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Effects of sourdough on rheological properties of dough, quality characteristics and staling time of wholemeal wheat croissants

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PAPER

Abstract

The present study aimed to obtain good quality croissants from wholegrain wheat flour using baking sourdoughs prepared from single starter cultures of *Pediococcus acidilactici* 02P108 (PA), *Pediococcus pentosaceus* SM2D17 (PP) and *Enteroccocus durans* 09B374 (ED) as an attempt to overcome the usual negative effects of the wholegrain flour on the characteristics of this specific bakery product group. Results showed that the addition of sourdough in the wholegrain wheat dough had similar performance as that of conventional baker's yeast regarding the rheological characteristics of dough. The dynamic viscosity of all sourdough-leavened samples remained higher than that of the control sample at all tested shear rates. A positive effect of sourdoughs used on the development of baking dough was observed in terms of specific volume improvement, higher degree of softening, and reduced baking loss. However, these positive effects were found as strain-specific. The use of *Enteroccocus durans* 09B374-made sourdough showed the most distinguished sensory characteristics and the best results regarding croissant staling during storage. The study demonstrated that sourdoughs used in wholemeal wheat croissant dough had positive effect on the quality characteristics and shelf-life of products. However, strain selection proved as of key importance for the successful production of wholemeal wheat croissants.

Keywords: croissant, lactic acid bacteria, rheology, sourdough, wholegrain flour

Introduction

The baking quality of wholemeal flour is inferior compared with white flour because of the reduced yield of wet gluten, unevenness of flour particles, higher content of dietary fibre, etc. Wholemeal flour has a higher water absorption attributed to the higher content of damaged starch and bran. Dough kneading is short and this problem is observed in the production process of croissants (Zhao *et al.,* 2017). Products made from wholemeal flour have a poorer organoleptic profile. In general, wholemeal bakery products have a darker colour, specific taste, smaller specific volume and denser texture. The distinct flavour is attributed to the higher amount of volatile compounds and amino acids (Brouns *et al*., 2012).

The following different types of leavening agents could be used in breadmaking: food additives (sodium bicarbonate and ammonium carbonate), baker's yeast (*Saccharomyces cerevisiae*) and sourdough. Commercial baker's yeast is used in breadmaking for centuries with the aim to improve the sensorial characteristics of bread (Lahue *et al*., 2020). Continuous research on isolation of *Saccharomyces cerevisiae* strains from various traditional products has been carried out for the selection of strains with valuable technological properties for breadmaking. In a study conducted by Angelov *et al.* (1996), the strain *Saccharomyces cerevisiae* 0511/3 was selected for potential commercial applications based on its biosynthetic and baking properties. In a screening study exploring different indigenous sources in Nepal, three strains of *Saccharomyces cerevisiae* (ENG, MUR3B and SUG1) that were isolated from grape (Murcha) and sugarcane demonstrated the best effect in dough fermentation and baking (Kardi *et al*., 2017).

Lactic acid bacteria (LAB) are traditionally used in breadmaking as a fermenting agent in sourdoughs. Sourdough fermentation is the oldest biotechnological process applied to leaven bakery goods and to improve bread texture, aroma and shelf-life (Cappa *et al*., 2016; Sun *et al*., 2020; Teleky *et al*., 2020). A number of studies have shown that the use of sourdough as leavening agent improves the processing characteristics of gluten-free doughs (Matos and Rosell, 2015; Moore *et al*., 2006, 2007; Ngemakwe *et al*., 2015; Venturi *et al*., 2012; Zlateva and Karadzhov, 2008). In some cases, this effect may be attributed to the potential of LAB to secrete extracellular polysaccharides (EPS), which could be a beneficial alternative to conventional thickeners used to modify viscosity, structure and stability of a wide range of foods (Moroni *et al*., 2009). These EPS may act as a substitute for hydrocolloids employed as food additives, and therefore the application of LAB could be a cost-efficient approach to improve the rheology of gluten-free doughs. In addition, these EPS have a beneficial prebiotic effect on intestinal microbiome by selectively stimulating the growth of beneficial microorganisms. The positive effect on the quality of bread and bakery products from wholemeal wheat flour (WWF) prepared by adding sourdough is also due to the softening effect on bran particles during fermentation, which leads to less obstruction of gluten network and formation of gas cells in baking dough (Rieder *et al*., 2012).

Nutritionists agree that the increased intake of wholegrain bakery products is beneficial for consumer's health (Ma *et al*., 2021); therefore, some researchers explore the use of wholemeal flour in the production of croissants, biscuits, crackers, crostini and pizza dough (Albagli *et al*., 2021; Li *et al*., 2013; Niccolai *et al*., 2019). Sourdough fermentation is increasingly used in seeking solutions to the technological challenges of using wholegrain flour, since many authors report positive effects on the quality of wholegrain wheat flour products. Alioğlu and Ozülkü (2021) explored the incorporation of wholegrain wheat flour in short dough biscuits by sourdough fermentation. The authors achieved a hardness value of the wholegrain flour sourdough biscuits which was not significantly different from that of the control biscuits, while the direct addition of wholegrain wheat flour increased the hardness value.

Many other scientific reports demonstrated that sourdough fermentation may affect positively the functional characteristics of leavened baked goods. By pre-treating raw materials, sourdough fermentation may stabilise or increase the functional value of wheat germ (part of a wheat kerne) and bran fractions (Gobetti *et al*., 2014). Sourdough fermentation may decrease the glycaemic response of bread, improve the properties of dietary fibre complex, and increase the uptake of minerals, vitamins and phytochemicals (Gobetti *et al*., 2014). The addition of sourdough in baking products also promotes better postprandial gastrointestinal function in healthy adults compared with the products prepared with brewer's yeast (Polese *et al*., 2018). The use of sourdough improves flavour, structure and stability of baked products (Poutanen *et al*., 2009). Cereal fermentations also show significant potential in improving the nutritional quality of foods and the sensory quality of wholegrain products.

Croissants are bakery products with characteristic laminated aerated-flaky structure formed by enveloping a sheet of butter or margarine in yeast dough, folding it to increase the number of layers to obtain a layered structure with thin fat/dough layers (Cauvain and Young, 2008; Grujić *et al.*, 2009). The attempts to prepare wholegrain croissants are challenged by negative effects on the structure and quality characteristics of the final product. Therefore, the aim of the present study was to explore whether it is possible to overcome these issues by the use of sourdough in the production of wholegrain wheat croissants.

