

Article

Dried Sourdough as a Functional Tool for Enhancing Carob-Enriched Wheat Bread

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Abstract

Functional bread development with clean-label ingredients remains a technological challenge due to the negative effects of certain functional additives on dough rheology and bread quality. The aim of this study was to evaluate the effectiveness of dried sourdough as a natural improver in carob-enriched bread. Dough formulations included 10–20% carob flour as a partial replacement of wheat flour, with dried sourdough added as a dough improver at 5–10%. The results demonstrated that the addition of 10% dried sourdough increased maximum creep compliance of dough with 10% and 15% carob flour by 26% and 56%, respectively. The addition of 5% and 10% dried sourdough to dough with 10% carob flour decreased its Newtonian viscosity by 24% and 36%, resulting in improved dough handling. Crumb pore structure was enhanced by the addition of 5% dried sourdough, with average pore surface area increasing around 2.5 times in breads with 15% and 20% carob flour. Incorporation of dried sourdough reduced bread hardness and chewiness by up to 40% in samples with 15% carob flour and by 20–30% in samples with 20% carob flour. Sensory properties of crumb structure (crumb development, pore fineness, elasticity and crumbliness), which were adversely affected by carob flour addition, showed varying levels of improvement by the addition of dried sourdough. These results demonstrate the feasibility of using dried sourdough as a natural improver in functional bakery formulations, supporting the development of clean-label products without synthetic additives.

Keywords: dried sourdough; carob bread; fundamental rheology; crumb texture; sensory quality



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1. Introduction

The growth in food industry and development of functional food is largely driven by rising consumer demand for artisanal and premium products. The most recent research has aimed at identifying new ingredients from a wide variety of sources to improve existing products that consumers find both acceptable and familiar. For instance, donkey myofibrillar protein has been used in the production of low-calorie emulsion-type sausages [1], while tannins extracted from different natural plants have been applied to improve the quality of broiler meat [2]. Furthermore, various novel techniques, such as machine-learning-driven approaches, have recently been employed to optimize the formulation and functionality of beverages [3]. In line with these recent trends, the present study aimed to reinvent carob (*Ceratonia siliqua* L.) as a valuable raw material.

Carob pulp flour has once been widely incorporated into Mediterranean culinary traditions; however, it became largely overlooked and underutilized over time [4]. Based on the current knowledge on the characteristics of carob pulp flour, it can be classified as a functional ingredient with the potential to enhance the nutritional quality of food by enriching the product with essential amino acids, dietary fibers, minerals, vitamins, and inositol [5]. The contribution of carob pulp flour to the development of functional products is also evident in terms of its polyphenolic compounds, which act as natural antioxidants [6]. However, when incorporated into bread dough formulation by substituting part of wheat flour, carob flour significantly affects dough rheology [7], which results in lower loaf volume and firmer crumb texture [8], negatively impacting overall consumer acceptability [9].

As a means of improving bread quality, another recurring trend in the bakery industry has been the renewed use of sourdough technology. The global sourdough market in 2025 was estimated at USD 3.25 billion and is continuously increasing, projected to reach USD 4.49 billion by 2030 [10]. The scientific evidence continues to accumulate, highlighting sourdough's potential to enhance nutrient availability, support glycemic control, and promote digestive health [11]. Sourdough application is not restricted to white bread production but also extends to the production of whole-grain and non-wheat cereal bread [12]. Wheat substitutes in cereal-based products have also been investigated, highlighting legumes, pseudo-cereals, cereal side-streams (such as bran, germ, and brewer's spent grain), and food industry by-products as valuable sources of proteins, fibers, vitamins, minerals, and bioactive compounds [13,14]. Although the nutritional value of non-wheat ingredients can be limited by high fiber content, lack of gluten, and sensory drawbacks, sourdough fermentation has been recognized as an effective tool to improve their technological and sensory quality, enabling their broader use in staple food fortification [15]. Similarly, the use of sourdough in combination with carob flour could lead to faster acidification and higher activity of lactic acid bacteria, thereby enhancing dough fermentation and improving bread quality [16].

The potential for improving the quality of bread with carob through the application of sourdough has been considered in only two scientific studies; however, in both cases, the carob flour was obtained by milling the whole carob fruit (pods and seeds) and was used for sourdough preparation [17,18]. The dough with carob sourdough showed higher consistency, longer development time, and lower quality class compared to the control, but the resulting bread had increased specific volume, reduced crumbliness, and consumer acceptance was comparable to white wheat bread [17]. According to the results of Karlıdağ et al. [18], higher levels (8–12%) of carob sourdough caused a significant increase in bread crumb hardness, resulting in reduced specific volume. However, lower levels (2–6%) of carob sourdough had no notable negative effects on the examined characteristics, particularly on consumer sensory acceptance. Furthermore, combining carob with proso millet flour and bran has been reported to improve fermentation performance, increase loaf volume, and reduce crumb hardness and chewiness of gluten-free flat-bread [19].

