 2019a), white wheat (Ebrahimi et al., 2020) and whole wheat (Sadeghi et al., 2019b) containing selected predominant antifungal LAB as potential protective starter culture on mold-free shelf-life of produced wheat breads, as well as their sensory characteristics, textural features and/or nutritional properties has been verified. These crucial effects are usually attributed to a broad mixture of metabolites produced by SD LAB or their potential for bioconversion of the raw substrates into functional bioactive compounds (Sadeghi et al., 2023).

It should be noted that bread baking is a complex process in which temperature is the main factor. In this process, the phenomena of heat and mass transfer also occur simultaneously with physicochemical and structural changes (Sommier et al., 2005). Bread is traditionally baked in conventional ovens using hot air (HA), with or without air circulation. Heat transfer in this method is low, and therefore, there is an increasing interest in alternative approaches. The use of infrared (IR) heating is a fast-cooking method that can be used to achieve high heat transfer rates and short cooking times (Olsson et al., 2005). The IR heat directly affects the thin outer layer of the product. Typically, this method cannot be used effectively for dense foods such as bread, as the surface will quickly heat up and brown before the heat can penetrate. Therefore, a combination of HA and IR may be useful in the bread-making process. Vapor is also commonly used to control the texture or color of the crust in the baking process. In addition, it is used as the main source of energy for baking the Chinese steamed bread, as well as in the preparation of a traditional bakery product in Northern Italy. Steamed breads are characterized by a relatively dense and chewy texture, a smooth and white leathery surface, unlike the brown crust of regular breads baked using HA. Moreover, increasing the porosity of crumb when using vapor in the oven, and its significant effect on the gelatinization of starch and protein-starch network has been reported (Altamirano-Fortoul et al., 2012; Li et al., 2020). Accordingly, combined applications of preservative/baking approaches have undeniable effects on shelf-life and textural features of the produced bread.

Baking of SD breads using novel strategies like IR and SHV has received considerable attention in order to enhance technological functionalities and to extend the shelf-life of the product. In other words, combined application of IR heating or SHV along with the HA baking method is a promising way to produce functional wheat bread containing controlled SD. In the present study, the combined application of HA + IR heating or SHV baking processes along with the controlled RBS or its water-soluble extract (WSE) was used to produce enriched wheat bread. Then, textural features, sensorial attributes and surface moldiness of the produced samples were analyzed and compared to the control wheat bread. Based on our best knowledge, this is the first report about the combined application of

controlled SD fermentation and IR/SHV baking processes to manufacture functional wheat bread.

2. Materials and Methods

2.1. Raw materials

Proximate composition of white wheat and RB (by-product of industrial rice processing with a particle size of less than 200 μm , a mixture of different varieties) flours used in the present study were analyzed according to the AACC (2010) approved methods. These ingredients were purchased from the local market in Gorgan, Iran. Chemical reagents and microbial culture media were also purchased in analytical grade.

2.2. Experimental design of the baking process

The baking system consisted of a toaster oven (Feller, Germany) that was redesigned. Inside this oven, four 1000 W electrical elements were used to increase the temperature, along with a fan to ensure a uniform temperature inside the chamber. An IR radiator (far IR lamp, 1500 W) was installed in a waveguide on the roof of the oven, and a variable transformer (MST-5KVA Delta, China) was used to adjust the IR power (28 W). The distance of the surface of the samples from the IR lamps was equal to 11.0 cm, the thickness of the bread was 4.0 cm, and the surface of the bread was also 49.5 (11.0 \times 4.5) cm^2 (Fig. 1a). An autoclave with a constant vapor flow rate of 770 mL/min was also used to provide SHV. In order to increase the vapor temperature, it was transferred through a fireproof silicone tube to the aluminum chamber with two 1000 W elements installed in the oven. The temperature of the elements was also adjusted with a thermostat. The SHV that comes out of this chamber enters the spiral copper pipe placed on the roof of the oven. In this tube, a number of holes with a diameter of 1 mm have been considered for the entry of vapor into the chamber. To measure the temperature during baking, a 1.3-mm-thick K-type thermocouple was used near the surface of the bread with a TM-947SD thermometer (Lutron, Japan) attached to it (Fig. 1b). The experiments were conducted at Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran.

