Influence of chickpea flour sourdough on technological properties and quality of bakery products

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Keywords:

Bread
Chickpea
Seeds
Flour
Sourdough
Lactic acid bacteria
Fermentation

Article history:

Received 01.10.2025
Received in revised form 20.12.2025
Accepted 31.12.2025

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DOI:
10.24263/2310-1008-2025-13-2-8

Abstract

Introduction. To address the limited biological value of refined wheat bread, this study investigated the technological properties of chickpea flour sourdoughs prepared with selected lactic acid bacteria and their effects on the quality of wheat bakery products.

Materials and methods. Chickpea sourdoughs were prepared from chickpea flour and water (1:1) and inoculated with *Lactiplantibacillus plantarum*, *Lentilactobacillus buchneri*, and their mixed culture, followed by fermentation at 32–35 °C. Sourdough acidity and microbial activity were determined, and wheat bread quality was evaluated based on key technological, physicochemical, and sensory parameters in triplicate experiments.

Results and discussion. Chickpea sourdough fermentation was characterized by a slow initial increase in acidity followed by a sharp rise between 7 and 10 h, reflecting the adaptation and activation of lactic acid bacteria. Maximum microbial activity was observed after 14–16 h of fermentation, whereas further prolongation led to excessive acidification and deterioration of technological properties. Sourdoughs fermented with Lactobacillus buchneri exhibited the highest acidification and gas-forming capacity, indicating intense metabolic activity but with an increased risk of excessive acidity. In contrast, Lactobacillus plantarum showed lower activity under conditions of limited fermentable sugars, resulting in a milder and more neutral aromatic profile but less uniform crumb porosity in the final bread. The use of a mixed starter culture ensured balanced acidification and stable microbial activity. Bread produced with mixed-culture sourdough demonstrated the highest specific volume, improved crumb structure, and superior sensory characteristics. The optimal conditions for chickpea sourdough preparation were identified as 14–16 h of fermentation at 32–35 °C, under which high lactic acid bacteria activity was achieved at a moderate final acidity of 12–16°.

Conclusions. Chickpea flour sourdoughs prepared with selected lactic acid bacteria significantly influenced fermentation behavior and bread quality, with an optimal fermentation time of 14–16 h. A mixed culture of *Lactiplantibacillus plantarum* and *Lentilactobacillus buchneri* provided the most balanced technological and sensory properties, indicating its potential for producing wheat bread enriched with chickpea flour.

ISSN: 2409-4951 (Online), 2310-1008(Print)

Introduction

Analysis of the current bakery assortment reveals a predominance of products manufactured from refined wheat flour of the highest and first grades. Such products are characterized by limited biological value due to an unbalanced amino acid composition, particularly lysine deficiency, as well as a low content of dietary fiber (Buyalska et al., 2020).

With the growing consumer demand for foods with enhanced biological value and functional properties, the incorporation of non-traditional raw materials into bakery production has become increasingly important (Guiné and Florença, 2024; Stabnikova et al., 2021). Numerous studies have focused on enhancing the quality of bread and flour-based confectionery products through the partial replacement of wheat flour with plant ingredients rich in dietary fiber and bioactive compounds (Chochkov et al., 2022; Perea-Escobar et al., 2025; Sanfilippo et al., 2023; Shevchenko et al., 2023; Stabnikova et al., 2022).

In this context, the application of legume flours in bakery technology represents a promising approach to improving the nutritional and biological quality of bakery products, in line with current food industry trends focused on health-oriented foods (Sadohara et al., 2022; Stabnikova and Paredes-López, 2024).

One of the most promising types of legume raw materials for the enrichment of bakery products is chickpea flour (Shrivastava and Chakraborty, 2018; Xing et al., 2021). Chickpeas typically contain 19–29 g of protein per 100 g, which is more than twice the amount found in cereal grains. Of particular value is the high content of lysine, an essential amino acid that is deficient in wheat flour. In addition, chickpeas are rich in dietary fiber, the content of which may exceed 20 g/100 g depending on the biotype, as well as in unsaturated fatty acids such as linoleic and oleic acids. Chickpea flour is also characterized by a low glycemic index (Santos et al., 2018; Wang et al., 2021).