Materials and Methods

Raw materials

The flour used in this study was wholemeal wheat flour (Mlivo, Bulgaria) composed of 69.9% carbohydrates, 13.2% protein, 2.2% fat, 12.8% moisture content and 1.85% ash. Compressed yeast was supplied by Lesaffre Bulgaria Ltd. (Sofia, Bulgaria). Table salt was supplied by Boils Food Company (Bulgaria), and fresh butter and margarine for lamination were purchased from the market.

Methods

The following wholemeal wheat flour characteristics were determined by applying the methods of analysis approved by American Association of Cereal Chemists (AACC International, 2010): moisture content (%) (AACC method 44-01.01), acidity (°N) (AACC method 02-31.01), ash content (%) (AACC method 08-01.01), gluten content (%) (AACC method 38-10.01), and gluten softening and particle size (μm) (AACC method 55-60.01).

Lactic acid bacteria

Three LAB strains were used in this study: *Pediococcus acidilactici* 02P108 (PA), *Pediococcus pentosaceus* SM2D17 (PP), and *Enteroccocus durans* 09B374 (ED); all from culture collection of the Department of Biotechnology, University of Food Technologies, Plovdiv, Bulgaria. The strains originated from typical Bulgarian sourdoughs (Petkova *et al*., 2021). Starter cultures for the sourdoughs were prepared from stock cultures of each strain stored in Microbank™ (Pro Lab Diagnostics Inc., Richmond Hill, Ontario, Canada) by cultivating in de Man–Rogosa–Sharpe (MRS) broth (Merck KGaA, Darmstadt, Germany) at 37°C for 48 h under aerobic conditions.

Sourdough preparation

Wholemeal wheat flour was used to prepare individual sourdough with each LAB strain. For this, 72-g flour and 126-g sterile water were mixed to obtain a dough yield (DY) of 198. Each starter culture was added to a batch of dough at an inoculum amount of 3 log colony-forming units (CFU)/g dough. The baking dough variants were then fermented at 37°C for 24 h.

Analyses of sourdough

Active acidity (pH) was determined by pH meter BASIC 20þ (Crison Instrument S.A., Barcelona, Spain). Total titratable acidity (TTA) was determined by titration with 0.1-N NaOH to pH 8.4 and expressed as millilitre (mL) of NaOH/10 g of sourdough. LAB-viable cell counts were determined on MRS agar plates at the beginning and end of sourdough fermentation. Moreover, the identity of starter cultures in each sourdough batch was confirmed by colony morphology and microscopic observations.

Croissant production

Control samples (CS) of croissant were prepared using the following formulation: 1,000 g of wholemeal wheat flour, 1.7% of salt (w/w, flour basis), 5.0% of fresh yeast (w/w, flour basis), 3.0% of sugar (w/w, flour basis), 4.0% of fresh butter (w/w, flour basis), 8.0% of eggs (w/w, flour basis), 40% of cold water (w/w flour basis, 4°C, and 50.0% of margarine for lamination (w/w, flour basis).

Each croissant test sample was prepared by using the above-mentioned recipe, but substituting fresh yeast with a single-strain sourdough at a concentration of 20 g/100 g of baking dough.

The following preparation procedure was adopted: All ingredients were mixed and kneaded in a spiral mixer (Diosna, model SP 12-SP160, Germany) for 1 min at slow speed and for 6 min at fast speed. Kneading of dough was carried out at 20–22°C. The prepared baking dough was divided into 130-g pieces. This was followed by a resting time of 15–20 min at 15–17°C; lamination with a thickness of 6–8 mm; application of margarine on dough sheet, and folding and consecutive lamination to a thickness of 6–8 mm; resting for 20–30 min at 3–4°C; five-fold lamination and folding; final lamination to 3-4 mm, and cutting in triangle forms and shaping; final fermentation for 60–90 min at 20–23°C; baking for 12–15 min at 220–230°C; and cooling down the samples for 3 h at room temperature (Vasileva *et al*., 2018).

Rheological properties of wholemeal wheat doughs

Dynamic viscosity

Viscosity of wholemeal wheat doughs was measured at the end of the fermentation process at 22–24°C by a rotary rheometer Rheomat RM180 (Mettler Toledo, Viroflay, France) based on Couette geometry using a rotating cylinder. The shear–stress of the doughs was measured at different shear rates (50, 100 and 200 s^{-1}). The apparent viscosity measurement was recorded for 3 min (Gemelas *et al*., 2018).

Dough characteristics by farinograph

The following dough characteristics were determined using a farinograph (Brabender GmbH & Co. KG, Duisburg, Germany): water absorption (%), dough development time (DDT, min), dough stability (min), softening (farinograph units/FU), and consistency (FU), according to the adopted AACC International (2010) methodology. A flour sample of 300 g was placed in the mixer of the apparatus and its blades were driven by the main switch. Dry mixing for 2–3 min was carried out for homogenisation and tempering of flour. The typewriter was then switched on and water from the burette was added. The first farinogram was a test to determine the exact water absorption of the flour. Afterwards, the dough sample was kneaded in the same way by adding the amount of water determined by the test (International Association for Cereal Science and Technology [IACST], 2021).

Croissants analyses

The quality of the prepared croissants was assessed by the following characteristics: Croissant volume was determined after baking and cooling for 3 h at room temperature by the rapeseed displacement method (AACC method 10-05 01) (AACC International, 2010). The specific volume was calculated by the volume (cm^3)–mass (g) ratio of each sample. Bake loss (%) was determined after weighing each croissant before and after baking (Kim and Lee, 2015).

Deformation characteristics of croissant crumb were determined as follows: The croissants were wrapped in plastic bags and stored at room temperature (20 ± 2°C) (Lönner and Preve-Akesson, 1989). The deformation properties (total, plastic and elastic deformation) of croissants crumb were studied at 3, 24, 48 and 72 h after baking. Total, elastic, and plastic deformation (D_p), presented in penetrometric units (PU), were measured by an automatic penetrometer (Zlateva and Chochkov, 2019). A 4-mm thick sample was cut from croissant and placed on flat surface of the lifting table of the device, which was raised until the upper surface of the sample lightly touched the lower end of the immersion body. The penetration value of the immersion body in the sample was recorded after 5 s to measure total deformation (D_t). The steel disk was removed and the immersion system was unloaded. Then the measurement was repeated for 10 s to analyse plastic deformation (D_p). The elastic deformation was obtained by subtracting plastic deformation (D_p) from total deformation (D_t).

Sensory analyses

Sensory analyses of the obtained croissants were performed by a descriptive panel of 25 panellists (52% women and 48% men), aged 22–60 years, who were familiar with sensory analyses of foods, but not specifically trained in the evaluation of sourdough goods. The analyses were carried out according to ISO 6658:2017 (International Standards Organization [ISO], 2017). The panellists were asked to score six parameters, such as appearance, crust colour, porosity, aroma, taste, and aftertaste. They expressed the intensity of each attribute on a 9-point hedonic scale (9 – extremely good; 1 – extremely bad).