2.3. Controlled fermented rice bran

To prepare controlled fermented RB, 10^7 colony-forming units (CFU)/g of *Pediococcus acidilactici* isolated from mature spontaneous RBS (Pourrashidi et al., 2023) was inoculated into a mixture of RB flour and sterile water with a dough yield (DY: the ratio of dough to flour \times 100) of 450. Then, the mixture was fermented at 37 °C for 24 h (Sadeghi et al., 2019a).

2.4. Preparation of water-soluble extract of rice bran sourdough

To produce WSE, RBS fermented by the selected LAB isolate with DY of 450 was centrifuged (Sigma, Germany; at 6000 g for 5 min) and filtered (0.45 μm), sterilized according to Coda et al. (2008) with some modifications. Then, the obtained supernatant was used as an alternative to water in bread formulation.

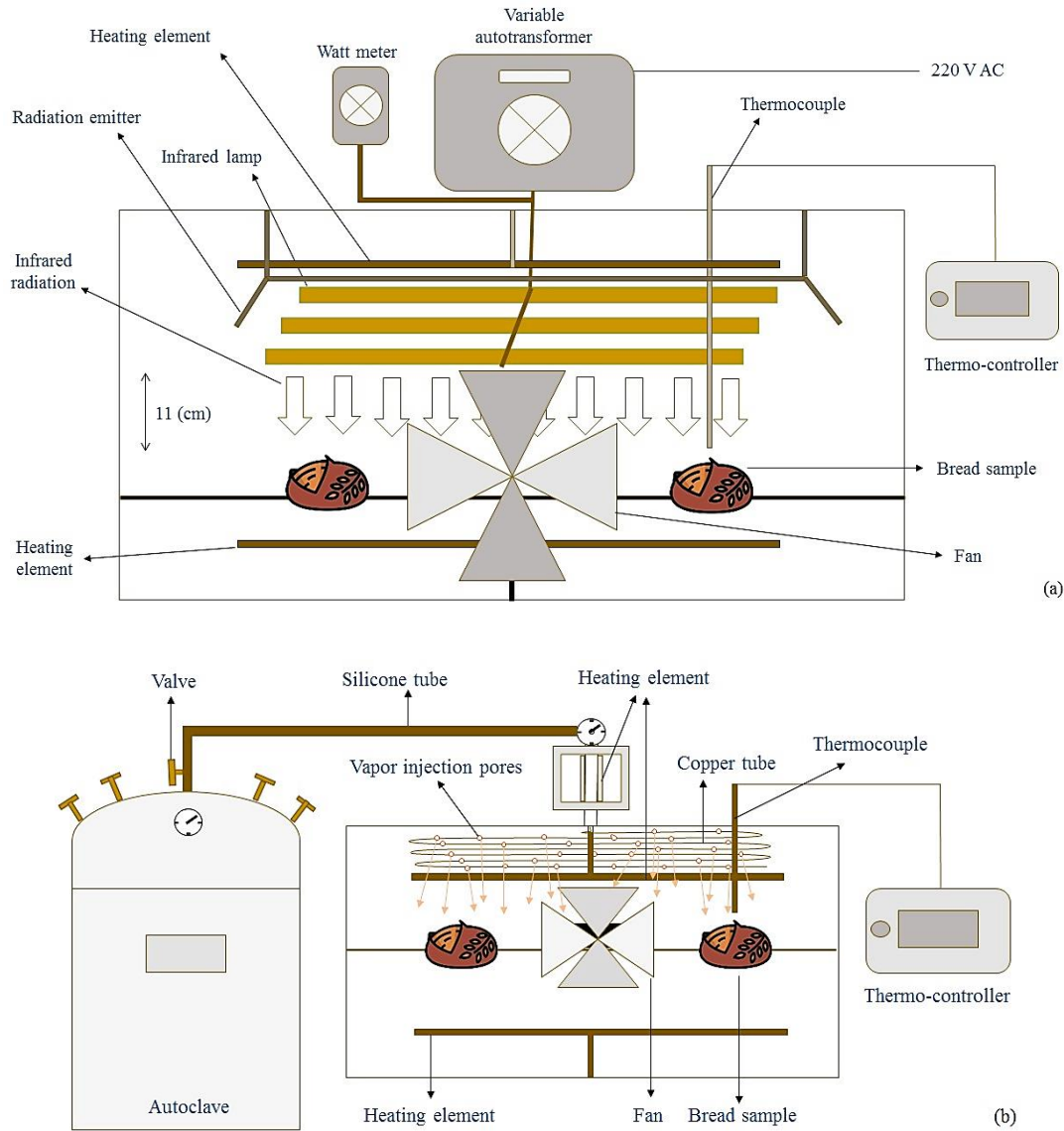


Fig. 1. A schematic diagram for combined applications of infrared heating (a) and superheated vapor (b) along with hot air in the bread-making process used in the present study.