Partial replacement of wheat flour with chickpea flour in bread formulations improves the nutritional value of the product due to increased contents of dietary fiber and protein, as well as amino acid complementation between legumes and cereals. However, the incorporation of chickpea flour into bread formulations also leads to technological challenges, manifested by a reduction in loaf volume, deterioration of crumb texture, and the appearance of a characteristic legume flavor. In wheat bread formulations containing chickpea flour, it is advisable to limit the replacement level to up to 10% of wheat flour. At this level of substitution, the dough, despite reduced extensibility, is characterized by good resistance to mechanical stress. Higher levels of chickpea flour addition result in increased dough stickiness and decreased dough stability, leading to bread with a firmer crumb and a significantly reduced volume (Boukid et al., 2019; Ouazib et al., 2016). Such effects of chickpea flour are primarily due to a reduction in gluten content in the dough as a result of partial replacement of wheat flour, and secondarily to conformational changes in gluten proteins associated with a significant increase in β-sheet structures within the protein matrix (Kotsiou et al., 2022; Mohammed et al., 2012).

Chickpea flour, similarly, to flours derived from other legumes, contains a range of antinutritional compounds, including oligosaccharides (raffinose, stachyose), phytic acid, and trypsin inhibitors, which may negatively affect nutrient absorption and cause undesirable physiological responses such as flatulence. To reduce the content of these antinutritional compounds, the application of pretreatment methods to legume raw materials is considered advisable when they are used in bakery production. For this purpose, processes such as fermentation, soaking, and germination are commonly applied. Fermentation of raw materials in the form of sourdoughs is regarded as the most effective approach for improving their nutritional profile, owing to a reduction in antinutrient concentration and enhanced bioavailability of macro- and micronutrients (Kahala et al., 2021; Kaur and Prasad, 2021).

ISSN: 2409-4951 (Online), 2310-1008(Print)

In breadmaking, sourdoughs based on wheat or rye flour are traditionally used. The use of sourdoughs prepared from non-traditional crops represents a promising direction in the development of baking technologies, providing a range of functional and technological advantages (Cheliabiieva and Sosedova, 2018; Conte, 2018).

Advances in sourdough biotechnology highlight the functional roles of lactic acid bacteria and yeast and their symbiotic interactions, resulting in a complex microbial ecosystem that maximizes the use of flour components (Arora et al., 2021). Additionally, the establishment of a mature and functional sourdough is influenced by several factors, including flour type, water, additional ingredients (Gobbetti et al., 2016), enzymatic activity (Ercolini et al., 2013), and fermentation conditions (De Vuyst et al., 2014; Minervini et al., 2014). Among these factors, the type of flour used is considered a critical determinant (Pontonio et al., 2017; Rizzello et al., 2016).

The integration of legume fermentation processes into modern breadmaking is predominantly achieved through the use of spontaneously fermented sourdoughs Mykhonik and Hetman, 2022). However, in industrial bakery production, the application of spontaneously fermented sourdoughs has certain limitations. Such sourdoughs are characterized by slower and less predictable fermentation dynamics, which largely depend on environmental conditions, including temperature, humidity, and raw material composition. Moreover, during their maintenance, there is an increased risk of contamination by undesirable microorganisms, which may adversely affect the quality and stability of the final product (Arora et al., 2021).

In contrast, inoculated sourdoughs obtained by the addition of specifically selected yeast and lactic acid bacteria strains provide a higher level of control over the fermentation process. This approach enables faster and more reproducible fermentation, reduces the risk of microbiological contamination, and enhances the technological safety and stability of the process. Consequently, inoculated sourdoughs are particularly effective under industrial conditions, where consistent process parameters and controlled fermentation times are required (Lima et al., 2023).

Fermentation — both spontaneous (Type-I) and guided by selected lactic acid bacteria (Type-II) has been shown to improve the nutritional profile of legumes by degrading anti-nutritional factors and enhancing protein digestibility, fiber bioavailability, and phenolic compounds (Curiel et al., 2015; Gobbetti et al., 2019; Rizzello et al., 2017; Schettino et al., 2019). Moreover, fermentation positively affects the technological and sensory properties of legume flour, promoting their use in industrial applications.