Image analyses of wholegrain wheat croissants with sourdough

Three slices of 1 cm were cut from the centre of the prepared croissants. The slices were scanned on a CanoScan LIDE 700F scanner with a resolution of 300 dots per inch (dpi). All image processing and pore analyses were performed by using Fiji distribution of the ImageJ software (Schindelin *et al*., 2012; Schneider *et al*., 2012). A square field was selected from the centre of each slice and analysed. The image was converted into 8-bit grey scale and the contrast was normalised. The segmentation process in which the pores were separated from the background (the solid phase) was performed automatically by the Otsu method (Scheuer *et al*., 2014). The analysed indicators were average size of pore, area, circularity, and solidity.

Statistical analyses

All analyses were conducted in triplicate. The obtained data were subjected to one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test in R (version 4.2.1; www.r-project.org; accessed on 26 May 2023). For compact letter display assignment, the MultcompLetters4 function was used from package multcompView (0.1). Differences were considered significant at $p < 0.05$.

Results and Discussion

The present study aimed to explore the effect of sourdough addition on the rheological properties of dough, quality characteristics and staling of croissants prepared from wholegrain wheat flour.

Flour characterisation

The main physicochemical characteristics of flour are presented in Table 1.

Table 1. Physicochemical characterisation of wholemeal flour (mean values ± standard deviations [SD]).

Index	Moisture content (%)	Acidity (°H)	Ash content (%)	Wet gluten content (%)	Gluten softening (mm)	Particles size (µm)
Wholemeal flour	12.8 ± 0.29	4.3 ± 0.14	1.8 ± 0.14	34.8 ± 0.83	6.0 ± 0.22	≤125

The used wholemeal flour had particle size of ≤125 µm. This parameter is very important for the rheological properties of dough, especially related to water absorption. The content of wet gluten in the wholemeal wheat flour was very high (34.8) and close to that of the high-quality white wheat flours, from which croissant dough is usually prepared. This parameter is extremely important for the development of dough and the structure of product; therefore, it is a key point to consider when choosing flour. Gluten softening was within the limits for croissant products (in the range of 3–8 mm). Moisture content, acidity and ash content were within the acceptable limits. The analyses showed that the selected wholegrain wheat flour was suitable for this work.

Active acidity (pH), total titratable acidity (TTA) and LAB viable counts of wholemeal wheat flour sourdoughs

Wholemeal wheat flour sourdoughs were prepared by using three single-strain LAB cultures: *Pediococcus acidilactici* 02P108 (PA), *Pediococcus pentosaceus* SM2D17 (PP), and *Enteroccocus durans* 09B374 (ED). Fermentation was carried out for 24 h at 37°C, and the obtained sourdoughs were characterised according to final pH, TTA and LAB viable counts (Table 2).

The LAB strains used originated from typical Bulgarian sourdoughs and were selected as the best-performing strains in a previous research conducted on non-gluten sourdough bread preparation (Chochkov *et al*., 2022). The results clearly indicated a good capacity of the three tested LAB strains to ferment wholemeal wheat flour dough with comparable levels of final active and titratable acidity and viable LAB counts. The three LAB strains belonged to homolactic genera (*Pediococcus* and *Enterococcus*) that reduced pyruvate molecules formed from the glucose metabolism mainly to lactic acid. This resulted in pleasant lactic acid aroma of all obtained sourdoughs. Data analysis showed no statistical differences in biomass concentration at the end of the fermentations among three sourdoughs (8.58–8.92 log CFU/g).

Table 2. Characterisation of wholemeal wheat flour sourdoughs.

Strain / Parameter	*Pediococcus acidilactici* 02P108 (PA)	*Pediococcus pentosaceus* SM2D17 (PP)	*Enteroccocus durans* 09B374 (ED)
pH	3.61 ± 0.09[a]	3.84 ± 0.09[a]	3.82 ± 0.10[a]
TTA	17.4 ± 0.1[a]	17.2 ± 0.2[a]	17.8 ± 0.2[a]
Log CFU/g	8.64 ± 0.32[a]	8.92 ± 0.60[a]	8.58 ± 0.52[a]

TTA: total titratable acidity; CFU: colony-forming units. The values indicated with different superscript letters in the same row differ significantly ($p < 0.05$).

The pH values ranged from 3.61 to 3.84, which were typical for sourdoughs with good development and quality. The lowest pH value (3.61) was reached in the PA strain sourdough, but it was not significantly different, compared with the other two sourdoughs. These values were similar to the pH values reported for Italian and French sourdoughs (Minervini *et al*., 2012; Vera *et al*., 2012).

One of the strains used to prepare sourdough in the current study was *Enteroccocus durans* species, which was found by other authors only at certain stages of sourdough fermentation and was less common as a choice for sourdough fermentation, compared with *Lactobacillus* species. Enterococci present in many fermented foods have been granted 'generally recognised as safe (GRAS)' status. It was previously reported that selected enterococci could play an important role in proteolysis during sourdough fermentation, and that the acidification of dough contributed to the inhibition of undesired microorganisms, such as moulds and rope bacteria (Corsetti *et al*., 2008; De Kwaadsteniet *et al*., 2005; El-Gendy *et al*., 2021). However, the production of organic acids and other metabolites with antimicrobial properties was determined by other factors as well, such as strain specificity, dough composition, fermentation conditions, *etc.* (De Vuyst and Neysens, 2005).

Rheological properties of wholemeal wheat dough with sourdough

The wholemeal wheat croissant doughs obtained with the addition of single-strain sourdoughs were subjected to rheological analysis (Table 3).

The water absorption of the control sample was high, which is a characteristic for high-ash content flours because of the content of brans, in particular the content of pentosanes, in the lowest (hyaline) layer of seed coats. It was observed that sourdough addition did not lead to significant changes regarding this indicator. In contrast, Chen *et al*. (2018) reported that the use of a sourdough starter resulted in a significant decrease in water absorption by the flour. This could be attributed to differences in raw materials and sourdough strain performance.

The indirect influence of mucilaginous substances on the strength of the flour, and especially on the quaternary structure of protein substances, is very important for the rheological properties of dough. Flour containing smaller particle size fractions and destructed particles absorb larger amount of water. The high-ash content flour shows increased gas formation, which is due to the higher content of damaged starch as well as decreased gas retention.

Table 3. Rheological properties of wholemeal wheat dough with sourdough (observations or mean values ± standard deviations, SD).