2.5. Loaf bread-making process

To prepare control loaf bread, a mixture of wheat flour and water with 2% (w/w) active dry yeast *Saccharomyces cerevisiae* was used. The first and second proofing steps of this mixture were held at 30 °C for 30 min and at 37 °C for 90 min (after dividing the dough), respectively. The control bread dough did not contain RBS or WSE, and it was processed by three types of baking processes including HA (at 185 ± 5 °C for 20 min), simultaneous HA + IR heating, and simultaneous HA + SHV. The optimized baking conditions were determined based on pre-treatments, after balancing the moisture and dry basis of the samples. To prepare loaf wheat breads containing RBS and WSE, respectively 20% w/w of controlled fermented RBS (DY of 450) and 20% v/w of filter sterilized WSE (instead of water in bread dough formulation) were added to the control dough with

the identical baking processes. Subsequently, the produced loaf bread samples were cooled for 2 h at room temperature and packed in zip-lock polyethylene bags for further analyses.

2.6. Textural features

To determine the crumb hardness of the produced samples, a texture analyzer (Plus Stable Micro Systems, UK) was used. Briefly, the compression test was performed 2 h after baking with a cylindrical aluminum probe (diameter of 25 mm) and probe speed of 1 mm/s to produce 50% compression in the initial thickness of the loaf slice with 20 mm thickness from the center of the bread (AACC, 2010). The specific volume of the produced breads was determined using the rapeseed displacement method (AACC, 2010). The used samples have the same weight and were prepared from the geometric

center of the bread. Crumb porosity was also measured according to the method described by [Chiavaro et al. \(2008\)](#) using Image J software version 1.52e (Image J Portable software, 2013).

2.7. Surface expansion of the indicator fungus

The growth of an indicator fungus on the surface of the produced bread samples was evaluated through measuring the mycelium expansion of *Aspergillus niger* ATCC 9029 and its black growth area based on the method of [Sadeghi et al. \(2019b\)](#) with minor modifications. Briefly, a sterile paper disc (6 mm in diameter) was placed at the center of the produced loaves in this challenge test. Then, 3 μL of fungal spores (10^6 spores/mL) were inoculated on the disk. After seven days of incubation, the diameter of mold growth around the disk was determined using Image J software compared to the control sample.

2.8. Overall acceptability

To investigate the overall acceptability (OA) of the produced breads, sensory evaluation was done 2 h after baking. Ten trained panelists (5 men and 5 women aged 22 to 45 years old) investigated the samples in terms of chew-ability, mouth feel, color and shape, taste and aroma based on a 5-point hedonic scale (1 = strongly dislike, 3 = neither like nor dislike, 5 = like very much). The samples were checked with 3-digit random codes, and panelists had access to the control sample and drinking water to minimize the error during the test. OA was also calculated based on the average scores of the panelists ([Katina et al., 2006](#)).

2.9. Statistical analysis

The results of the present research were statistically analyzed based on a completely randomized design in three replicates using SPSS software (version 20). The means were also compared using Duncan's test at $P < 0.05$, and Microsoft Office Excel 2016 was used to draw the charts.