Fermentation of chickpea flour using selected lactic acid bacteria strains is an effective biotechnological approach for the targeted modification of its nutritional, biological, and functional–technological properties. The application of *Lactiplantibacillus plantarum* (formerly *Lactobacillus plantarum*), *Limosilactobacillus fermentum*, *Pediococcus pentosaceus*, and *Levilactobacillus brevis* ensured active microbial development in the chickpea flour substrate and intensive acidification, resulting in a pH decrease from 6.2–6.5 to 4.0–4.5 after 24–48 h of fermentation at approximately 30 °C. The reduction in pH, combined with the proteolytic activity of lactic acid bacteria, leads to partial hydrolysis of chickpea proteins, manifested by an increased content of free amino acids and low-molecular-weight peptides. The most pronounced proteolytic effect was observed when *Lactiplantibacillus plantarum* was used, indicating its high potential for improving the digestibility and biological value of plant protein. At the same time, the degradation of protein–polyphenol complexes was observed, which limit amino acid availability in non-fermented chickpea flour. A significant outcome of lactic acid fermentation is the reduction of antinutritional compounds, particularly phytic acid, whose content decreases by 40–60% depending on the strain applied. This effect is attributed to the activation of endogenous chickpea phytases under acidic conditions, as well as

ISSN: 2409-4951 (Online), 2310-1008(Print)

to the phytase activity of certain lactic acid bacteria strains, primarily *Lactiplantibacillus plantarum* and *Pediococcus pentosaceus*. This leads to increased bioavailability of mineral elements, particularly iron, zinc, and calcium. In addition, fermentation contributes to the partial inactivation of protease inhibitors and a reduction in the content of raffinose and stachyose oligosaccharides. Lactic acid fermentation also has a positive effect on the antioxidant properties of chickpea flour. This is associated with the release of phenolic compounds from their bound forms as a result of enzymatic transformations, which further enhances the functional value of the product (Chiacchio et al., 2025; Di Biase et al., 2019; Sáez et al., 2022).

Thus, lactic acid fermentation is an effective biotechnological tool for modifying the protein and mineral composition of chickpea flour, reducing the content of antinutritional factors, and improving its technological properties. Fermented chickpea flour can therefore be considered a promising ingredient for the development of functional bakery products. At the same time, the use of chickpea flour fermented with selected lactic acid bacteria strains in breadmaking technology requires further investigation of the technological properties of chickpea sourdough and its influence on the quality characteristics of the finished products.

Materials and methods

Materials

Pure cultures of lactic acid bacteria *Lactiplantibacillus plantarum* (formerly *Lactobacillus plantarum*) UKM B-2694 (hereinafter *L. plantarum*) and *Lentilactobacillus buchneri* (formerly *Lactobacillus buchneri*) UKM B-2666 (hereinafter L. *buchneri*), obtained from the Ukrainian Collection of Microorganisms of the D.K. Zabolotny Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine, were used for the preparation of chickpea sourdough. Chickpea flour (TM "Sto Pudov") with an initial acidity of 10° was used for dough preparation.

Preparation of chickpea sourdough samples

During the study, three sourdough samples were prepared and inoculated with different lactic acid bacteria cultures: sample 1 - *L. buchneri*; sample 2 - *L. plantarum*; sample 3 - a mixed culture of *L. plantarum* and *L. buchneri*.

To prepare the sourdough, chickpea flour and water at a temperature of 30–32 °C were mixed at a ratio of 1:1, and 1 ml of a suspension of lyophilized lactic acid bacteria culture was added per 100 g of the water–flour mixture (Table 1).

Table 1

Formulation for chickpea sourdough preparation

Raw material	Sample 1	Sample 2	Sample 3
Chickpea flour, g	100.0	100.0	100.0
Water, g	100.0	100.0	100.0
Pure culture of *L. buchneri*, ml	2.0	-	1.0
Pure culture of *L. plantarum*, ml	-	2.0	1.0

The samples were fermented at 32–35 °C. During fermentation, the acidity of the sourdough and the activity of lactic acid bacteria were monitored periodically.

ISSN: 2409-4951 (Online), 2310-1008(Print)

Preparation of dough samples

Wheat bread was baked with the addition of 10% chickpea flour (control) as a partial replacement for wheat flour. Experimental samples were prepared with the addition of chickpea sourdough containing the same amount of chickpea flour as in the control sample. Dough mixing was performed using an ESHER dough mixer (Italy) at first speed for 4–6 min and at second speed for 6–8 min. The initial dough temperature was 25–26 °C. The dough was left to ferment for 90 min at a temperature of 30–32 °C. After fermentation, dough pieces were shaped and placed in a proofing chamber (Sveba Dahlin AB DC-21, Sweden) at 35–38 °C, after which they were baked in a deck oven (Sveba Dahlin AB DC-21, Sweden) at 210–230 °C for 30–35 min.

