DOI: http://dx.doi.org/10.35941/jtaf.26714.8.5.2026.20-34

PHYSICAL AND SENSORY CHARACTERISTICS OF SOURDOUGH BREAD ENRICHED WITH BEETROOT (*Beta vulgaris* L.) POWDER

Monika Rahardjo*, Monang Sihombing, Benedicta Miquella Adisty Wulandari

Food Technology, Faculty of Healthy Science, Satya Wacana Christian University
**)Corresponding author: monika.rahardjo@uksw.edu*

Submission: 16.9.2025; Acceptance: 16.2.2026; Published: 27.4.2026

ABSTRACT

This study investigated the effect of beetroot powder incorporation on the physicochemical, textural, and sensory properties of sourdough bread as part of efforts to develop nutritionally enhanced bakery products with acceptable quality. Four formulations of composite flour of 300 g were prepared: a control (without beetroot powder) and sourdough breads substituion of beetroot powder of 5, 10, and 15%. The physicochemical and textural characteristics were evaluated using texture profile analysis, including hardness, cohesiveness, gumminess, chewiness, adhesiveness, stiffness, and springiness, while sensory attributes were assessed based on appearance, aroma, taste, texture, and overall acceptability. The results demonstrated that increasing beetroot powder levels significantly affected most textural parameters. The highest values of hardness (254.79 gf), gumminess (57.75), and chewiness (4.51) were observed in bread with substitutuion with beetroot powder of 15%, indicating a denser crumb structure at 15% substitution level. Cohesiveness and stiffness increased with beetroot addition, whereas springiness generally decreased, suggesting a trade-off between structural rigidity and elasticity of the dough. Sensory evaluation revealed that the control bread achieved higher scores across most attributes; however, the bread with beetroot powder substitution of 10% recorded the highest overall acceptability among the beetroot-enriched breads (3.90 ± 0.84). Moderate beetroot incorporation enhanced the visual appeal and flavor balance without masking the characteristic of the sourdough. However, excessive beetroot substitution negatively affected sensory quality due to the dominant earthy flavor and less desirable texture. In conclusion, 10% beetroot powder substitution provides an optimal balance between nutritional enhancement, textural quality, and consumer acceptance, offering valuable insights for the formulation of functional sourdough bread products.

Keywords: beetroot powder, functional bakery products, sensory evaluation, sourdough bread, physical analysis

INTRODUCTION

Indonesia is renowned for its rich biodiversity, particularly in the production of tropical fruits; however, beetroot (*Beta vulgaris* L.) stands out because of its unique nutritional benefits and potential applications in food processing. The health implications of beetroot consumption are significant. As indicated in multiple studies, beetroot is a powerhouse of nutrients, including essential vitamins such as vitamin C and minerals, including iron and calcium (Amelia et al., 2024). Its bioactive compounds, particularly betalains and nitrates, contribute significantly to health benefits, such as lowering blood pressure, enhancing physical performance, and reducing oxidative stress (Amelia et al., 2024; Mirmiran et al., 2020). The antioxidant properties of beetroot, attributed to its high phenolic and carotenoid content, further underscore its importance in preventing non-communicable diseases (Liu et al., 2022).

Despite these benefits, beetroot remains underutilized in various culinary applications, particularly in regions such as Indonesia, where its culinary uses have yet to reach their full potential. One avenue for expanding beetroot usage is its incorporation into food products, such as sourdough bread. Beetroot flour, derived from dried beetroot, offers an innovative way to enhance the nutritional profiles of baked goods. The natural colorants and potential health benefits of dietary nitrates found in beetroot flour can improve not only the appearance but also the overall health profile of bread products (Constantin et al., 2025).

Sourdough bread presents several distinct health benefits compared to industrial bread made using instant yeast. A core advantage of sourdough bread lies in its fermentation process, which fundamentally alters its nutritional composition. Sourdough fermentation involves a symbiotic relationship between lactic acid bacteria (LAB) and wild yeasts, which enhances nutrient bioavailability. Studies have indicated that sourdough fermentation can reduce anti-nutritional factors, such as phytic acid, thereby potentially increasing mineral availability in bread (D'Amico et al., 2023; Ribet et al., 2023). Furthermore, sourdough bread has been shown to lower the glycemic response due to the fermentation process, which alters the starch structure (D'Amico et al., 2023; Ribet et al., 2023).

The incorporation of beetroot powder into sourdough bread formulations offers several benefits. Beetroot powder is rich in nutrients, particularly nitrates, antioxidants, and dietary fiber, which enhance the health-promoting properties of sourdough bread. Nitrates from beetroot powder have been shown to improve vascular function and lower blood pressure, potentially conferring additional cardiovascular benefits (Akamine et al., 2023). Furthermore, the earthy sweetness of beetroot can improve the sensory profile of bread, providing an attractive color and taste without the need for added sugars (Alkay et al., 2024). The addition of beetroot powder can also increase the fiber content of bread, supporting better digestive health (Koistinen et al., 2018; Lau et al., 2021). Incorporating beetroot powder into sourdough bread has the potential to enhance not only the visual appeal through vibrant color but also the nutritional benefits due to the natural compounds found in beetroot. Thus, assessing the texture and sensory properties of food is fundamental for predicting consumer acceptance.

Given these considerations, this study aimed to analyze the physical and sensory characteristics of sourdough bread incorporated with beetroot powder. We hypothesized that the incorporation of beetroot powder would positively influence the antioxidant content, texture, volume development, and overall sensory acceptability of the bread. The novelty of this research lies in the integration of a functional, nutrient-rich, and underutilized ingredient into a traditional fermentation-based bread system. This approach contributes to food innovation that aligns with health trends and promotes the value of local biodiversity in the development of functional bakery products.

MATERIALS AND METHODS

Materials

The ingredients used in this study were those used to make sourdough bread, including flour (Bogasari Cakra Kembar brand), sugar (Gulaku Premium brand), sourdough starter (made by the researcher using natural yeast fermented from salak pondoh fruit (Rahardjo and Sihombing, 2023), water (Aqua brand), salt (Dolphin brand), and butter (Anchor unsalted butter).

Experimental Design and Data Analysis

This study was conducted at the Food Processing Laboratory of the Faculty of Health Sciences, Salatiga, from February to March 2025. The methods used in this research were divided into several steps, starting from sourdough bread making, texture analysis, sensory analysis, and data analysis.