3. Results and Discussion

3.1. Textural features

White wheat flour (68% extraction rate) contained 13.10% moisture, 11.25% protein ($N \times 5.70$), 0.60 fat, 74.50 total carbohydrate and 0.55% ash. RB flour had also 19.40% protein ($N \times 5.70$), 14.18% fat, 12.04% moisture, 11.08% ash and 43.30% total carbohydrate. The amounts of crumb hardness, porosity and specific volume of the produced breads are shown in [Table 1](#). Accordingly, the lowest crumb hardness (1.78 N) was observed in the RBS added sample processed using HA + IR heating. Generally, the application of RBS and WSE increased the crumb hardness of the produced samples baked using the HA method. Meanwhile, SD breads produced using HA + IR and also HA + SHV showed significantly ($P < 0.05$) lower crumb hardness than those of samples supplemented with WSE and processed using the same baking method. Furthermore, produced SD breads using different baking processes exhibited higher porosity and specific volume compared to almost all of the samples. The effects of the HA + IR baking method on increasing crumb porosity were also significantly higher than those of the other baking processes. Meanwhile, among the

samples produced with WSE, the bread produced with HA + IR had the highest specific volume.

Accordingly, the effect of SD fermentation on the improvement of textural features of the produced bread was higher than that of the WSE. Moreover, an increasing in porosity and specific volume had a positive correlation with a reduction of crumb hardness in SD added samples, especially those produced using HA and HA + IR baking methods. The lower crumb hardness of the RBS added sample baked using the HA + IR method may be partially associated with positive effects of SD fermentation due to production of organic acids and CO_2 , as well as activities of indigenous or microbial enzymes in the proper pH obtained after SD fermentation ([Sadeghi et al., 2023](#); [Rahimi et al., 2025](#)). Notably, the hard surface of the produced crust under IR heating also resulted in maintenance of the crumb moisture and subsequent crumb softness in the aforementioned sample. Another proposed reason for the influence of non-endosperm components on bread textural quality is the interaction between fiber and gluten. Moreover, the addition of cereal bran causes dilution of gluten, which is probably a reason for the reduction of crumb hardness in the produced SD breads in the present study. It is also evident that the controlled fermentation of RBS increased carbohydrates consumed by the yeasts, which causes more gas production and reduction of the crumb hardness ([Noort et al., 2010](#)). [Purliis \(2014\)](#) also reported that application of IR besides convection led to the improvement of thermal input, baking time and weight loss compared to the conventional bread baking process. Findings of [Ploteau et al. \(2015\)](#) also revealed the positive effect of short IR emitters on conventional baking efficiency of French bread. In the same vein, [Farahmand et al. \(2015\)](#) reported that the control bread had higher crumb hardness compared to the sample containing 10% RBS at the end of the storage period. As concluded by the authors, the high capacity of water binding to RB can lead to the maintenance of moisture in the crumb for a more extended period and delaying the hardening of the bread texture. Moreover, the application of the IR process reduces cooking time compared to convection and conduction heating due to the more efficient heat transfer to the surface. Considering the high speed of cooking with the IR process, reducing the baking time may produce a softer texture. Accordingly, less weight loss occurs, resulting in more moisture retention in the crumb, which leads to lower crumb hardness with a longer shelf-life ([Rastogi, 2012](#)).

3.2. Surface moldiness

Surface growth of *A. niger* as an indicator mold on SD breads produced using all the baking processes was significantly ($P < 0.05$) lower than that of the samples produced using the same baking method. Moreover, the HA + IR baking process was more effective than the other applied methods in reducing surface moldiness in the challenge test. Interestingly, the inhibitory effect of WSE on the black zone area of the mold growth in the sample baked using HA + SHV was higher than of the other samples ([Fig. 2 and 3](#)).

Mold growth in breads containing RBS was significantly lower than that of the control bread, as reported by [Farahmand et al. \(2015\)](#), which is in line with our findings. This inhibitory effect was associated with the synergistic interaction between lower pH caused by the production of organic acids and other antifungal metabolites produced by SD LAB. It is also reported that the low pH obtained after SD fermentation leads to the reduction and elimination of mold growth on the produced SD bread. Moreover, the production of antifungal metabolites by some SD LAB has been verified. In addition, conversion of some bioactive compounds like natural

Table 1. Crumb hardness, porosity and specific volume of wheat bread samples containing rice bran sourdough or its water-soluble extract produced using different baking strategies compared to the control sample.