Samples	Rheological characteristics				
	Water absorption (%)	Consistency (FU)	DDT (min)	Stability (min)	Degree of softening (FU)
Control	75.0 ± 2.45[a]	500	5.0	15.0 ± 1.41[a]	20 ± 1.41[b]
PA	74.8 ± 1.71[a]	500	5.0	16.0 ± 0.82[a]	25 ± 0.82[ab]
PP	74.9 ± 0.22[a]	500	5.0	14.5 ± 0.62[a]	30 ± 1.63[a]
ED	75.1 ± 0.16[a]	500	5.0	15.5 ± 0.59[a]	25 ± 2.16[ab]

CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374; DDT: dough development time; FU: Farinograph units.
Mean values with different superscript letters within the same column differ significantly ($p < 0.05$).

Dough development time (DDT) for the control sample was quite long (5 min), and the same was observed for all test samples. These results showed that the used sourdoughs did not have any effect on this index. On the contrary, Qinhui *et al.* (2021) reported that the addition of sourdough led to an increase in the development time of dough. Our results could be explained by the high protein content of dough, since the water added during kneading was first absorbed by proteins, which had lower molecular weight; then the water was absorbed by the surface-attached free starch granules, and, finally, by the albumen of small and large intact parts of the endosperm. As a result, this index did not change for any of the test samples during the experiment.

The control sample had relatively high stability (15 min) and low degree of softening (20 FU), which could be explained by the fact that proteins absorb about 75% of water by osmosis and about 25% is bound by adsorption.

The addition of sourdough did not lead to significant changes in stability. However, the use of all three sourdoughs resulted in significantly higher dough softening levels (25–30 FU), compared with the control sample (20 FU). The observed values of dough stability and increased degree of softening are important for dough stability during the technological process of croissant production, and are the reason for slight increase in the specific volume of the obtained croissant samples.

Influence of sourdough on the dynamic viscosity of wholemeal wheat dough

Viscosity is a measure of the resistance of a fluid to the displacement of some of the layers relative to each other. It is perceived as 'thickness' or pouring resistance. Viscosity represents the internal resistance (stress) of a fluid to flow and it may be considered as a measure of fluid's friction. The effect of three sourdoughs on the dynamic viscosity of wholemeal wheat dough at different shear rates (50, 100 and 200 s^{-1}) is presented in Figure 1 (A–C).

It is interesting to note that at all shear rates used, the viscosity of the wholemeal wheat doughs prepared with sourdoughs is higher, compared with the control sample. At low levels of rotation of the working body (50 s^{-1}, min), the average level of viscosity of the control sample was 1.19 Pa.s. Sourdough with strain ED gave the highest viscosity increase of 164%, followed by strain samples PA and PP, with 103% and 121%, respectively, compared with the control sample. This could be due to decrease in the solubility of β-glucans and proteins found in flour, which simultaneously lead to an increase in the viscosity of test samples (Lazaridou *et al*., 2014).

Generally, by increasing the shear rate, the dynamic viscosity of all test samples decreased. All the same, in all tests, the dynamic viscosity of all sourdough samples remained higher than that of the control. At the highest applied level of frequency (200 s^{-1}, min), the viscosity of the control sample decreased below 1, reaching 0.67 Pa.s. Similar results were reported by Savkina *et al.* (2019), where the dynamic viscosity decreased at the end of fermentation by 2.2 times. A similar decrease was reported in every dough analysed by Kulamavra *et al.* (2009). These data demonstrated that sourdough samples were less viscous and more elastic.

In addition, rheological measurements were made throughout the fermentation period to determine how each starter culture affected dough viscosity. For all dough samples, viscosity decreased until the end of fermentation, and for all sourdough samples the level of decrease was higher, compared with the control sample. The same was observed by other authors (Teleky *et al*., 2022; Voinea *et al*., 2020) who illustrated that viscosity decreased during fermentation if sourdough was incorporated in the dough recipe.