Methods

Sourdough acidity. A 5 g sample of sourdough was triturated with 50 ml of distilled water in a porcelain mortar until a homogeneous suspension was obtained. Subsequently, 3–5 drops of a 1% alcoholic phenolphthalein solution were added, and the suspension was titrated with 0.1 mol/l NaOH until a pale pink coloration persisted for 20–30 s. The acidity value was calculated by multiplying the volume of 0.1 mol/l NaOH consumed by 2 (Godunko et al., 2024).

Lactic acid bacteria activity. A 20 g sample of sourdough was mixed with 40 ml of water at 40 °C until a homogeneous suspension was obtained. From this suspension, 10 ml aliquots were transferred into two test tubes. To the test sample, 1 ml of a 0.05% aqueous methylene blue solution was added, while the second test tube served as a control. The tubes were incubated at 40 °C.

The activity of lactic acid bacteria was assessed based on the time (in minutes) required for decolorization of the test sample. Activity was classified as low when decolorization occurred within 90–100 min, high at 35–50 min, and very high at 7–25 min (Godunko et al., 2024).

Specific volume of bread. Bread volume was determined using the traditional rapeseed displacement method. Measurements were performed in duplicate, and deviations between parallel determinations did not exceed 5%. The specific volume of bread was calculated by dividing the loaf volume by its weight and expressed to the nearest 0.01 ml/g (Zhu et al., 2016).

Porosity of bread. The porosity of bread reflects the volume of the pores in a certain volume of the crumb, expressed as a percentage to the total volume (Verheyen et al., 2015).

Bread shape stability (H/D). The height and diameter of hearth bread were measured using a ruler or a specialized measuring device. The shape stability index (H/D) was calculated as the ratio of product height (H) to product diameter (D) (Drobot et al., 2015).

Bread crumb moisture content. Two metal weighing dishes were each loaded with 5 g of ground bread crumb. The dishes containing the crumb were placed in a drying oven (SESh-3M) and dried for 45 min at a temperature of 130 °C. After drying, the dishes were transferred to a desiccator and cooled for 20–120 min. The cooled dishes were then weighed, and the mass fraction of moisture in the bread crumb was calculated (Drobot et al., 2015):

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$$W = ((m_1 - m_2)/m) \times 100\%,$$

where m is the mass of the bread crumb sample before drying; m_1 is the mass of the box with the sample before drying; m_2 is the mass of the box with the sample after drying.

Crust and crumb color of bread. The bread slice crumb and crust colour were analysed using a colorimeter Chroma meter CR-200 (Minolta, Osaka, Japan). Three colour-coordinates were recorded: (1) $L*$ (dark-light); (2) $a*$ (green-red) and (3) $b*$ (blue-yellow) as well as the total colour difference ($\Delta E*$) which was subsequently recorded to understand human perceivable differences (e.g., less than one: non-perceivable differences, one to three: minor perceivable differences and more than three: perceivable differences) (Norton et al., 2025):

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2},$$

where L_0^*, a_0^*, and b_0^* are the color parameters of the control sample, and L^*, a^*, and b^* are those of the experimental sample. Each parameter was measured at five different points, and the mean value was used for calculations.

Statistical analysis

The reliability of the obtained results was ensured by performing the experiments in triplicate. The experimental data were subjected to statistical analysis using standard Microsoft Office software packages.

Results and discussions

Chickpea sourdough development using pure cultures of lactic acid bacteria

The study of the dynamics of acidity accumulation, as the main indicator characterizing sourdough maturation, showed that at the initial stage of sourdough development the accumulation of acidity in all sourdough samples occurred slowly and uniformly. The data on acidity accumulation in the sourdough samples are presented in Table 2.

Table 2

Acidity of sourdoughs during fermentation, degrees

Fermentation time, h	Sample 1 (*L. buchneri*)	Sample 2 (*L. plantarum*)	Sample 3 (mixture of *L. plantarum* and *L. buchneri*)
0	5.0	5.0	5.0
4	6.0	6.0	6.0
7	7.0	7.0	7.0
10	12.0	11.8	12.0
14	15.0	14.0	15.0
16	16.0	14.7	15.5
24	25.5	23.0	25.0

ISSN: 2409-4951 (Online), 2310-1008(Print)

During the first four hours of fermentation, an increase of 1 degree of acidity was observed in all sourdough samples. Further evaluation of acidity during sourdough fermentation showed that a significant increase in acidity occurred after seven hours of fermentation: in the period from 7 to 10 h of fermentation, that is, over three hours, the acidity increased by 5 degrees. After the 10th hour of fermentation, a change in the dynamics of acidity accumulation was observed. In the sourdough samples containing lactic acid bacteria *L. buchneri* and the mixed culture of *L. buchneri* and *L. plantarum*, acidity accumulation proceeded similarly, whereas in the sourdough containing *L. plantarum* the acidity at 14 h of fermentation reached 14 degrees, which was 1 degree lower than in the other samples. At 16 h of fermentation, the acidity in the sourdough sample containing *L. plantarum* was also lower than in the sample containing *L. buchneri* (by 1.3 degrees); a slightly lower rate of acidity accumulation was also observed in the sample containing the mixed culture of lactic acid bacteria.