Sourdough bread making

The white bread recipe was adapted from Forkish (2022), with the sourdough starter used as a substitute for instant yeast and the incorporation of beet powder in the formulation. The sourdough bread formulations were water 100 g, salt 3 g, butter 15 g, and sourdough starter 50 g, while a 300 g composite flour of wheat and beetroot powder was added. The beetroot powder was substituted in the 300 g wheat flour with a 0, 15, 30 and 45 g, which equivalen to 0, 5, 10, and 15%.

The dry and wet ingredients were first weighed and placed in separate large plastic containers. The two ingredients were then mixed, and the dough was kneaded until smooth by checking the window pane. The dough that has passed the windowpane check

DOI: http://dx.doi.org/10.35941/jtaf.26714.8.5.2026.20-34

is left for bulk fermentation for 2.5-3.0 h, then weighed and cut to adjust to the size of the pan, proofing to the size of the pan height, and finally baked for 25-30 minutes until the surface of the bread is golden brown. Once baked, the bread was analyzed.

Physical analysis

Physical analysis included texture analysis performed using a Texture Analyzer (Lloyd TA Plus) in accordance with the procedure described by Kulthe et al. (2014), where the resulting analysis results were hardness, cohesiveness, springiness, gumminess, chewiness, fracture force, adhesive force, adhesiveness, and stiffness. Each sample was analyzed thrice.

Sensory analysis

Sensory analysis was performed using the acceptance test of preference rating (Meilgaard et al., 2016) of five parameters: appearance, aroma, taste, texture, and overall acceptance. The rating used is a rating with 5 scales (scale 1 is the least preferred and scale 5 is the most preferred). The panelists used for the sensory test were 50 untrained panelists.

Data analysis

All data obtained were analyzed using analysis of variance (ANOVA), then continued with Duncan's Multiple Range Test at $\alpha = 5\%$ to determine the treatment level that provides a real difference. All statistical tests were performed using IBM SPSS Statistics 29 software.

RESULTS AND DISCUSSION

Physical Analysis

The physical analysis of bread texture is essential in both academic research and industrial applications because it provides an objective evaluation of the quality attributes that directly influence consumer acceptance and shelf life. Textural properties, such as hardness, chewiness, springiness, and cohesiveness, serve as indicators of a bread's structural integrity and overall palatability (Wang et al., 2025). The results of the physical analysis in this study are presented in Table 1.

Table 1. Effects of beetroot powder substitution on physical characteristics of breads

Beetroot powder (g)	Hardness (gf)	Cohesiveness	Springiness (mm)	Springiness Index	Gumminess (N)	Chewiness (kgf.mm)	Adhesiveness (N.cm)	Stiffness (gf/cm)
0	129.19±12,25^{A}	0,05±0,017^{A}	12,29±0,30^{C}	1,55±0,12^{B}	6,92±2,36^{A}	0,83±0,27^{A}	0,01±0,01^{A}	0,02±0,00^{A}
15	152.85±79,34^{B}	0,12±0,04^{B}	5,53±2,36^{A}	0,51±0,09^{A}	25,95±15,56^{B}	1,63±1,50^{B}	0,03±0,00^{B}	0,04±0,00^{B}
30	177.96±8,70^{B}	0,12±0,04^{B}	7,82±2,20^{B}	0,54±0,21^{A}	30,33±6,70^{B}	1,67±0,29^{B}	0,05±0,00^{C}	0,02±0,00^{A}
45	254.79±23,09^{C}	0,23±0,08^{C}	7,97±0,73^{C}	0,55±0,04^{A}	57,75±8,87^{C}	4,51±0,75^{C}	0,02±0,00^{A,B}	0,03±0,00^{A,B}

Note: Data (mean±SD) were derived from three replications. The data were analyzed by ANOVA. The data within the same column followed by different letters showed significant difference (DMRT, $p<0,05$). The beetroot powder was added in a 300 g composite flour system of wheat and beetroot.

Hardness is a crucial parameter in the texture analysis of bread that directly correlates with sensory perception and consumer acceptance. It typically refers to the force required to compress or bite through the bread, which affects the overall mouthfeel and enjoyment of the product. The importance of analyzing hardness lies in its ability to provide insights into the quality and freshness of bread, as greater hardness is often associated with staling and reduced palatability (Sahin et al., 2024). Regarding the incorporation of beetroot powder in sourdough bread, studies have indicated that the addition of beetroot powder can result in increased hardness when included in higher amounts. In this study, sourdough bread formulations containing 15% beetroot powder exhibited the highest hardness values. This could be due to several factors, including the impact of beetroot powder on dough structure, moisture content, and interactions with starch and gluten (Ani et al., 2022). Moreover, while the inclusion of sourdough typically mitigates hardness, the contrasting effects of a substantial addition of beetroot powder can improve the structural integrity of the bread, thereby increasing its overall hardness compared to the sourdough bread control (Škrobot et al., 2022; Wolter et al., 2014).

Further exploration indicated that when the percentage of beetroot powder exceeded the 15% threshold, the resulting hardness increased further. This can be attributed to the higher concentrations of beetroot powder, which led to significant changes in the moisture content and gluten structure within the dough, resulting in a denser and firmer crumb structure (Roby et al., 2020). The addition of various components, such as beetroot powder, directly influences the rheological properties of the dough, which ultimately plays a role in determining the textural attributes of the final product (Škrobot et al., 2022).

Cohesiveness in texture analysis, particularly in bread, refers to the ability of a material to maintain its structure during deformation, reflecting the internal interactions among the components of the bread matrix. It is quantitatively assessed through texture analysis as the ratio of the area under the stress-strain curve during the second compression cycle to that of the first (Mondal and Eun, 2023). Cohesiveness is important because it correlates with the perceived freshness and quality of the bread; lower cohesiveness often indicates that the bread is more prone to crumbling or disintegration during consumption (Matos and Rosell, 2012).

In this study, the addition of beetroot powder significantly affected the cohesiveness. Sourdough bread without such incorporation generally exhibits lower cohesiveness due to the basic yeast-fermented dough structure, which may not retain moisture and structural integrity as effectively as formulations enriched with other components, such as beetroot powder. The presence of beetroot powder, especially at a moderate incorporation level of approximately 15%, tends to enhance the gluten network or create new interactions within the dough matrix, leading to increased cohesiveness (Ani et al., 2022).

Springiness refers to the ability of the bread crumb to recover its shape after deformation, which is a measure of the elasticity of the bread texture. This is a significant characteristic of texture analysis, as it correlates with the perceived freshness and quality of the bread. A higher springiness value typically indicates a more desirable and elastic texture that consumers associate with freshness and quality (Matos and Rosell, 2012). The springiness index, often quantified through texture profile analysis (TPA), provides a numerical representation of this property, enabling standardized comparisons of different bread formulations (Alkay et al. 2022).