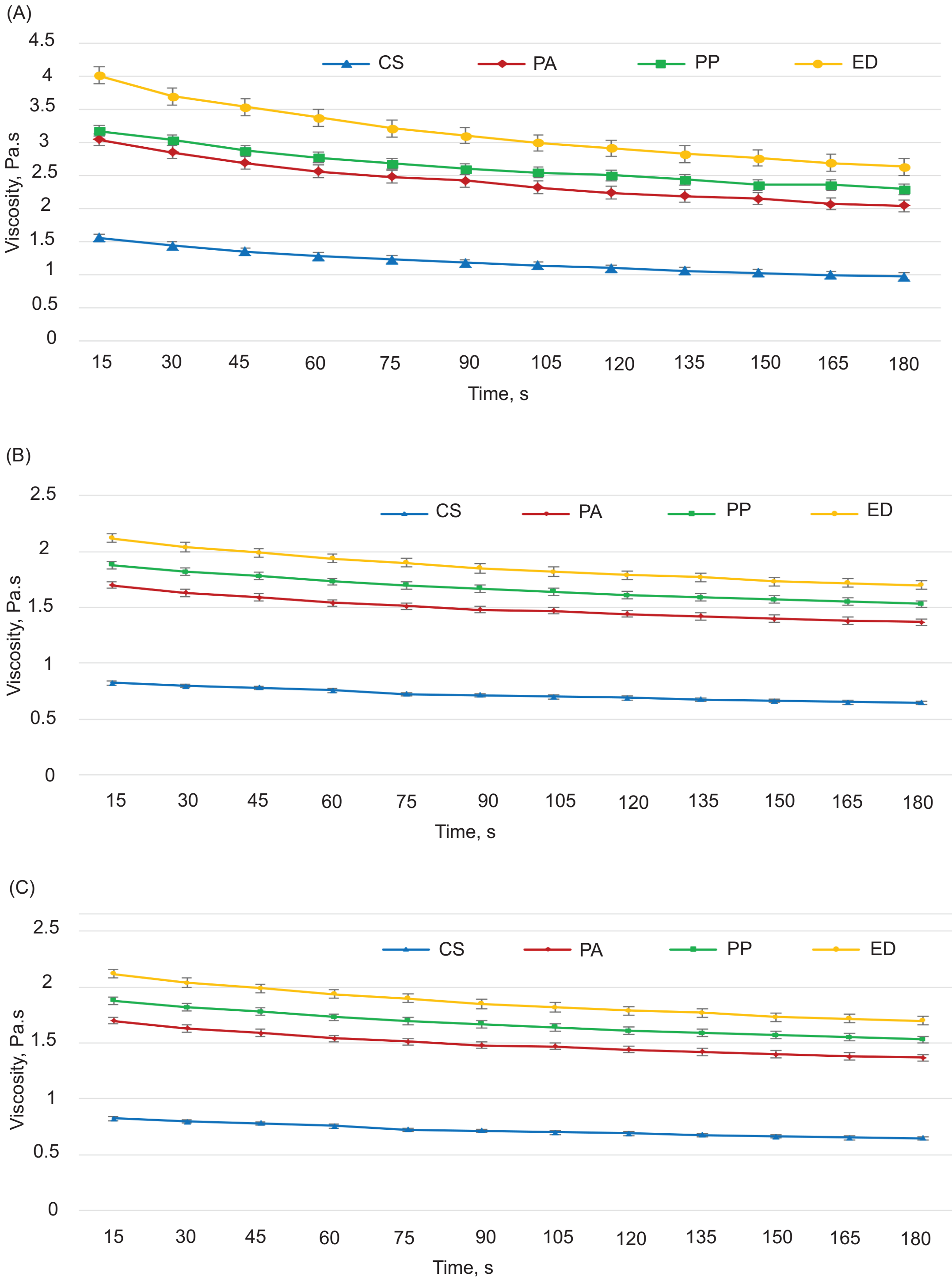

Figure 1. Influence of sourdoughs on the dynamic viscosity of wholemeal wheat dough (mean values ± standard deviations, SD). Shear rate: (A) 50 s^{-1}; (B) 100 s^{-1}; and (C) 200 s^{-1}. CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374.

On the other hand, it was found that the addition of sourdough increased viscosity of dough. The difference between the control and sample PA was 63%; difference for sample PP was 79%, and difference for sample ED was 100%. According to some authors, viscosity of the dough could increase or decrease depending on the strain of LAB used. Steamed bread leavened with *Fructolactobacillus sanfranciscensis* (FS) and *Lactobacillus delbrueckii*, subsp. *bulgaricus* (LB) starters had the softest crumb texture, whereas *Lactiplantibacillus plantarum* (LP) and *Levilactobacillus brevis* (LBr) starters produced the lowest setback viscosity (Wu *et al.*, 2012). Gemelas *et al.* (2018) investigated the development of a fermented dairy product as an ingredient to be added to low-fat bakery products. The authors found that LAB could produce hydrocolloid exopolysaccharides (EPS), which had the ability to increase dough viscosity. Other authors also demonstrated that the dextran produced by LAB significantly increased the viscosity of sourdough samples (Coda *et al.*, 2018; Katina *et al.*, 2009). Galli *et al.* (2020) obtained similar results and concluded that the *in situ* dextran production led to the highest increase in viscosity (5.90 Pa·s). Mojisola *et al.* (2013) investigated the possibility to improve dough properties through starch modification by utilising sourdough fermentation. These authors concluded that sourdough fermentation increased viscosity by affecting starch.

Further, the main baking characteristics (specific volume and baking loss) of the obtained croissants were assessed, and the results are presented in Table 4.

During the final fermentation, a greater formation of gas in sourdough samples, compared with the control sample, was observed visually, but the gas bubbles failed to remain in the volume of dough. As a result, an increase in volume was observed only up to the 65th minute, with no further volume development. This showed that the final fermentation had stopped earlier. No further volume development was observed upon baking, which could be explained by the reduced gas-holding capacity of wholemeal wheat dough. These observations matched the results obtained for the specific volume of croissants with sourdough. Only sample PA showed significantly higher specific volume values (4.03 cm^3), compared with the control sample (3.80 cm^3). This indicated that the positive effect of addition of sourdough on dough development was correlated to strain specificity.

Table 4. Baking characteristics (specific volume and baking loss) of wholemeal wheat croissants with sourdough (mean values ± standard deviations, SD).

Samples	Specific volume (cm^3/g)	Baking loss (%)
Control	3.80 ± 0.06^b	11.50 ± 0.36^a
PA	3.82 ± 0.05^b	11.52 ± 0.36^a
PP	4.03 ± 0.02^a	11.72 ± 0.07^a
ED	3.81 ± 0.03^b	10.61 ± 0.21^b

CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374. Mean values with different superscript letters in the same column differ significantly ($p < 0.05$).

Sensory profile of wholemeal wheat croissants with sourdough

Different methods of sensory analysis are applied to determine the quality of baked products, including croissants, by developing sensory attributes for volume, texture, colour, flavour, and aroma (Stefanova and Zlateva, 2018). Results for sensory profile of wholemeal wheat croissants with sourdough are presented in Figure 2.

It was found that the use of sourdough samples improved the appearance and colour of crust, with highest effect observed for sample ED (Figure 2). In general, taste and aroma were pleasant – sample ED had more pronounced aroma, while in the other two test samples, these parameters were much weaker, with barely perceptible differences observed between them. The slightly expressed taste and aroma of two sourdough samples could be due to the masking effect of wholemeal wheat flour used for food matrix. Development of porosity (crumb structure) was most pronounced in test sample ED, with an increase of about 25%, compared with the control sample. For test samples PA and PP, the indicators taste and aftertaste were also less perceptive, and very similar to those of the control sample.

In other studies, sourdough starters based on rye flour were characterised by a pronounced pleasant aroma, which was attributed to rye flour itself, and the specific fermentation microbiota of LAB and yeast samples (Boreczek *et al.*, 2020; Koistinen *et al.*, 2018; Németh and Tömösközi, 2021). It must be noted that during dough preparation, sourdough microbiota undergoes significant changes, affecting its physiological and biochemical properties, which affect the sensory characteristics of final products (Litwinek *et al.*, 2022).

Image analysis of wholegrain wheat croissants with sourdough

The structure of the crumb of croissants is an important indicator for consumer acceptance. These products are required to have a good distribution of crumb structure. Therefore, crumb structure in the obtained croissant samples was also analysed in the study. Photographic images and binary images produced by the analytic software are presented in Figure 3, and the analytical results of the average pore size, area, circularity, and solidity are displayed in Table 5.