Fermentation of the sourdough for 24 h demonstrated the preservation of the differences in acidity development among the samples. After 24 h, sourdoughs with high acidity values in the range of 23.0–25.5 degrees were obtained. Considering the aim of the study to obtain chickpea sourdough suitable for bread production with a lower acidity level, a parallel investigation of the activity of lactic acid bacteria in these sourdoughs was conducted. The results of this investigation are presented in Table 3.8.

Determination of the activity of lactic acid bacteria in the experimental sourdoughs showed that high and very high activity levels were reached after 14–16 h of fermentation. Prior to this time, the activity of lactic acid bacteria in the sourdoughs remained low.

During the study, it was found that in sourdoughs inoculated with *L. buchneri* and with the mixed culture of *L. buchneri* and *L. plantarum*, the activity of lactic acid bacteria was very high, whereas in the sourdough sample inoculated with *L. plantarum* the activity was high; moreover, the duration of indicator discoloration during the analysis of this sourdough was twice as long as in the other samples.

Table 3

Activity of lactic acid bacteria in sourdoughs during fermentation

Fermentation time, h	**Sample 1 (*L. buchneri*)**	**Sample 2 (*L. plantarum*)**	**Sample 3 (mixture of *L. plantarum* and *L. buchneri*)**
4	>100 min	>100 min	>100 min
7	>100 min	>100 min	>100 min
10	70-100 min (low)	70-100 min (low)	70-100 min (low)
14	21 min (very high)	48 min (high)	24 min (very high)
16	18 min (very high)	40 min (high)	21 min (very high)

The observed differences in the activity of lactic acid bacteria may be attributed to the different adaptability of these cultures to the chickpea flour substrate and to differences in their metabolic fermentation mechanisms. Chickpea flour contains a limited amount of sugars required for the growth and metabolic activity of *L. plantarum* strains. In particular, chickpea flour contains 0.05–0.2% glucose, 0.02–0.15% fructose, 0.3–1.2% sucrose, and 0.05–0.3% maltose. When the content of fermentable sugars in the sourdough is low, *L. plantarum* bacteria reduce their activity, in contrast to *L. buchneri*, which are heterofermentative cultures capable of metabolizing other nutrients.

ISSN: 2409-4951 (Online), 2310-1008(Print)

In addition, *L. buchneri* bacteria produce acetic acid as a result of fermentation processes, in contrast to *L. plantarum*, which predominantly produce lactic acid. This also contributes to the formation of higher acidity values (Di Biase et al., 2019). In the sourdough sample obtained using a combination of these two cultures, the lower activity of *L. plantarum* is compensated by the activity of *L. buchneri*, which promotes the achievement of acidity and lactic acid microbiota activity at a level comparable to that of the sample containing *L. buchneri* alone.

Chickpea flour is characterized by a relatively low content of simple sugars available for lactic acid fermentation, the total amount of which, according to literature data, does not exceed 0.4–1.8% of dry matter. The major proportion of carbohydrates is represented by raffinose-family oligosaccharides, which cannot be directly utilized by most lactic acid bacteria (Begum et al., 2023). The limited availability of fermentable sugars, combined with the high buffering capacity of chickpea raw material, determines the specific features of sourdough acidification and may explain the lower titratable acidity values observed in sourdoughs inoculated with homofermentative cultures of *L. plantarum*.

Therefore: (1) the duration of chickpea sourdough development using pure cultures of *L. plantarum* and *L. buchneri* was 14–16 h at 32–35 °C; (2) the final acidity of mature sourdoughs was 13–16 ° for sourdoughs inoculated with *L. buchneri*, 12–15 ° for sourdoughs inoculated with *L. plantarum*, and 13–16 ° for sourdoughs inoculated with the combined culture of *L. plantarum* and *L. buchneri*; (3) lactic acid bacteria activity at this stage was high or very high: very high for sourdoughs with *L. buchneri*, high for sourdoughs with *L. plantarum*, and very high for sourdoughs with the combined culture; (4) the mature sourdough exhibited the appearance of a well-aerated, loose mass.