Bread sample/baking method	Crumb hardness (N)	Porosity (%)	Specific volume (cm ³ /g)
C/HA	4.94 ± 0.35 ^{Aa}	8.80 ± 0.35 ^{Cb}	2.71 ± 0.26 ^{Ab}
RBS/HA	5.79 ± 0.56 ^{Aa}	17.35 ± 0.63 ^{Aa}	3.82 ± 0.26 ^{Aa}
WSE/HA	6.30 ± 0.43 ^{Aa}	10.40 ± 0.28 ^{Bb}	2.54 ± 0.02 ^{Bb}
C/HA+IR	3.11 ± 0.43 ^{Bab}	12.75 ± 0.49 ^{Ba}	3.57 ± 0.24 ^{Aa}
RBS/HA+IR	1.78 ± 0.34 ^{Cb}	16.05 ± 0.35 ^{Aa}	3.76 ± 0.24 ^{Aa}
WSE/HA+IR	4.65 ± 0.43 ^{Ab}	13.20 ± 0.56 ^{Ba}	4.05 ± 0.08 ^{Aa}
C/HA+SHV	1.95 ± 0.39 ^{Bb}	11.07 ± 0.31 ^{Aa}	2.71 ± 0.34 ^{Ab}
RBS/HA+SHV	2.17 ± 0.34 ^{Bb}	12.30 ± 0.28 ^{Ab}	2.87 ± 0.04 ^{Ab}
WSE/HA+SHV	6.86 ± 0.40 ^{Aa}	11.45 ± 0.21 ^{Ab}	2.69 ± 0.09 ^{Ab}

In each column, different uppercase letters show significant difference ($P < 0.05$) among samples produced using the same baking method, and different lowercase letters indicate significant difference among samples containing the same formulation. C: control, RBS: rice bran sourdough, WSE: water soluble extract, HA: hot air, IR: infrared, SHV: superheated vapor.

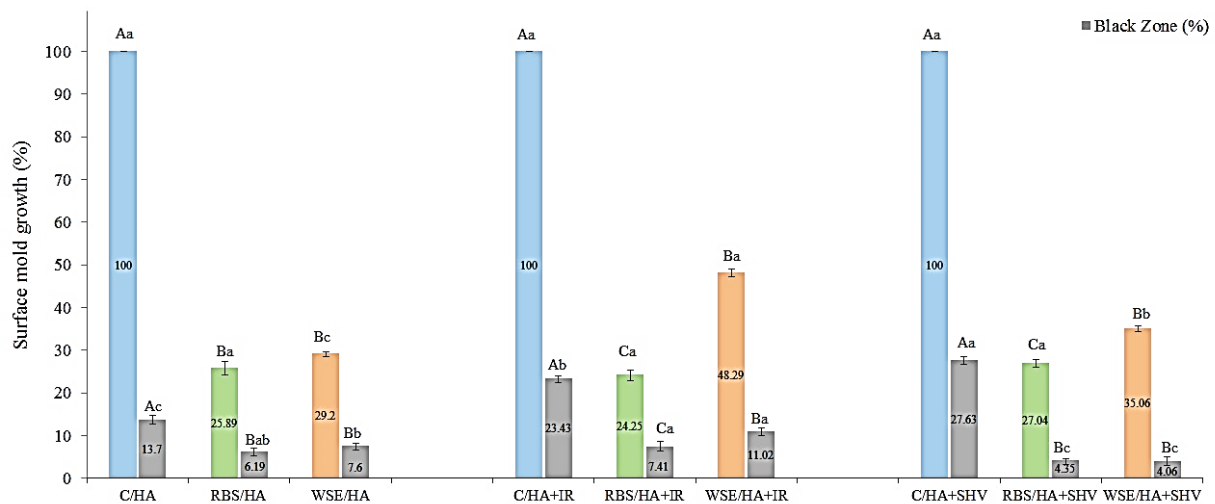


Fig. 2. Surface moldiness and black zone area of the *A. niger* growth on the slices of produced loaf bread samples after seven days of incubation at room temperature in a challenge test as described in the materials and methods section. Different uppercase letters indicate significant difference ($P < 0.05$) among samples containing different formulations and produced using the same baking method., Different lowercase letters show significant differences among the produced breads with the same formulation that were baked using different methods. C: control, RBS: rice bran sourdough, WSE: water soluble extract, HA: hot air, IR: infrared, SHV: superheated vapor.