It was observed that the control sample and sample PA had the same results for average pore size (127.5 mm^2). Smaller pores were developed in sample PP (100 mm^2), while strain ED generated the largest average pore size of 143 mm^2. These results indicated good development

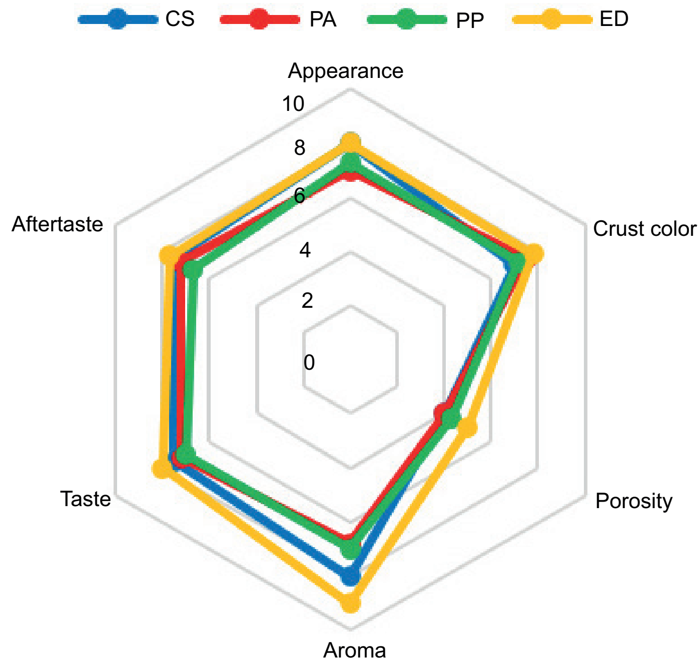

Figure 2. Sensory profile of wholemeal wheat croissants with sourdough (mean values ± standard deviations, SD). CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374.

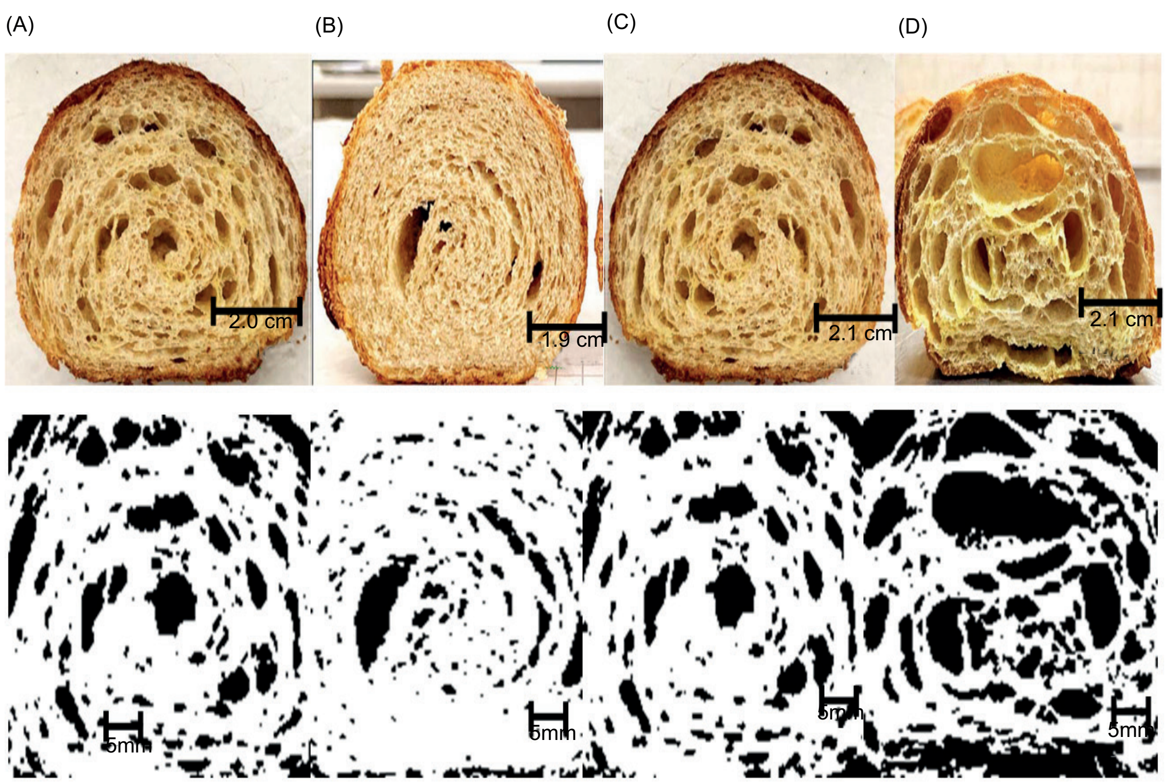

Figure 3. Images and binary images of croissants with sourdough. (A) Control sample (CS); (B) *Pediococcus acidilactici* 02P108 (PA); (C) *Pediococcus pentosaceus* SM2D17 (PP); and (D) *Enteroccocus durans* 09B374 (ED).

Table 5. Pore size, area, circularity, and the solidity of pore of wholemeal wheat croissants with sourdough (mean values ± standard deviations, SD).

Samples	Average size of pore, mm^2 (±SD)	Area, % (±SD)	Circularity (±SD)	Solidity (±SD)
Control	127.5 ± 1.13^b	74.13 ± 0.66^d	0.767 ± 0.02^b	1.00 ± 0.00^a
PA	127.5 ± 1.39^b	86.25 ± 0.31^c	0.782 ± 0.02^b	1.00 ± 0.00^a
PP	100.0 ± 1.61^c	100.00 ± 2.59^b	1.000 ± 0.00^a	1.00 ± 0.00^a
ED	143.0 ± 0.54^a	141.00 ± 0.51^a	1.000 ± 0.00^a	0.97 ± 0.01^b

CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374. Mean values with different superscript letters in the same column differ significantly ($p < 0.05$).

of croissant crumbs with addition of sourdough from *Pediococcus acidilactici* and *Enteroccocus durans*, but less developed volume with the use of *Pediococcus pentosaceus*.

Compared with the control sample, a significant increase in pore area percentage was observed for all sourdough samples (16.3%, 34.9% and 90.2% for PA, PP and ED, respectively).

A higher pore percentage area presents a better developed environment in the product, while circularity is an index that describes how closely the cross section of the pore approximates a perfect circle. The closer the value of this parameter to 1, the more rounded is the pore cross section. The control sample and sample PA had similar results. Samples PP and ED had significantly better performance (30.3 %) compared with the control sample. Considering solidity of the samples prepared with sourdough, only sample ED was significantly different from other samples, with an average value of 0.97. This result again indicated that effects on the quality characteristics of wholemeal wheat croissants leavened with sourdough were strain-specific; therefore, a careful choice of a sourdough starter culture is required for the best results.

Deformation characteristics of wholemeal wheat croissants with sourdough

Bourne (1978) described extensively the use of instrumental texture profile analysis by using force, deformation, and work measurement to determine the texture parameters of hardness, fracturability, cohesiveness, adhesiveness, springiness, gumminess and chewiness. In the present study, estimation of the shelf life of the prepared wholemeal wheat croissants with sourdoughs was based on the time of occurrence of mould growth and the analysis of deformation characteristics—total, plastic and elastic deformation—measured by an automatic penetrometer of croissant crumb (Figure 4).