In the context of sourdough bread, the texture and quality can vary significantly depending on the ingredients. The results of this study indicate that the sourdough bread control typically exhibits a higher springiness index than those containing beetroot powder. This difference can be attributed to the strength of the gluten network, which is often compromised when beetroot powder is added (Aringalayan et al. 2022). The resulting bread may exhibit decreased elasticity and an increased rate of starch retrogradation, negatively impacting textural properties such as springiness (Nasehi et al., 2018).

The incorporation of beetroot powder may initially result in similar or slightly enhanced springiness at lower concentrations; however, increased concentrations can alter the dough matrix, leading to higher water absorption while weakening the gluten framework, which adversely affects the structure. Consequently, springiness decreased as the proportion of beetroot powder increased, leading to a more rigid crumb structure lacking desirable elasticity (Boz, 2015; Ranawana et al., 2016). Nonetheless, some findings suggest that within certain limits, beetroot inclusion can positively affect moisture retention and perceived springiness, particularly when balanced with other formulation factors (Begum et al., 2020).

Gumminess is an essential parameter for analyzing the texture of bread, especially sourdough. It combines elements of cohesiveness and hardness and indicates the energy required to chew a product thoroughly before swallowing. This texture attribute is critical for consumer acceptance and

DOI: http://dx.doi.org/10.35941/jtaf.26714.8.5.2026.20-34

influences the overall quality perception of bread, as it affects the mouthfeel and initial bite. High gumminess can indicate undesirable textural qualities in bread, such as excessive chewiness and density, which can detract from the consumer experience.

In this study, we observed that the incorporation of beetroot powder significantly affected the gumminess measurement. Specifically, sourdough bread without beetroot powder typically exhibits lower gumminess than its beetroot-enhanced counterparts. This difference can be attributed to the structural changes induced by the addition of beetroot powder, which influences the water retention and gluten matrix interactions of the dough. The introduction of beetroot powder into the formulation interacts with the gluten matrix of the dough, leading to increased water binding capacity and improved dough elasticity. These interactions can enhance the cohesiveness of the bread crumb, contributing to a higher gumminess value than that of traditional sourdough formulations.

Moreover, as the percentage of beetroot powder in the bread increased, the gumminess values also increased. This can be explained by the dual mechanisms of enhanced water retention and the formation of a thicker gel-like structure within the bread matrix. Higher concentrations of beetroot powder contribute to more sugar and fiber and promote better hydration of starches and proteins, leading to a more uniform crumb structure that resists crumbling and enhances gumminess. Additionally, the interaction of soluble fibers from beetroot with starch can lead to modified retrogradation behavior during cooling, further positively influencing the bread texture.

Chewiness is a critical textural attribute of bread that significantly influences the overall sensory experience and palatability (Dunteman and Lee, 2023; Tian et al., 2024). It is characterized by resistance to biting and the effort required to chew, contributing to the mouthfeel and enjoyment of the eating experience. A finer balance in chewiness is particularly important in sourdough bread, where texture plays a role in consumer acceptance and may interact with nutritional and metabolic aspects (Nouska et al., 2023).

In this study, the control sourdough bread typically exhibited lower chewiness values than the formulations that incorporated beetroot powder. This difference can be attributed to the unique interactions between sourdough ferments and the structural properties of the bread matrix created during fermentation. It has been established that sourdough fermentation processes can lead to variations in chewiness due to the breakdown of gluten structures and alterations in starch behavior (Terrazas-Avila et al., 2024). Microbial activity and fermentation duration impact these interactions, often resulting in softer bread with reduced chewiness (Naji-Tabasi et al., 2023).

In contrast, incorporating beetroot powder into sourdough bread formulations can enhance the chewiness characteristics. This phenomenon can be explained by the influence of dietary fibers and bioactive compounds present in beetroot powder, which modify the rheological properties of the dough. As the percentage of beetroot powder increased, the hydration of the dough matrix also increased, leading to more cohesive and elastic properties that enhanced chewiness (Rizzello et al., 2012; Tian et al., 2024). The balance between the additional fiber content and moisture retention achieved through beetroot powder is essential, as it can counteract the typical softening of the crumb associated with standard sourdough bread (Zhang et al., 2012). Moreover, studies have indicated that higher levels of dietary fiber, such as those found in beetroot, contribute to a denser crumb structure, which often results in increased chewiness due to reduced gas bubbles during fermentation (Škrobot et al., 2022).

In analyzing the importance of adhesiveness within the context of bread texture, it is crucial to recognize that adhesiveness plays a vital role in the final sensory attributes of bread, influencing consumer acceptance and the overall quality of the bread. Adhesiveness, a texture parameter, refers to the degree of stickiness of the bread, which affects the mouthfeel and can impact mechanical handling during production, ultimately influencing the quality and consumer satisfaction with the product (Raczyk et al., 2022).

The adhesiveness of sourdough bread without beetroot powder tended to be lower than that with beetroot powder. This is primarily because traditional sourdoughs are based on gluten, which contributes to a cohesive and elastic dough, reducing stickiness. In contrast, the addition of beetroot powder modifies the gluten network, introducing additional water-soluble compounds and fibers that alter the rheological properties of the dough (Ani et al., 2022; Raczyk et al., 2022). Consequently, the presence of beetroot powder can lead to an increase in moisture retention and a change in structure, which can enhance the adhesive qualities of the bread, making it feel stickier upon consumption.

Interestingly, the increase in the percentage of beetroot powder further increased the adhesiveness of the bread. This phenomenon can be attributed to several factors such as the following. First, increased beetroot powder adds more soluble fiber and polysaccharides to the dough, which enhances moisture retention and, consequently, increases adhesion properties. Beetroot fibers are known to form hydrophilic interactions with water molecules, thereby increasing the pliability and stickiness of the bread structure (Ani et al., 2022). Additionally, an excess of beetroot powder alters starch gelatinization and fiber matrix formation during baking, leading to a softer, more adhesive crumb texture (Clifford et al., 2015). High fiber content is associated with greater water absorption capabilities, which likely increases the observed adhesiveness during texture analysis (Hobbs et al., 2012; Preethi et al., 2020).

However, in this study, the situation markedly changed when the beetroot powder concentration in the sourdough bread formulation reached approximately 15%, indicating that a decrease in adhesiveness was noted at this threshold. This unexpected reduction in adhesiveness may be due to the interaction of beetroot components with the gluten network within the bread. As the beetroot concentration increases, the gluten structure may become compromised due to the competing hydrophilic properties of beetroot constituents, thereby reducing the stickiness of the dough (Ranawana et al., 2016; Vasconcellos et al., 2016).