It should be noted that the transformation of sourdough consistency into such a loosened structure occurred from the 14th hour of fermentation, since sensory evaluation at the 12th hour of fermentation indicated that the sourdough was still a rather viscous, flowable mass. Comparative visual evaluation of the consistency and appearance of the sourdoughs showed that, in the case of fermentation with *L. buchneri*, the sourdough exhibited the loosest and most aerated consistency, containing a large number of large gas cells in its structure. This is due to the fact that, in addition to organic acids, *L. buchneri* actively produce carbon dioxide. The sourdough sample prepared using *L. plantarum* had a less loose consistency; the gas cells in its structure were smaller in size and fewer in number, and the overall consistency was denser, since these bacteria predominantly produce lactic acid and only very small amounts of carbon dioxide. The sourdough sample prepared with the mixed culture of lactic acid bacteria exhibited a consistency similar to that of the *L. buchneri* sample; however, the gas cells were smaller, resulting in a lower degree of aeration. This effect was expected considering the influence of *L. plantarum* on sourdough consistency; thus, this sample occupied an intermediate position between the two above-mentioned sourdoughs.

The obtained mature sourdoughs were evaluated based on sensory characteristics (Table 4).

According to the sensory evaluation, the aroma of all sourdoughs was acceptable for this type of semi-finished product, with no signs of unpleasant odors; the aroma characteristics were within the range typical of sourdough products. It was established that the sourdough fermented with *L. buchneri* exhibited a pleasant alcoholic–acidic aroma, with slight fruity notes reminiscent of apple and legume nuances. The sourdough fermented with *L. plantarum* was characterized by a lactic aroma with pronounced legume notes. The sourdough prepared with the mixed culture exhibited the most intense and complex aroma, which was more difficult to characterize: a distinct alcoholic–acidic character with lactic acid notes was perceived, along with a slight aroma reminiscent of sauerkraut; legume notes similar to green pea aroma were also detected.

ISSN: 2409-4951 (Online), 2310-1008(Print)

Table 4

Quality indicators of chickpea sourdoughs

Indicator	Sample 1 (*L. buchneri*)	Sample 2 (*L. plantarum*)	Sample 3 (mixture of *L. plantarum and L. buchneri*)
Initial acidity, degrees	5.0	5.2	5.2
Final acidity, degrees	15.6	14.2	15.0
Aroma	Alcoholic–acidic with slight fruity notes; faint legume aroma	Pronounced lactic aroma initially, followed by the development of a chickpea–nutty aroma, more intense than in the *L. buchneri* sample	More intense than in the other samples; immediately perceived alcoholic–acidic aroma combined with lactic and slight sauerkraut notes, followed by chickpea–nutty notes
Taste	Sour, with a slight legume aftertaste	Sour, the perception of acidity diminishes rapidly, with a legume aftertaste	The sourest among all samples; no lingering aftertaste

Thus, it was established that the selected lactic acid bacteria cultures ensure the fermentation of chickpea flour during sourdough preparation and, within 14–16 h of fermentation of the semi-finished product, promote the production of a sourdough characterized by high lactic acid bacteria activity. However, this activity is not sufficient for the sourdough to fully perform the function of a leavening agent in the dough system. Therefore, when using these sourdoughs, it is advisable to include compressed yeast in the formulation of bakery products, while the sourdoughs will primarily serve as acidifying agents and carriers of aromatic compounds.

Effect of chickpea sourdoughs inoculated with different lactic acid bacteria strains on bread quality

Considering the technological recommendations for the preparation of chickpea sourdoughs established above, it became necessary to investigate the effect of sourdoughs produced under these conditions on the quality of wheat bread. The results of the analysis are presented in Table 5.

Figures 1 and 2 present the baked products: the control sample, the sample with the addition of chickpea flour, and the sample with the addition of sourdough.

According to the research results, the bread containing chickpea flour exhibited medium and fine porosity with pore walls of medium thickness. The crumb was elastic. In all samples containing sourdough, an increase in crumb elasticity was observed, and the crumb acquired a more cream-colored appearance.