During the observed storage period of 72 h, as expected, the total deformation of all croissants decreased gradually (Figure 4). Generally, sample PA did not differ significantly from the control sample except the first measurement at hour 3. On the other hand, samples PP and ED differed significantly from sample PA and the control. Total deformation in sample ED was more than 10% than that of the control at each measurement point.

Plastic deformation of sourdough croissants during storage was also evaluated (Figure 5). Similar to total deformation, the levels of this parameter were also significantly higher for sample ED at all measurements, and for sample PP at hour 3. Plastic deformation of all samples decreased gradually up to 72 h, but at the end of the experiment, it was significantly higher for sourdough croissants, compared with the control sample. The crumb of sample ED retained its plasticity to the maximum level, which was most pronounced at the end of 72 h. Plasticity of this sample decreased by 12.2% between 3 and 72 h, compared with 19.4% reduction in the control sample.

The third shelf-life parameter of wholemeal croissants with addition of sourdoughs was elastic deformation (Figure 6). Again, results for sample ED showed maximum values, compared with the other samples. In due course of time, the elastic deformation decreased in all test samples, and after 72 h, the lowest value was observed for the control sample. At the end of the storage time test, sample ED had an elastic deformation of 700% higher than that of the control sample. Over the test period, from 3rd to 72nd h, elastic deformation of sample ED decreased by 29%, while that of samples PP and PA decreased by more than 45% and 60%, respectively.

Overall, the results obtained from the assessment of the deformation characteristics of croissants with sourdough indicated that strain specificity had a significant impact on the shelf life of products. Addition of ED sourdough provided the best results in terms of staling, and preserved product softness in a much better manner

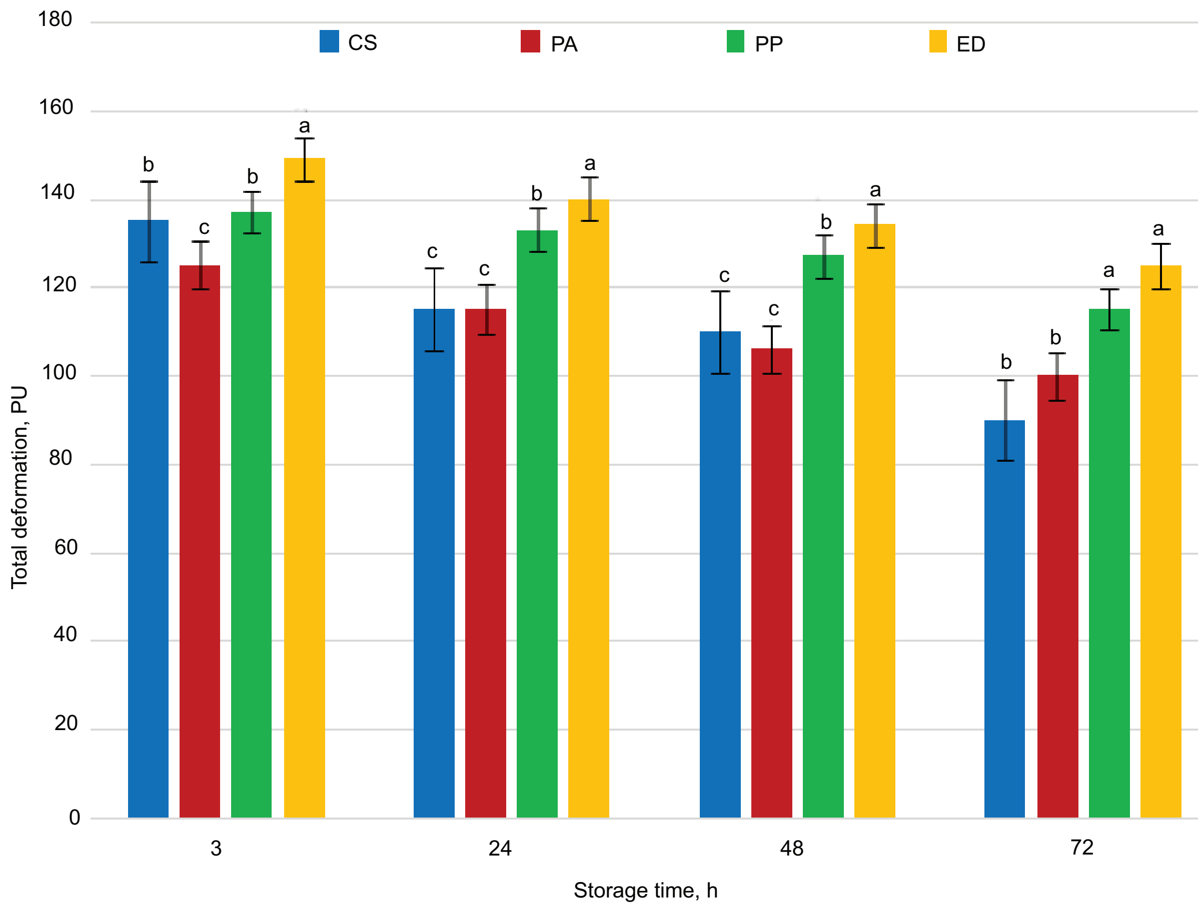

Figure 4. **Total deformation of wholemeal wheat croissants with sourdough (mean values ± standard deviations, SD). Mean values with different letters within the same storage time differ significantly (*p* < 0.05). CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374.**

than the control and other two sourdoughs strains. The obtained results also demonstrated that, in general, the addition of sourdoughs to wholemeal croissant dough had a significant beneficial effect on product's shelf life.

Conclusions

The current study aimed to obtain croissants from wholegrain wheat flour by using sourdough instead of baker's yeast as a leavening agent in an attempt to compensate the drawbacks of using wholemeal wheat flour. Three sourdoughs were prepared by using single cultures of *Pediococcus acidilactici* 02P108, *Pediococcus pentosaceus* SM2D17 and *Enteroccocus durans* 09B374, and their effects were investigated on main quality characteristics during dough preparation, baking, and storage. Results showed that the addition of sourdough in the wholemeal wheat dough did not lead to significant changes in the rheological characteristics of dough, compared with the control sample leavened with baker's yeast. Moreover, increasing of shear rate during mixing resulted in decreased dynamic viscosity of all test samples; however, all sourdough-leavened samples had higher dynamic viscosity than the control sample. Other positive effect of sourdoughs on dough development was demonstrated through higher degree of softening of all sourdough samples, specific volume improvement by strain PP, and reduced baking loss by strain ED. Addition of sourdough made with sample ED showed the most distinguished sensory characteristics, compared with the control, as well as the best results concerning croissant staling during 72-h storage.