In the context of texture analysis of bread, stiffness refers to the resistance of the bread crumb to deformation under an applied force. It is characterized by the maximum force exerted during compression tests, where higher values typically indicate firmer crumb structures. This study indicates that the sourdough bread control generally exhibited lower stiffness than the bread formulations incorporating beetroot powder. The incorporation of beetroot powder alters the physicochemical properties of the dough, leading to changes in water absorption and gluten matrix interactions, which can ultimately affect the stiffness of the final bread product (Adamczyk et al., 2021; Ani et al., 2022). However, as the percentage of beetroot powder in the formulation increased, the stiffness increased, contrary to the initial decrease at lower concentrations (such as 10%). This behavior can be attributed to changes in moisture content, structure, and interactions between starch and fiber components introduced by beetroot powder.

However, when the concentration is adjusted to higher levels, the additional beetroot powder can lead to a firmer crumb due to elevated fiber content or changes in the hydration properties, which enhances gluten development and contributes to a more structured matrix, thus increasing stiffness again at higher concentrations (e.g., 15%) (Ani et al. 2022). This nonlinear response (initial decrease in stiffness at 10% followed by an increase at 15%) highlights the complexity of ingredient interactions in bread formulation and demonstrates the importance of optimizing component ratios to achieve the desired textural characteristics. Moreover, the unique properties of beetroot powder, such as its high dietary fiber content, can significantly modify the structure and texture of the bread crumb, thereby impacting consumer acceptance and sensory outcomes (Ani et al., 2022).

Sensory Analysis

Sensory analysis is crucial in bread research and journal writing because it

DOI: http://dx.doi.org/10.35941/jtaf.26714.8.5.2026.20-34

provides a comprehensive evaluation of a product's overall quality, encompassing flavor, aroma, texture, and appearance, attributes that may not be fully captured by chemical or instrumental methods alone. Sensory methods can account for human perceptions, such as flavor intensity and overall acceptability, thus offering a more holistic view of consumer experience (Elía, 2011). The results of the sensory analysis are presented in Table 2.

Table 2. Effects of beetroot powder substitution on sensory characteristics of breads

Beetroot powder (g)	Appearance	Aroma	Taste	Texture	*Overall*
0	4.50±0.68^{C}	3.90±0.84^{C}	4.14±0.88^{C}	3.86±0.81^{B}	4.16±0.77^{C}
15	3.78±0.93^{A}	3.60±0.90^{A}	4.00±0.93^{B}	3.92±0.83^{B}	3.82±0.83^{B}
30	3.80±0.97$^{A, B}$	3.78±0.89^{B}	4.14±0.86^{C}	3.96±0.83^{B}	3.90±0.84$^{B, C}$
45	3.86±1.01^{B}	3.76±0.94^{B}	3.12±1.04^{A}	3.66±0.89^{A}	3.74±0.94^{A}

Note: Data (mean±SD) were derived from 150 sensory responses. The data were analyzed by ANOVA. The data within the same column followed by different letters showed significant difference (DMRT, p<0,05). The beetroot powder was added in a 300 g composite flour system of wheat and beetroot.

In sensory analysis, the appearance of bread plays a crucial role, as it directly influences consumer acceptance and overall perception of quality. Studies emphasize that sensory attributes, including appearance, significantly affect the acceptability of various bread types, as consumers often rely on visual characteristics, such as color and shape, before making a purchasing decision (Callejo, 2011). Appearance not only dictates initial impressions but also informs consumers about taste and quality expectations (Sahin et al., 2024).

In this study, it was observed that the sourdough bread control (without additional ingredients such as beetroot powder) received higher appearance ratings than those incorporated with beetroot powder. This may be attributed to the color and visual texture modifications imparted by the food coloring effect of beetroot. Although beetroot has nutritional benefits, it can alter the perceived freshness and wholesomeness of bread, potentially lowering its sensory appeal (Hernández-Figueroa et al., 2024; Katsi et al., 2021). The traditional visual characteristics associated with sourdough bread, including crust coloration and crumb structure, are often perceived as more desirable by consumers, leading to higher ratings for the control sample (Katsi et al., 2021).

Interestingly, as the percentage of beetroot powder in the bread formulation increased, the appearance rating also increased. This phenomenon can result from the enhanced color depth and visual contrast provided by beetroot powder. Vivid coloration may attract consumers by presenting a unique and innovative product, thus increasing its aesthetic appeal (Nasir et al., 2020; Sahin et al., 2024). Additionally, incorporating vegetable powders, such as beetroot, can generate curiosity, particularly among health-conscious consumers who appreciate the added nutritional value. However, to balance this appeal with sensory attributes such as texture and aroma, it is essential that the percentage of beetroot does not compromise other critical factors that contribute to the overall sensory profile of the bread (Sahin et al., 2024).

Aroma plays a crucial role in the sensory analysis of bread, influencing consumer acceptance and enjoyment. In the context of bread, particularly sourdough, aroma arises from a complex interplay of fermentation, Maillard reactions, and the biochemical activity of yeast and lactic acid bacteria (LAB) during leavening (Aslankoohi et al., 2016; Winters et al., 2019; Zolfaghari et al., 2017). These biochemical processes generate a bouquet of volatile compounds, including alcohols, esters, and aldehydes, which contribute to the characteristic flavor profiles that consumers expect from high-quality bread (Heitmann et al., 2017; Mietton et al., 2022). Moreover, studies have shown that a desirable aroma profile may enhance the overall sensory acceptance of a product, as the complexity of aroma compounds can elevate the perception of freshness and quality in baked goods (Callejo, 2011; Paravisini et al., 2019).

When comparing the aroma profiles of sourdough bread to those of sourdough incorporated with beetroot powder, the fundamental difference lies in the presence and ratios of aromatic compounds produced during fermentation and subsequent baking. Typically, sourdough bread exhibits a stronger and more appealing aroma owing to the fermentation process, which produces more volatile compounds, such as hexanal and 2-nonenal, that are associated with positive sensory evaluations (Birch et al., 2013; Katsi et al., 2021). In contrast, the incorporation of beetroot powder, particularly at lower concentrations, can introduce different aroma profiles that may be less acceptable to consumers. However, it has been observed that at moderate levels, beetroot powder can add complexity to the aroma without overpowering it. This preference might be linked to the balance of sweetness and earthy notes introduced by beetroot, which can complement the traditional sourdough aroma (Corona et al., 2016; Moskowitz et al., 2012).