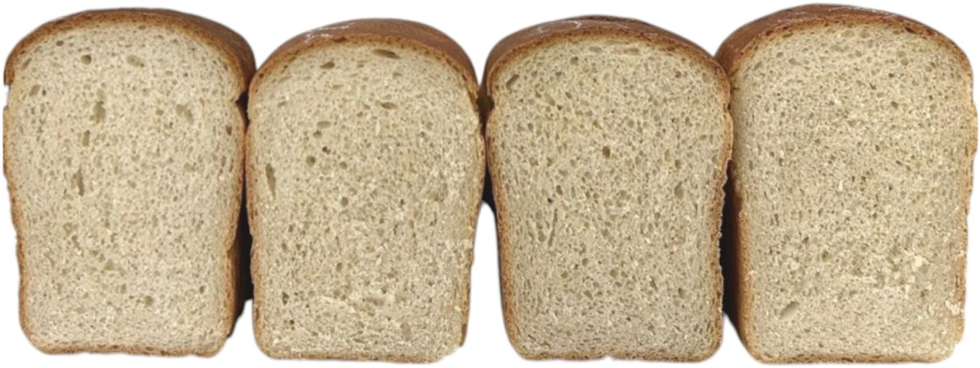
ISSN: 2409-4951 (Online), 2310-1008(Print)

Table 5

Sensory and physicochemical characteristics of the bread

Parameter	**Control with chickpea flour**	***L. buchneri* sourdough**	***L. plantarum* sourdough**	**Mixture of *L. plantarum* and *L. buchneri***
Shape	Regular, without cracks	Regular, without cracks	Regular, without cracks	Regular, without cracks
Surface	Smooth	Smooth	Smooth	Smooth
Crust color	Dark golden	Golden	Dark golden	Golden
Crumb characteristics	Cream-colored; non-uniform porosity, predominantly medium with inclusions of large pores; medium cell wall thickness; elastic	Cream-colored; non-uniform medium porosity; medium cell wall thickness, with inclusions of large pores; more elastic than the control	Cream-colored; uniform medium porosity; medium cell wall thickness; more elastic than the *L. buchneri* sample	Cream-colored; non-uniform fine porosity; thick cell walls, with inclusions of medium and large pores; more elastic than the *L. buchneri* and *L. plantarum* samples
Taste	Slight legume aftertaste	Slight acidity perceived at the beginning of mastication; very mild legume flavor; pleasant aftertaste	Less sour than the *L. buchneri* sample; legume flavor more pronounced	Slight sourness perceived at the beginning of mastication; flavor more harmonious and pleasant than in the *L. buchneri* sample
Aroma	More pronounced legume aroma	Acidic, with almost imperceptible legume notes	Less intense, with slight acidity and somewhat legume notes	More intense aroma with pronounced acidity
Moisture, %	42.6	42.3	42.2	42.4
Acidity, degrees	1.8	2.8	2.2	2.8
Porosity, %	67	66	67	69
Specific volume, ml/g	2.5	2.3	2.5	2.8
Shape stability, H/D	0.44	0.44	0.38	0.42

ISSN: 2409-4951 (Online), 2310-1008(Print)



Control with chickpea flour | With *L. buchneri* sourdough | With *L. plantarum* sourdough | With *L. buchneri* + *L. plantarum* sourdough

Figure 1. Pan bread products

Control with chickpea flour | With *L. buchneri* sourdough | With *L. plantarum* sourdough | With *L. buchneri* + *L. plantarum* sourdough

Figure 2. Free-standing bread

In breads prepared with *L. buchneri* sourdough and with the mixed culture, the crumb structure became finer compared to the control, with the formation of pore walls of medium thickness. In breads prepared with *L. plantarum* sourdough, the porosity was markedly non-uniform, predominantly fine, with thicker pore walls and inclusions of large pores.

The control bread was characterized by a pleasant wheat bread aroma with slight notes of legume flour. In samples containing sourdough, the aroma was pleasant and more pronounced. Despite the use of an accelerated dough preparation method, the aroma of the products was rich, resembling that obtained by a long fermentation process. In breads with sourdough, a slight acidic aftertaste was perceived, while legume notes were not detected. The crumb of bread prepared with *L. plantarum* sourdough was coarser during mastication. Based on sensory evaluation, the breads prepared with *L. buchneri* sourdough and with the mixed-culture sourdough were more attractive.

To ensure a more objective evaluation of the color characteristics of the breads (crust and crumb), the colorimetric method in the CIELab system was applied (Table 6).