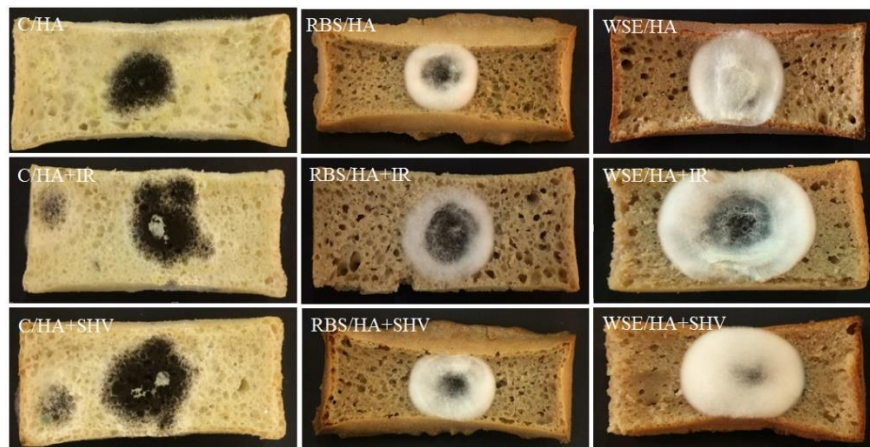


Fig. 3. Surface growth of *A. niger* on the slices of produced loaf bread samples after seven days of incubation at room temperature in a challenge test. C: control, RBS: rice bran sourdough, WSE: water soluble extract, HA: hot air, IR: infrared, SHV: superheated vapor.

antioxidants into antifungal agents during SD fermentation has been approved in previous studies as the key parameters for *in situ* antifungal activity of SD (Sadeghi et al., 2023). A direct correlation between antioxidant and antifungal activities of controlled RBS was also verified in the study of Sadeghi et al. (2019a). Importantly, the black growth zone of *A. niger*, as a sporulation potential index is also related to its ability to produce harmful secondary metabolites like mycotoxins. Accordingly, reduction of the black zone area of *A. niger* growth is an important factor in control of its hazards for consumers' health (Ebrahimi et al., 2020). Although the application of IR in the baking process may reduce the softness of the produced crust, its effect on the reduction of surface moldiness is a promising task. Accordingly, the combined application of IR baking and SD fermentation resulted in the simultaneous modification of bread quality characteristics and its shelf-life. It is hypothesized that the effect of IR baking on the reduction of surface moldiness is associated with the creation of a hard layer on the crust layer that maintains crumb moisture and enhances effective release or distribution of inhibitory metabolites produced during SD fermentation. In addition, indirect effects of IR on SD metabolites to increase their inhibitory activities are also possible. Probably, the HA process can improve the effectiveness of IR heating by increasing its penetration depth.

3.3. Sensory properties

Produced SD breads using HA and also HA + IR baking methods showed higher OA than those of the other samples processed with the same formulation. Among the produced samples, only the control bread produced using the HA + SHV baking method showed higher OA than that of the SD bread processed using the same baking method. At the same time, there was no significant difference ($P > 0.05$) between the aforementioned samples (Fig. 4).

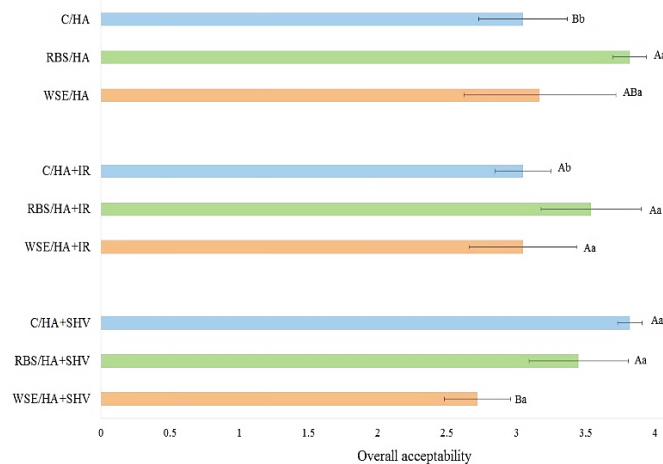


Fig. 4. Overall acceptability of wheat bread samples containing rice bran sourdough or its water-soluble extract produced using different baking strategies compared to the control sample. Different uppercase letters indicate significant difference ($P < 0.05$) among samples containing different formulations and produced using the same baking method (columns with different colors), and different lowercase letters show significant difference among the produced breads with the same formulation that were baked using different methods (columns with the same color). C: control, RBS: rice bran sourdough, WSE: water soluble extract, HA: hot air, IR: infrared, SHV: superheated vapor.