The observation that a higher percentage of beetroot powder initially enhanced aroma ratings, while a threshold (approximately 15%) caused a decline in rating values, can be explained through sensory perception theory and the saturation point of aromatic compounds. Lower concentrations of beetroot powder may result in a pleasant additive effect, where the earthy sweetness of beetroot harmonizes with the characteristic smell of sourdough (Paravisini et al., 2019; Pico et al., 2017). However, exceeding the optimal concentration may overpower the inherent aromas of sourdough with excessively earthy and vegetal notes, detracting from the overall complexity appreciated by consumers (Haque et al., 2020; Suha et al., 2021).

Taste parameters in the sensory analysis of bread are critical for understanding consumer preferences and product acceptability. It encompasses various attributes, including sweetness, sourness, bitterness, and saltiness, which contribute to the overall flavor profile of bread products. This parameter is particularly important in sourdough bread, as the fermentation process significantly influences these sensory attributes owing to the activity of lactic acid bacteria (LAB) and yeast. LAB produce organic acids during fermentation, contributing to the sour taste characteristic of sourdough bread while enhancing its texture and nutritional quality (Zhao and Gänzle, 2016). Consumer preferences often favor bread varieties with distinct tastes that align with personal preferences, making the tasting component paramount for product development (Škrobot et al., 2022; Supasil et al., 2022).

When exploring why the taste rating of conventional sourdough bread was higher than that of sourdough bread incorporated with 5% and 15% beetroot powder, it is essential to consider the impact of beetroot's earthy flavor and sweetness. Studies have shown that the addition of beetroot powder may introduce off-flavors or distract from the typical sour notes expected in sourdough, potentially lowering the overall taste (Harth et al., 2018). Moreover, while 10% beetroot powder incorporation harmonizes well with the traditional sourdough flavor, with no significant departure from the sourdough bread control taste profile, higher concentrations likely overshadow the sour notes through excessive sweetness or earthy flavors, thereby diminishing consumer preference.

The unique case of 10% beetroot powder, which reflected taste ratings similar to those of traditional sourdough, can be attributed to a balance in which the added sweetness complements rather than overwhelms the sour flavors contributed by LAB fermentation. This balance showcases how specific ingredient levels can affect sensory properties while maintaining desirable sourdough characteristics (Hanis-Syazwani et al., 2018). Conversely, the inconsistent results with the 15% incorporation level may indicate that at this ratio, the earthy and sweet flavors from the beetroot become overwhelming, leading to lower product acceptance. This trend has been observed in other studies, where the

DOI: http://dx.doi.org/10.35941/jtaf.26714.8.5.2026.20-34

excessive incorporation of certain ingredients negatively impacted sensory characteristics (Roby et al., 2020).

In sensory analysis, the texture of bread is a vital attribute that influences consumer preferences and overall acceptability. It encompasses various measurable qualities, such as hardness, chewiness, cohesiveness, and springiness, which collectively determine the mouthfeel and enjoyment of the product. The texture of bread significantly affects its quality and consumer appeal, as it is linked to the freshness, internal structure, and mechanical properties of the crumb, which are influenced by fermentation and baking conditions (Sidari et al., 2020).

When comparing sourdough bread with varying concentrations of beetroot powder, it was observed that bread with 5% and 10% beetroot exhibited higher texture parameter values than traditional sourdough bread without additives. This can be attributed to the interplay between the gluten network and non-gluten components introduced by beetroot powder. The addition of these powders influences moisture retention and elasticity, softening the texture when used within these limits (Ani et al., 2022).

However, when 15% beetroot powder was incorporated into the formulation, the texture parameter values were the lowest. This adverse effect occurred due to excessive amounts of beetroot powder, leading to the disruption of the gluten matrix necessary for maintaining the structure of the bread. A saturation point is reached where microbial and enzymatic activities essential for proper fermentation are hindered, resulting in a less cohesive and more fragile crumb structure (Popescu et al., 2022; Raczyk et al., 2022). This suggests a negative impact on the textural integrity of bread, as high concentrations dilute the effectiveness of gluten, which is crucial for texture.

In sensory analysis, overall acceptability is a critical parameter that reflects consumers' perceptions of a product based on a combination of attributes, including taste, aroma, texture, and visual appeal. This parameter is particularly important in the evaluation of bread, as it serves as an overall indicator of consumer preference and satisfaction, which are essential for successful marketability (Tafti et al., 2013). In this study, sourdough bread made solely with wheat flour typically scored higher in overall acceptability than sourdough bread incorporating beetroot powder because of the inherent properties of sourdough, which enhance flavor complexity, texture, and moistness. The distinct sour notes and improved fermentation aspects contribute to a more balanced sensory profile that is generally favored over the potentially overpowering flavors or altered textures introduced by the beetroot powder.

Regarding the incorporation of beetroot powder in sourdough bread formulations, a 10% addition yielded the highest overall acceptability scores compared to lower (5%) or higher (15%) concentrations. This phenomenon can be attributed to the optimal balance of added flavor, color, and potential nutritional benefits, without overwhelming the bread's base character. Sensory assessments have indicated that at this concentration, the aroma, texture, and appearance are generally viewed as appealing, likely because this level enhances the visual appeal and flavor without introducing excessive earthiness or sweetness (Ani et al., 2022).

The 5% formulation may not provide sufficient distinctive qualities of beetroot for consumers to appreciate its presence, leading to lower acceptability scores. However, at 15%, beetroot integration may cause textural changes that detract from the chewy and satisfying qualities expected from sourdough bread (Babaoğlu et al., 2021). Overall, these findings underscore the importance of ingredient balance and sensory integration of various components in bread formulation to effectively cater to consumer preferences and optimize overall acceptability.

CONCLUSION

The incorporation of beetroot powder into sourdough bread significantly altered both the textural and sensory attributes, with effects proportional to the concentration used. Higher beetroot levels increased hardness, gumminess, chewiness, and stiffness due to the enhanced fiber content and altered gluten network interactions. However, they also reduced springiness and, at excessive levels, negatively impacted the aroma, taste, and overall acceptability. Sensory analysis confirmed that 10% beetroot powder substitution achieved the best balance, offering improved color and distinctive flavor while maintaining a desirable sourdough texture and palatability. Conversely, 15% incorporation led to an undesirable dense crumb structure and reduced consumer liking. Therefore, for the development of functional bread products, moderate beetroot enrichment (approximately 10%) is recommended to optimize nutritional benefits without compromising quality or consumer preference.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Directorate of Research and Community Service, Satya Wacana Christian University, for funding this research and enabling its successful completion.