Despite the limited studies on the application of sourdough technology for carob bread production, the use of dried sourdough has emerged as a rising approach in the bakery industry, standing out as a convenient and effective natural improver [20]. Dried sourdough, also known as Type III sourdough, is produced by drying liquid sourdoughs (Type II) through methods like freeze-drying, spray-drying, or drum drying. This process preserves the beneficial properties of the fermentation while enhancing shelf stability and ease of handling [21]. The dried form retains the lactic acid bacteria and organic acids that contribute to improved bread texture, flavor, and shelf life [22].

To the best of our knowledge, the use of industrially produced dried sourdough for the development of carob-enriched wheat bread has not yet been systematically examined and

is limited to our previous work [23]. Previous studies involving carob sourdough [17,18] compared bread containing whole carob fruit to standard wheat bread. In contrast, the aim of the present study was to specifically investigate the effects of dried sourdough used in carob-enriched bread formulations, thereby focusing on the functional and technological contribution of the sourdough itself. Particular emphasis was placed on the assessment of dried sourdough effects on dough rheological behavior by fundamental non-destructive methods, as well as evaluating the physical properties and sensory quality of the obtained breads. This study expands the current understanding of the interactions between carob flour and dried sourdough within a complex dough system. Furthermore, it demonstrates the feasibility of applying industrially produced dried sourdough in small- and medium-sized bakery operations without the need for maintaining starter cultures. The findings contribute to the advancement of clean-label bakery technologies and support the growing trend toward natural, functional bakery products.

2. Materials and Methods

2.1. Ingredients

All ingredients used for the preparation of dough and bread samples were purchased from local markets in Serbia: wheat flour (Kikindski mlin AD, Kikinda, Serbia), yeast (Lesaffre, Budapest, Hungary), salt (Solana d.d., Tuzla, BiH), carob flour (Vega ADM, Senta, Serbia) and dried sourdough “Pecipan soft” (Kvasac d.o.o., Prigorje Brdovečko, Croatia).

2.2. Fundamental Rheological Measurements

Dynamic oscillatory measurements and creep and recovery tests were performed using Haake Rheo Stress 600 rotational viscometer (Thermo Electron Corporation, Karlsruhe, Germany) with the serrated set plate–plate sensor P35 Ti L (plate diameter 35 mm and gap 2 mm). For the preparation of dough samples, wheat flour, carob flour, and dried sourdough were added according to the established experimental design (Table 1), while the amount of water was adjusted based on the water absorption determined in our previous research [23]. Carob flour was prehydrated for 15 min with 2.65 g of water per gram of carob flour, a ratio determined in preliminary experiments reported in our previous study [23], and this amount was included in the total water needed to prepare the dough and achieve optimal consistency. Prepared dough samples were then placed between the plates of the rotational viscometer and were tempered for 3 min at 30 °C. The procedures for measuring and the models for evaluating dough rheology were fully outlined in our prior publication [24]. Rheological measurements were conducted in triplicate.

Table 1. Experimental plan.

Sample	Wheat Flour (g)	Carob Flour (g)	Dried Sourdough (%) ¹
1	90	10	0
2	85	15	0
3	80	20	0
4	90	10	5
5	85	15	5
6	80	20	5
7	90	10	10
8	85	15	10
9	80	20	10

¹ Dried sourdough was added to the total flour mass; total flour mass (100 g) = wheat flour + carob flour.

2.3. Bread Sample Preparation

Bread formulations were prepared according to the experimental plan presented in Table 1. Carob flour was incorporated into the formulation as a partial replacement of wheat flour, while dried sourdough was added to the total flour mass. Each dough sample contained 2% salt and 2.5% yeast, and the amount of water was added based on the water absorption.

Dough preparation and baking were carried out under controlled conditions as previously described in our earlier work [23]. Briefly, dough samples were fermented at 30 °C for 60 min, then divided and molded, proofed and baked at 220 °C until a 10% weight loss was achieved. After cooling, bread samples were packaged in polyethylene bags and stored at ambient conditions.