ISSN: 2409-4951 (Online), 2310-1008(Print)

Table 6

Colorimetric parameters of breads determined in the CIELab system

Bread with	L* (crust)	L* (crumb)	a* (crust)	a* (crumb)	b* (crust)	b* (crumb)	ΔE
Control with chickpea flour	47.45	65.10	15.10	0.55	21.83	14.32	-
sourdough (*L. buchneri*)	48.82	63.25	14.80	5.01	22.65	13.47	5.7
sourdough (*L. plantarum*)	48.93	64.18	14.44	2.50	21.59	10.65	4.0
sourdough (*L. buchneri* + *L. plantarum*)	47.85	62.43	15.60	3.14	21.07	14.34	6.2

The L* parameter was used to evaluate the degree of darkening of the crust and crumb within a range from 0 (black) to 100 (white). The L* values for the crust varied only slightly (47.45–48.93), indicating the absence of a significant effect of sourdough type on crust color intensity. All samples were subjected to similar conditions of non-enzymatic browning reactions during baking.

In the crumb, the L* value decreased slightly in samples prepared with sourdough, indicating moderate crumb darkening when sourdough was used; this effect was most pronounced for the mixed culture, which is consistent with the intensification of fermentation processes and acid formation.

The value of the parameter characterizing changes in the color spectrum within the green–red range (a*) indicates that the control bread containing chickpea flour exhibited a very low a* value (0.55), corresponding to an almost neutral, “cool” tone. The use of sourdoughs resulted in an increase in this parameter, indicating the formation of warmer cream–reddish hues in the crumb, most pronounced when the heterofermentative sourdough (*L. buchneri*) was used. This effect is associated with the formation of fermentation products and changes in the protein–starch matrix.

Evaluation of the b* parameter is related to the identification of color tones within the blue–yellow range. All chickpea-containing breads were characterized by elevated b* values, corresponding to the yellow hue inherent to legume raw materials. The *L. plantarum* sourdough significantly reduced the intensity of the yellow hue, whereas the mixed culture maintained it at a level comparable to the chickpea-containing control.

Thus, the color evaluation of the breads showed the following: control with chickpea flour: the lightest crumb, minimal red component (a*), and a pronounced yellow tone (b*), typical of non-fermented chickpea flour; *L. buchneri* sourdough: resulted in a warmer and slightly darker crumb color, with moderate retention of the yellow hue; *L. plantarum* sourdough: provided the smallest deviation in lightness compared to the control and reduced the yellow tone, forming a more neutral crumb color; mixed *L. buchneri* + *L. plantarum* sourdough: caused the greatest crumb darkening while preserving an intense yellow tone, indicating a synergistic effect of the cultures on the pigment profile.

ISSN: 2409-4951 (Online), 2310-1008(Print)

Evaluation of the physicochemical parameters showed that the largest product volume was characteristic of the bread prepared with the mixed-culture sourdough. This bread also exhibited good shape stability of the hearth bread.

Conclusions

It was established that the type of lactic acid bacteria significantly influences the dynamics of acid accumulation, microbial activity, and the properties of chickpea sourdoughs. Sourdough based on *Lentilactobacillus buchneri* exhibited the highest acidity and microbial activity, while sourdough prepared with *Lactiplantibacillus plantarum* showed lower acidity and moderate activity, producing a milder and more neutral aromatic profile. Sourdough prepared with the mixed culture combined the advantages of both strains, providing an optimal balance of acidity, aroma, and technological properties. The optimal conditions for chickpea sourdough preparation were 14–16 h of fermentation at 32–35 °C, under which high or very high lactic acid bacteria activity was achieved at a moderate final acidity of 12–16 °. Chickpea flour–based sourdoughs function primarily as acidifying agents and carriers of aromatic compounds rather than as complete leavening agents, making their use in combination with compressed baker's yeast advisable. The most balanced physicochemical and sensory characteristics of the finished bakery products were obtained using sourdough prepared with the mixed culture of *Lactiplantibacillus plantarum* and *Lentilactobacillus buchneri*.

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Cite:

Ukr J Food Sci Style

Godunko Ye., Bondarenko Yu. (2025), Influence of chickpea flour sourdough on technological properties and quality of bakery products, *Ukrainian Journal of Food Science*, 13(2), pp. 211–226, https://doi.org/10.24263/2310-1008-2025-13-2-8

APA Style

Godunko Ye., & Bondarenko Yu. (2025). Influence of chickpea flour sourdough on technological properties and quality of bakery products. *Ukrainian Journal of Food Science, 13*(2), 211–226. https://doi.org/10.24263/2310-1008-2025-13-2-8

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