REFERENCES

Adamczyk, G., Ivanišová, E., Kaszuba, J., Bobel, I., Khvostenko, K., Chmiel, M., Falendysh, N., 2021. Quality assessment of wheat bread incorporating chia seeds. Foods 10, 2376. https://doi.org/10.3390/foods10102376

Akamine, I.T., Mansoldo, F.R.P., Vermelho, A.B., 2023. Probiotics in sourdough bread fermentation: current status. Fermentation 9, 90. https://doi.org/10.3390/fermentation9020090

Alkay, Z., Falah, F., Cankurt, H., Dertli, E., 2024. Exploring the Nutritional Impact of Sourdough Fermentation: Mechanisms and Functional Potential. Foods 13, 1732. https://doi.org/10.3390/foods13111732

Alkay, Z., Yılmaz, M.T., Can, A.M., İspirli, H., Dertli, E., 2022. The effect of flours of different immature cereal grains on sourdough and sourdough bread: Microbiological, rheological, textural and sugar profiles. Food Processing Preservation 46. https://doi.org/10.1111/jfpp.17097

Amelia, R.T., Ardyanto, T.D., Sari, Y., 2024. Investigation of antioxidant activity from beetroot juice (Beta vulgaris L) as a healthy drink for the prevention of non-communicable disease. Aceh. Nutri. J. 9, 82. https://doi.org/10.30867/action.v9i1.1444

Ani, I.F., Adetola, A.B., Alfa, T., Ajuzie, N.C., Ibagere, O.F., Akinlade, A.R., Omotoye, A.A., 2022. Quality assessment of bread made from whole wheat flour and beetroot powder. jdan 13, 11–18. https://doi.org/10.4314/jdan.v13i1.2

Aringalayan, N.M., Singh, R., Mishra, S., Thangalakshmi, S., Kaur, B.P., Bajpai, V.K., Singh, A., 2022. Optimization and characterization of malted proso millet (*Panicum miliaceum*) based bread. eFood 3, e29. https://doi.org/10.1002/efd2.29

Aslankoohi, E., Herrera-Malaver, B., Rezaei, M.N., Steensels, J., Courtin, C.M., Verstrepen, K.J., 2016. Non-Conventional Yeast Strains Increase the Aroma Complexity of Bread. PLoS ONE 11, e0165126. https://doi.org/10.1371/journal.pone.0165126

Begum, Y.A., Baishya, P., Das, M.J., Chakraborty, S., Deka, S.C., 2020. Novel approach for the development of dietary fibre-anthocyanin enriched functional bread from culinary banana bract. Int J of Food Sci Tech 55, 3455–3462. https://doi.org/10.1111/ijfs.14678

Babaoğlu, H.C., Tontul, S.A., Akin, N., 2021. Fiber enrichment of sourdough bread by inulin rich Jerusalem artichoke powder. Food Processing Preservation 45. https://doi.org/10.1111/jfpp.15928

Birch, A.N., Petersen, M.A., Hansen, Å.S., 2013. The aroma profile of wheat bread crumb influenced by yeast concentration and fermentation temperature. LWT - Food Science and Technology 50, 480–488. https://doi.org/10.1016/j.lwt.2012.08.019

Boz, H., 2015. The effects of *Cephalaria syriaca* flour on dough and bread containing different levels of barley flour. Journal of Food Quality 38, 328–336. https://doi.org/10.1111/jfq.12155

Callejo, M.J., 2011. Present situation on the descriptive sensory analysis of bread: On the descriptive sensory analysis of bread. Journal of Sensory Studies 26, 255–268. https://doi.org/10.1111/j.1745-459X.2011.00341.x

Clifford, T., Howatson, G., West, D., Stevenson, E., 2015. The potential benefits of red beetroot supplementation in health and disease. Nutrients 7, 2801–2822. https://doi.org/10.3390/nu7042801

Constantin, O.E., Stoica, F., Lazăr (Mistrianu), S., Andronoiu, D.G., Turturică, M., Stănciuc, N., Rațu, R.N., Croitoru, C., Râpeanu, G., 2025. A Sustainable approach: Repurposing red beetroot peels for innovative meringue products. Foods 14, 317. https://doi.org/10.3390/foods14020317

Corona, O., Alfonzo, A., Ventimiglia, G., Nasca, A., Francesca, N., Martorana, A., Moschetti, G., Settanni, L., 2016. Industrial application of selected lactic acid bacteria isolated from local semolinas for typical sourdough bread production. Food Microbiology 59, 43–56. https://doi.org/10.1016/j.fm.2016.05.006

D'Amico, V., Gänzle, M., Call, L., Zwirzitz, B., Grausgruber, H., D'Amico, S., Brouns, F., 2023. Does sourdough bread provide clinically relevant health benefits? Front. Nutr. 10. https://doi.org/10.3389/fnut.2023.1230043

Dunteman, A.N., Lee, S., 2023. Characterizing the effect of sodium reduction and monosodium glutamate supplementation on white and multigrain breads. Journal of Food Science 88, 1128–1143. https://doi.org/10.1111/1750-3841.16460

Elía, M., 2011. A procedure for sensory evaluation of bread: protocol developed by a trained panel: bread sensory analyses. Journal of Sensory Studies 26, 269–277. https://doi.org/10.1111/j.1745-459X.2011.00342.x

Forkish, K., 2022. Evolutions in Bread: artisan pan breads and dutch-oven loaves at home, First edition. ed. Ten Speed Press, [Berkeley] California.

Hanis-Syazwani, M., Boarinwa, I.F., Lasekan, O., Muhammad, K., 2018. Influence of starter culture on the physicochemical properties of rice bran sourdough and physical quality of sourdough bread. Food Res. 2, 340–349. https://doi.org/10.26656/fr.2017.2(4).045

Haque, M.M., Hossain, Md.A., Zim, A.F.M.I.U., Aziz, Md.A., Hoque, Md.A., 2020. Quality Analysis of Soy Bread and Its Effects on Glycemic Index. Curr Res Nutr Food Sci 8, 79–87. https://doi.org/10.12944/CRNFSJ.8.1.07

Harth, H., Van Kerrebroeck, S., De Vuyst, L., 2018. Impact of process conditions on the microbial community dynamics and metabolite production kinetics of teff sourdough fermentations under bakery and laboratory conditions. Food Science & Nutrition 6, 1438–1455. https://doi.org/10.1002/fsn3.690