2.4. Crumb Pore Structure

To evaluate the crumb structure of bread, digital image analysis was employed [25]. Three central slices from each loaf were scanned by a 200 dpi resolution scanner (Laser Jet Pro MFP M130a, HP Inc., Palo Alto, CA, USA). From each scanned image, two regions of 2 × 2 cm were cropped, then processed and analyzed using ImageJ 1.54d (<http://imagej.net/ij/>, accessed on 15 May 2024), according to the methodology of Mastilović et al. [26]. A sensitivity threshold of 0.1 mm was applied to exclude smaller structures that could bias the results. The analysis provided data on the total number of pores and their surface area, from which pore density (1/cm²), mean pore surface area (mm²), proportion of pore surface area (%), and proportion of pore wall surface area (%) were calculated.

2.5. Textural Properties

Texture Analyser TA.HDplus (Stable Micro Systems, Godalming, UK) was used to perform the Texture Profile Analysis (TPA) test [27]. Bread slices (18 mm thickness) were subjected to a weight load equivalent to 45% of the sample thickness. The initial testing speed was 10 mm/s, and second speed was 5 mm/s. Measurements were performed 24 h after baking and in five replicates. Texture Exponent 32 software version 4.0.11.0 (Stable Micro Systems, Surrey, UK) was used for obtaining data on hardness, springiness, resilience, cohesiveness, and chewiness.

2.6. Crumb Sensory Quality

Quantitative descriptive analysis (QDA) was applied for the evaluation of the bread crumb quality. A panel of 10 trained assessors was used to evaluate bread crumb attributes [28]. The panel followed a structured training protocol based on established procedures [29,30]. Panelists completed four pre-study training sessions using reference samples to standardize their perception of evaluated attributes and scale usage, ensuring reproducibility and consistency. During the study, calibration was performed at the beginning of each testing day using standard reference breads to align panelists' scoring and minimize variability. Five quality attributes were scored on a 1–5 scale: crumb development, pore fineness, elasticity, crumbliness, and color uniformity. The QDA scoring scale with descriptors is provided in Appendix A, Table A1. Based on the scores for individual bread samples, a QDA diagram was constructed. A larger enclosed area formed by connecting the scores of each quality parameter on the QDA diagram indicates superior sensory quality of the bread crumb.

2.7. Statistical Analysis

The results were statistically analyzed using analysis of variance (ANOVA), and the significance of differences between mean values was assessed by Tukey's post hoc test

($p < 0.05$). Experimental data were processed using the Statistica 13.3 software package (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Rheological Parameters

The influence of carob flour level and the effects of dried sourdough addition as a dough improver on the viscoelastic properties of wheat dough were evaluated through fundamental, non-destructive rheological tests conducted within the linear viscoelastic region. These included dynamic oscillatory measurements and a creep recovery test.

The characteristic viscoelastic nature of cross-linked dough networks is shown in Figure 1 by storage modulus (G') and loss modulus (G''). G' was higher than the G'' for all examined samples and both moduli exhibited a pronounced linear dependence on frequency. Such viscoelastic behavior typically indicates enhanced mobility of protein chains within the gluten network and a potential adaptability of the dough to applied mechanical forces [31].

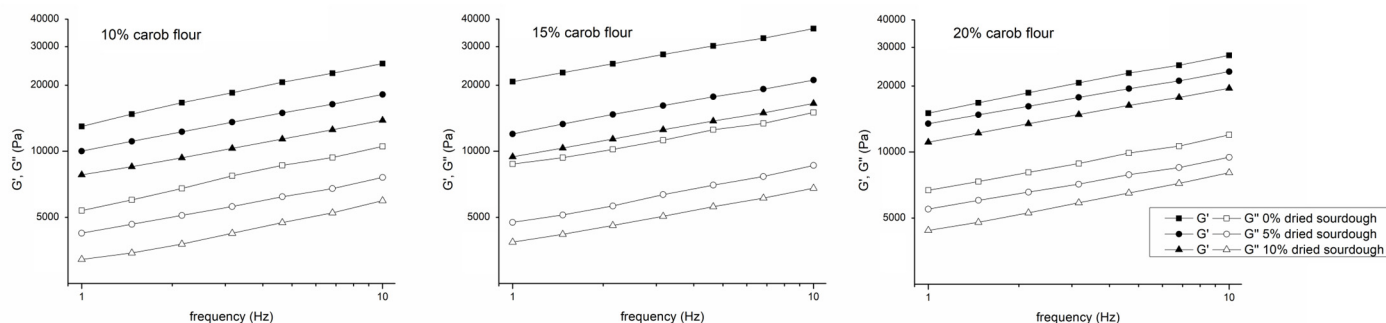


Figure 1. Dependence of storage modulus (G') and loss modulus (G'') on frequency for dough samples containing different amounts of dried sourdough and carob flour.