Panirani et al. (2023) concluded that combined IR–conventional resulted in lower baking time in comparison with conventional method. Moreover, this combination showed higher firmness, shearing force and specific volume expansion, as well as higher scores of flavor and taste compared to the other baking methods. It is also reported that the use of high levels of RB in wheat bread had negative effects on the quality characteristics of the product (Espinales et al., 2022). In the study of Özkaya et al. (2018), the addition of RB to the dough significantly increased crumb hardness due to the negative effect of bran on the destruction of gas bubbles. Competition for water absorption by soluble and insoluble fibers that leads to insufficient hydration of gluten and starch, as well as physical effects of bran particles and fiber on the gluten network are also effective factors in this phenomenon (Heiniö et al., 2016). Considering the importance of bioactive compounds in RB, its revalorization using controlled SD fermentation for its application as a natural bakery bio-additive/improver to produce functional clean-label bread has received considerable attention. Different parameters, including the type of starter cultures and their population affect acidification rate and production of microbial metabolites like enzymes and organic acids that subsequently influence crumb textural features and sensory attributes of the produced SD bread (Sadeghi et al., 2019a). It is reported that the positive effect of controlled SD containing cereal's bran on OA of the supplemented products may be attributed to enhanced proteolysis, acidification, and formation of volatile compounds due to the increased ash content of SD (Katina et al., 2006). Production of volatile and non-volatile compounds, as well as flavor active precursors during SD fermentation with positive effects on bread OA, has also been approved. Furthermore, production of reducing sugars leads to the increase of Maillard reaction at low pH of the SD in the presence of hydrolyzed proteins and/or peptides, especially at high temperatures of the baking process (Sadeghi et al., 2023). Moreover, the effects of IR heating on the modification of crust color and crumb moisture content have an undeniable role in the sensory properties of the product. In the same vein, positive correlation between OA and crumb softness was verified by the obtained results in the present study. Accordingly, crumb softness and brown color of the crust in RBS added samples are also important in OA of these products.

4. Conclusion

Fermentation and baking are two main steps in the bread-making process. There is also verified evidence about the positive effects of controlled SD fermentation on quality properties and shelf-life of the produced bread. Accordingly, the selection of a proper SD starter culture and the optimization of fermentation conditions are important in determining the SD potential and subsequent characteristics of the product. In addition, the development of efficient baking methods has crucial effects on the technological functionalities of the produced bread. Importantly, the combined application of effective fermentation and proper baking processes is necessary to enhance different aspects in the processing chain of this staple food and ensure the future of bread processing. Interestingly, the combined application of IR heating and HA baking methods showed promising effects on prolonged shelf-life and improved quality indices of the produced wheat bread supplemented with RBS in the present study. Moreover, comparison among the produced samples revealed potential applications of WSE obtained from controlled fermentation of food by-products (like RB) as a water alternative in bread formulation to improve textural features, sensory

properties and shelf-life of the product, especially baked with a proper baking method. The combined application of controlled fermented RBS and HA + IR baking strategy resulted in a reduction of crumb hardness and surface moldiness in the produced wheat bread. Accordingly, it is possible via application of proper fermentation and baking approaches to reduce bread staling and to extend its mold-free shelf-life, which are the most significant obstacles during the storage period of bread. Considering the importance of mold-free shelf-life, textural features and sensorial attributes of wheat bread, the production of enriched bread with value-added industrial by-products using innovative processing methods like controlled SD fermentation and multiple cooking approaches has received considerable attention. Application of protective starter cultures in controlled SD fermentation in combination with modified plant-based and microbial-based bioactive compounds is also a fundamental issue for the manufacture of functional SD bread in the near future.

CRedit authorship contribution statement

Mahdi Pourrashidi: Formal analysis. Alireza Sadeghi: Conceptualization, Validation, Supervision, Project administration, Writing–review & editing. Aman Mohammad Ziaifar: Data curation, Validation. Mohammad Ghorbani: Data curation, Validation.

Data availability

Data will be made available on request.

Conflict of interest

The authors declare that there is no conflict of interest.

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