Heitmann, M., Zannini, E., Axel, C., Arendt, E., 2017. Correlation of flavor profile to sensory analysis of bread produced with different *Saccharomyces cerevisiae* originating from the baking and beverage industry. Cereal Chem 94, 746–751. https://doi.org/10.1094/CCHEM-03-17-0044-R

Hernández-Figueroa, R.H., Mani-López, E., Ramírez-Corona, N., López-Malo, A., 2024. Optimizing Lactic Acid Bacteria Proportions in Sourdough to Enhance Antifungal Activity and Quality of Partially and Fully Baked Bread. Foods 13, 2318. https://doi.org/10.3390/foods13152318

Hobbs, D.A., Kaffa, N., George, T.W., Methven, L., Lovegrove, J.A., 2012. Blood pressure-lowering effects of beetroot juice and novel beetroot-enriched bread products in normotensive male subjects. Br J Nutr 108, 2066–2074. https://doi.org/10.1017/S0007114512000190

Katsi, P., Kosma, I.S., Michailidou, S., Argiriou, A., Badeka, A.V., Kontominas, M.G., 2021. Characterization of artisanal spontaneous sourdough wheat bread from central greece: evaluation of physico-chemical, microbiological, and sensory properties in relation to conventional yeast leavened wheat bread. Foods 10, 635. https://doi.org/10.3390/foods10030635

Koistinen, V.M., Mattila, O., Katina, K., Poutanen, K., Aura, A.-M., Hanhineva, K., 2018. Metabolic profiling of sourdough fermented wheat and rye bread. Sci Rep 8. https://doi.org/10.1038/s41598-018-24149-w

Kulthe, A.A., Pawar, V.D., Kotecha, P.M., Chavan, U.D., Bansode, V.V., 2014. Development of high protein and low calorie cookies. J Food Sci Technol 51, 153–157. https://doi.org/10.1007/s13197-011-0465-2

Lau, S.W., Chong, A.Q., Chin, N.L., Talib, R.A., Basha, R.K., 2021. Sourdough microbiome comparison and benefits. Microorganisms 9, 1355. https://doi.org/10.3390/microorganisms9071355

Liu, Y., Sabadash, S., Duan, Z., Gao, D., 2022. Influence of different microwave-assisted drying methods on the physical properties, bioactive compounds and antioxidant activity of beetroots. EEJET 1, 15–25. https://doi.org/10.15587/1729-4061.2022.251942

Matos, M.E., Rosell, C.M., 2012. Relationship between instrumental parameters and sensory characteristics in gluten-free breads. Eur Food Res Technol 235, 107–117. https://doi.org/10.1007/s00217-012-1736-5

Meilgaard, M.C., Civille, G.V., Carr, B.T., 2016. Sensory evaluation techniques, Fifth edition. ed. CRC Press, Taylor & Francis Group, CRC Press is an imprint of the Taylor & Francis Group, an Informa business, Boca Raton.

Mietton, L., Samson, M.-F., Marlin, T., Godet, T., Nolleau, V., Guezenec, S., Segond, D., Nidelet, T., Desclaux, D., Sicard, D., 2022. Impact of leavening agent and wheat variety on bread organoleptic and nutritional quality. Microorganisms 10, 1416. https://doi.org/10.3390/microorganisms10071416

Mirmiran, P., Houshialsadat, Z., Gaeini, Z., Bahadoran, Z., Azizi, F., 2020. Functional properties of beetroot (*Beta vulgaris*) in management of cardio-metabolic diseases. Nutr Metab (Lond) 17. https://doi.org/10.1186/s12986-019-0421-0

Mondal, S.C., Eun, J., 2023. Effects of burdock root flour (*Arctium lappa*) on yeast fermentation power, microstructure, quality, and storability of bread made with partial replacement of wheat flour. Cereal Chem 100, 696–

707. https://doi.org/10.1002/cche.10647

Moskowitz, M.R., Bin, Q., Elias, R.J., Peterson, D.G., 2012. Influence of endogenous ferulic acid in whole wheat flour on bread crust aroma. J. Agric. Food Chem. 60, 11245–11252. https://doi.org/10.1021/jf303750y

Naji-Tabasi, S., Shahidi-Noghabi, M., Davtalab, M., 2023. Optimization of fermentation conditions in Barbari bread based on mixed whole flour (barley and sprouted wheat) and sourdough. Food sci. technol. int. 29, 126–137. https://doi.org/10.1177/10820132211063972

Nasehi, B., Jaldani, S., Barzegar, H., 2018. Optimization of physical and imaging properties of flat bread enriched with quinoa flour. Nutr Food Sci Res 5, 33–42. https://doi.org/10.29252/nfsr.5.3.33

Nasir, S., Allai, F.M., Gani, M., Ganaie, S., Gul, K., Jabeen, A., Majeed, D., 2020. Physical, Textural, Rheological, and Sensory Characteristics of Amaranth-Based Wheat Flour Bread. International Journal of Food Science 2020, 1–9. https://doi.org/10.1155/2020/8874872

Nouska, C., Hatzikamari, M., Matsakidou, A., Biliaderis, C.G., Lazaridou, A., 2023. Enhancement of textural and sensory characteristics of wheat bread using a chickpea sourdough fermented with a selected autochthonous microorganism. Foods 12, 3112. https://doi.org/10.3390/foods12163112

Paravisini, L., Sneddon, K.A., Peterson, D.G., 2019. Comparison of the Aroma profiles of intermediate wheatgrass and wheat bread crusts. Molecules 24, 2484. https://doi.org/10.3390/molecules24132484

Pico, J., Bernal, J.L., Gómez, M., 2017. Influence of different flours and starches on gluten-free bread aroma. J Food Sci Technol 54, 1433–1441. https://doi.org/10.1007/s13197-017-2562-3

Popescu, L., Ceșco, T., Gurev, A., Ghendov-Mosanu, A., Sturza, R., Tarna, R., 2022. Impact of apple pomace powder on the bioactivity, and the sensory and textural characteristics of yogurt. Foods 11, 3565. https://doi.org/10.3390/foods11223565

Preethi, R., Deotale, S.M., Moses, J.A., Anandharamakrishnan, C., 2020. Conductive hydro drying of beetroot (*Beta vulgaris* L.) pulp: Insights for natural food colorant applications. J Food Process Engineering 43, e13557. https://doi.org/10.1111/jfpe.13557

Raczyk, M., Kruszewski, B., Zachariasz, E., 2022. Effect of tomato, beetroot and carrot juice addition on physicochemical, antioxidant and texture properties of wheat bread. Antioxidants 11, 2178. https://doi.org/10.3390/antiox11112178