Furthermore, obtained experimental results of G' as a function of frequency were fitted using a linear (power law) model. Based on this model, the intercept (G'_0) and slope (n) values were calculated in accordance with the methodology of Ortolan et al. [32]. All samples showed high R^2 values (Table 2), suggesting a high fit between the experimental data and proposed model, further confirming the viscoelastic character of the dough samples over a wide frequency range [33]. An increase in the proportion of carob flour in the dough led to a notable rise in storage modulus. At a 5% increment in carob flour content, G' values increased by 11% to as much as 56%. A similar trend was observed by Salinas et al. [11], who reported that the increase in G' at higher carob flour levels (30%) may be attributed to the formation of a rheologically heterogeneous matrix, likely due to the high dietary fiber content of carob flour.

According to the changes in G'_0 values presented in Table 2, a decreasing trend was observed with the increasing level of dried sourdough in samples containing a constant proportion of carob flour. Mentioned changes were statistically significant ($p < 0.05$) and indicate a reduction in the elastic properties of the dough as the amount of dried sourdough increases, contributing to a softer dough structure. A similar trend was reported by Alioğlu et al. [34] when investigating sourdough prepared from whole wheat flour in short dough biscuits. Conversely, Sun et al. [35] reported that the incorporation of specific LAB strains into whole wheat bread dough increased G' values. In our case, the reduction in elastic properties was desirable, since the dough was already relatively rigid due to the presence of carob flour [23]. This was probably due to the interactions between gluten and the structural components of carob flour, primarily proteins and dietary fibers [36]. A two-way analysis

of variance (ANOVA) confirmed the significant influence ($p < 0.05$) of both independent variables on changes in dough elasticity as well as the presence of their interaction (Table 3).

Table 2. Power law equation parameters depending on the amount of carob flour and dry sourdough.

Independent Variables	G_0' (kPa)	n	R^2
10% carob flour			
0% dried sourdough	13.31 ± 0.08^a	0.279 ± 0.002^f	0.9989
5% dried sourdough	10.06 ± 0.04^d	0.256 ± 0.001^d	0.9999
10% dried sourdough	7.73 ± 0.11^b	0.252 ± 0.001^{de}	0.9998
15% carob flour			
0% dried sourdough	20.84 ± 0.17^h	0.240 ± 0.003^{bc}	0.9997
5% dried sourdough	12.16 ± 0.14^f	0.241 ± 0.005^{bc}	0.9994
10% dried sourdough	9.45 ± 0.08^c	0.243 ± 0.002^{bc}	0.9999
20% carob flour			
0% dried sourdough	15.22 ± 0.10^g	0.259 ± 0.001^d	0.9994
5% dried sourdough	13.49 ± 0.18^a	0.236 ± 0.002^b	0.9999
10% dried sourdough	11.14 ± 0.05^e	0.245 ± 0.004^{bcd}	0.9998

G_0' —the intercept; n—the corresponding slope; R^2 —the coefficient of determination. Mean $\pm$ SD (n = 3); different superscript letters in columns represent statistically significant difference ($p < 0.05$).

Table 3. Two-way ANOVA of the effects of investigated factors on power law parameters (G_0' i n) and Tan δ .

Power Law Parameters	Factors	p-Value
G_0'	carob flour, C	<0.001 *
	dried sourdough, S	<0.001 *
	C $\times$ S	<0.001 *
n	carob flour, C	<0.001 *
	dried sourdough, S	<0.001 *
	C $\times$ S	0.001 *
Tan δ	carob flour, C	0.097
	dried sourdough, S	0.056
	C $\times$ S	0.146

* statistically significant ($p < 0.05$).

Changes in both viscoelastic moduli (G' and G'') under the influence of the independent variables was further expressed through the parameter Tan δ , which represents the ratio of the loss modulus to the storage modulus (Figure 2). With the increase in carob flour from 15 to 20% in dough without dried sourdough, a significant increase in Tan δ was observed ($p < 0.05$). The increase in Tan δ is directly associated with a reduction in elastic dominance and a greater contribution of the viscous component to the overall viscoelastic behavior of the dough [37]. When 5% of dried sourdough was added to the sample with 20% carob flour, Tan δ decreased significantly ($p < 0.05$), reaching values comparable to those of other samples containing both carob flour and dried sourdough. However, two-way ANOVA showed that the changes in Tan δ in dough enriched with carob flour and dried sourdough were not statistically significant ($p > 0.05$; Table 3), as the ratio between the elastic and viscous structural interactions remained relatively balanced, indicating that the viscoelastic character of the dough samples was preserved.