The current study demonstrated that the application of sourdoughs to the wholemeal wheat croissant dough is a successful approach for obtaining products with good quality characteristics and prolonged shelf life. Strain specificity proved to be significant for dough rheology, the baking characteristics, and quality preservation

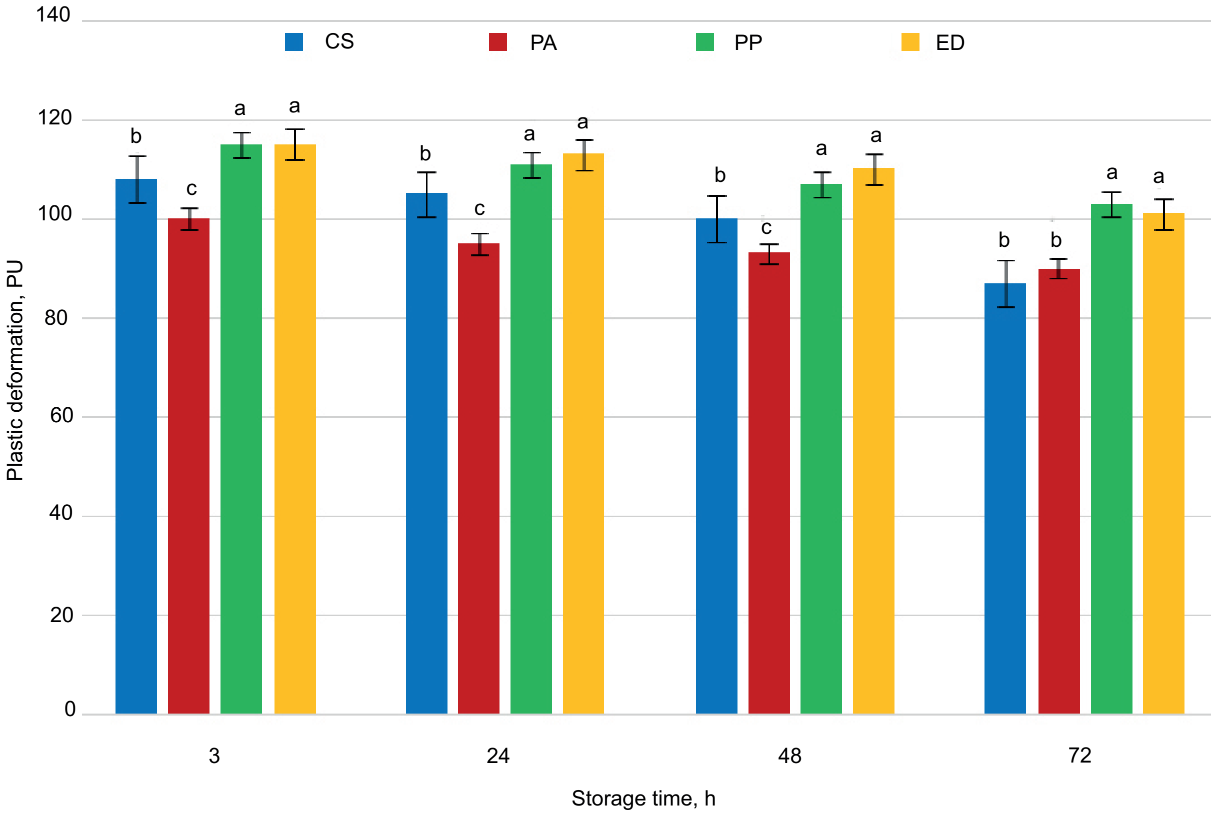

Figure 5. **Plastic deformation of wholemeal wheat croissants with sourdough (mean values ± standard deviations, SD). Mean values with different letters within the same storage time differ significantly (p < 0.05). CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374.**

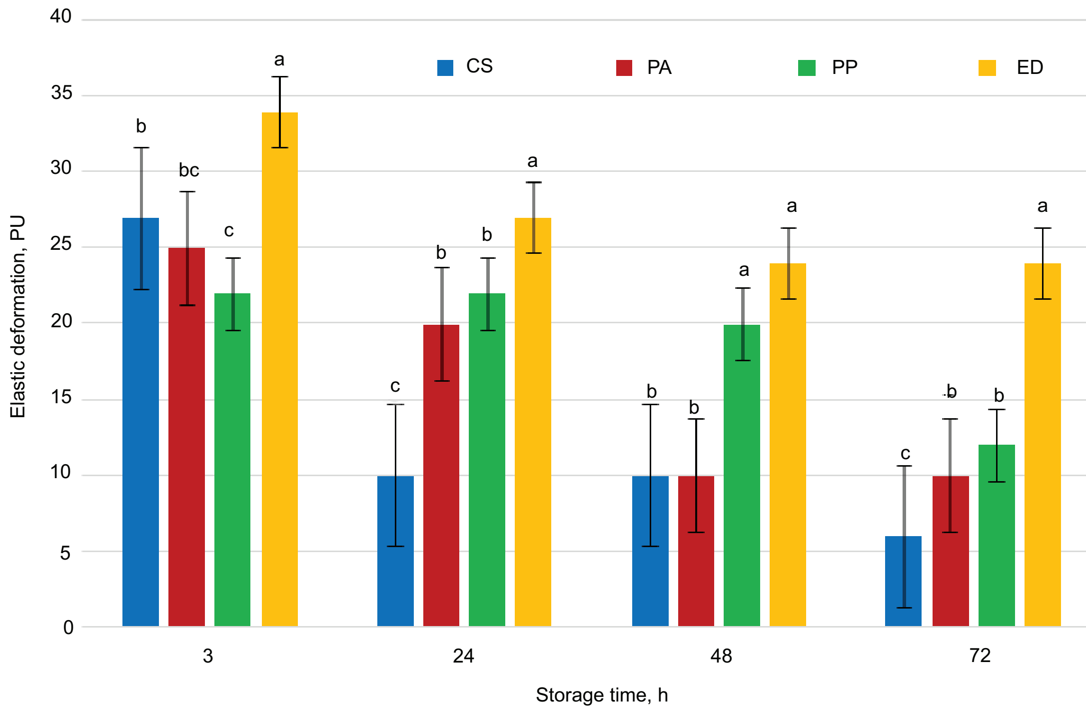

Figure 6. **Elastic deformation of wholemeal wheat croissants with sourdough (mean values ± standard deviations, SD). Mean values with different letters within the same storage time differ significantly (p < 0.05). CS: control sample; PA: *Pediococcus acidilactici* 02P108; PP: *Pediococcus pentosaceus* SM2D17; ED: *Enteroccocus durans* 09B374.**

throughout storage. Therefore, it is important to perform a careful starter culture selection.

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Conflicts of Interest

The authors declared no conflict of interest.

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