Rahardjo, M., Sihombing, M., 2023. Pemanfaatan air botani dari buah salak pondoh (*Salacca zalacca* var pondoh) untuk pembuatan roti tawar sourdough. TP 14, 269–279. https://doi.org/10.35891/tp.v14i2.4295

Ranawana, V., Campbell, F., Bestwick, C., Nicol, P., Milne, L., Duthie, G., Raikos, V., 2016. Breads fortified with freeze-dried vegetables: quality and nutritional attributes. Part II: Breads not containing oil as an ingredient. Foods 5, 62. https://doi.org/10.3390/foods5030062

Ribet, L., Dessalles, R., Lesens, C., Brusselaers, N., Durand-Dubief, M., 2023. Nutritional benefits of sourdoughs: A systematic review. Advances in Nutrition 14, 22–29. https://doi.org/10.1016/j.advnut.2022.10.003

Rizzello, C.G., Coda, R., Mazzacane, F., Minervini, D., Gobbetti, M., 2012. Micronized by-products from debranned durum wheat and sourdough fermentation enhanced the nutritional, textural and sensory features of bread. Food Research International 46, 304–313. https://doi.org/10.1016/j.foodres.2011.12.024

Roby, B.H.M, Muhialdin, B.J., Abadl, M.M.T., Nor, N.A.M, Marzlan, A.A., Lim, S.A.H., Mustapha, N.A., Hussin, A.S.M., 2020. Physical properties, storage stability, and consumer acceptability for sourdough bread produced using encapsulated kombucha sourdough starter culture. Journal of Food Science 85, 2286–2295. https://doi.org/10.1111/1750-3841.15302

Sahin, M., Ozgolet, M., Cankurt, H., Dertli, E., 2024. Harnessing the role of three Lactic Acid Bacteria (LAB) strains for type ii sourdough production and influence of sourdoughs on bread quality and maillard reaction products. Foods 13, 1801. https://doi.org/10.3390/foods13121801

Sidari, R., Martorana, A., Zappia, C., Mincione, A., Giuffrè, A.M., 2020. Persistence and effect of a multistrain starter culture on antioxidant and rheological properties of novel wheat sourdoughs and bread. Foods 9, 1258. https://doi.org/10.3390/foods9091258

Škrobot, D., Dapčević-Hadnađev, T., Tomić, J., Maravić, N., Popović, N., Jovanov, P., Hadnađev, M., 2022. Techno-functional performance of emmer, spelt and khorasan in spontaneously fermented sourdough bread. Foods 11, 3927. https://doi.org/10.3390/foods11233927

Suha, M., Humaina, A., Nafuha Niyaz, H., Naila, A., 2021. Sensory properties of white bread enriched with lemon juice, corn flour and baking soda. MNJR 9, 38–47. https://doi.org/10.62338/1bnwd591

Supasil, R., Suttisansanee, U., Santivarangkna, C., Tangsuphoom, N., Khemthong, C., Chupeerach, C., On-nom, N., 2022. Improvement of sourdough and bread qualities by fermented water of asian pears and assam tea leaves with co-cultures of *Lactiplantibacillus plantarum* and *Saccharomyces cerevisiae*. Foods 11, 2071. https://doi.org/10.3390/foods11142071

Tafti, A.G., Peighambardoust, S.H., Hesari, J., Bahrami, A., Bonab, E.S., 2013. Physico-chemical and functional properties of spray-dried sourdough in breadmaking. Food sci. technol. int. 19, 271–278. https://doi.org/10.1177/1082013212452415

Terrazas-Avila, P., Palma-Rodríguez, H.M., Navarro-Cortez, R.O., Hernández-Uribe, J.P., Piloni-Martini, J., Vargas-Torres, A., 2024. The effects of fermentation time on sourdough bread: An analysis of texture profile, starch digestion rate, and protein hydrolysis rate. Journal of Texture Studies 55, e12831. https://doi.org/10.1111/jtxs.12831

Tian, X., Fang, Q., Zhang, X., Yu, S., Dai, C., Huang, X., 2024. Visualization of moisture content, reducing sugars, and chewiness in bread during oral processing based on hyperspectral imaging technology. Foods 13, 3589. https://doi.org/10.3390/foods13223589

Vasconcellos, J., Conte-Junior, C., Silva, D., Pierucci, A.P., Paschoalin, V., Alvares, T.S., 2016. Comparison of total antioxidant potential, and total phenolic, nitrate, sugar, and organic acid contents in beetroot juice, chips, powder, and cooked beetroot. Food Sci Biotechnol 25, 79–84. https://doi.org/10.1007/s10068-016-0011-0

DOI: http://dx.doi.org/10.35941/jtaf.26714.8.5.2026.20-34

Wang, C., Wang, Y., Wang, N., Ren, J., 2025. Influence of onion peel extract on the dough characteristics of high-gluten wheat flour and the quality of bread. Foods 14, 1618. https://doi.org/10.3390/foods14091618

Winters, M., Panayotides, D., Bayrak, M., Rémont, G., Viejo, C.G., Liu, D., Le, B., Liu, Y., Luo, J., Zhang, P., Howell, K., 2019. Defined co-cultures of yeast and bacteria modify the aroma, crumb and sensory properties of bread. J Appl Microbiol 127, 778–793. https://doi.org/10.1111/jam.14349

Wolter, A., Hager, A.-S., Zannini, E., Czerny, M., Arendt, E.K., 2014. Impact of sourdough fermented with Lactobacillus plantarum FST 1.7 on baking and sensory properties of gluten-free breads. Eur Food Res Technol 239, 1–12. https://doi.org/10.1007/s00217-014-2184-1

Zhang, J.H., Zeng, J., Li, G.L., Gao, H.Y., 2012. Effect of stearoyl lactate calcium-sodium as promising improvers for wheat bread. AMR 554–556, 1406–1409. https://doi.org/10.4028/www.scientific.net/AMR.554-556.1406

Zhao, C.J., Gänzle, M.G., 2016. Synthesis of taste-active γ-glutamyl dipeptides during sourdough fermentation by *Lactobacillus reuteri*. J. Agric. Food Chem. 64, 7561–7568. https://doi.org/10.1021/acs.jafc.6b02298

Zolfaghari, M.S., Ardebili, S.M.S., Asadi, G.H., Larijani, K., 2017. Effect of sourdough, bakery yeast and sodium bicarbonate on volatile compounds, and sensory evaluation of lavash bread: Effect of sourdough, bakery yeast and sodium bicarbonate. Journal of Food Processing and Preservation 41, e12973. https://doi.org/10.1111/jfpp.12973