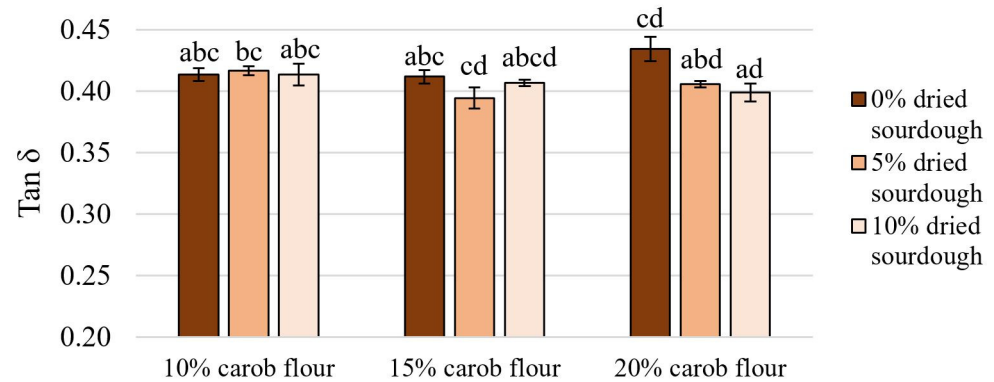


Figure 2. Influence of the amount of dried sourdough and carob flour on Tan δ . Different letters above the bars represent statistically significant difference ($p < 0.05$).

The ability of dough to withstand a certain amount of stress, as well as the measure of dough deformation and the level of recovery of its elastic part can be determined and defined by the creep and recovery test [38,39]. Examining the creep and recovery curves after the application of constant stress allows the characterization of the viscoelastic behavior of dough over longer time intervals and provides insight into the resistance of viscoelastic systems to non-destructive force [40]. Therefore, this method was applied to further evaluate the viscoelastic behavior of dough with carob flour and the effect of dried sourdough, and the corresponding creep curves were obtained (Figure 3).

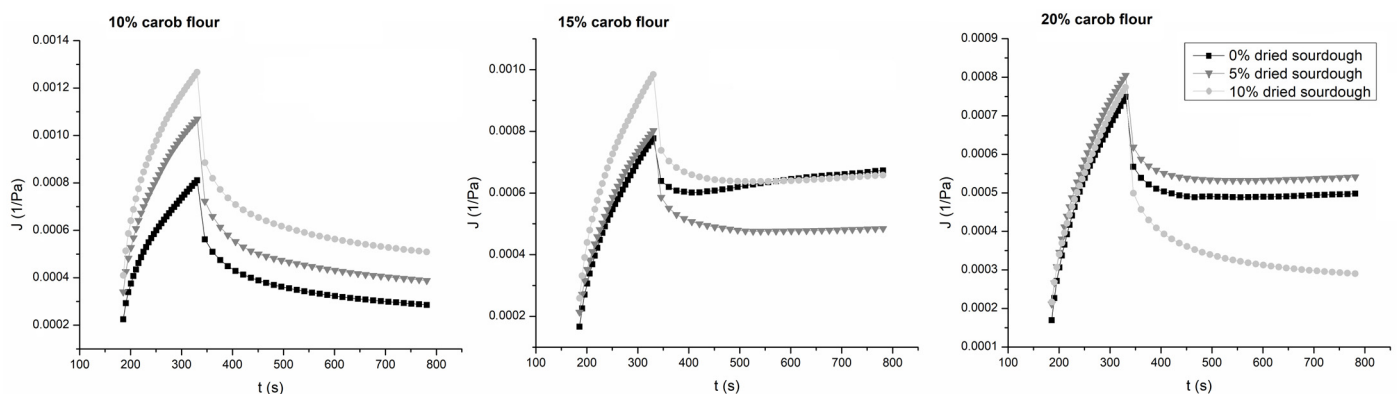


Figure 3. Creep and recovery curves influenced by the amount of dried sourdough in dough with different share of carob flour.

The appearance of the obtained creep and recovery curves for the observed dough samples confirmed the typical viscoelastic behavior. A high R^2 for the creep phase (>0.99) and a relatively high R^2 for the recovery phase (>0.94) indicated an agreement of the obtained curves with the Burger model (Table 4). Changes in compliance parameters reflect the structural strength of the system, especially its elasticity and deformation adaptability. The amount of carob flour did not significantly affect maximum compliance (J_{max}), which is the most important among compliance parameters. Nevertheless, a significant decrease ($p < 0.05$) in the value of the J_0 parameter was observed with an increase in the proportion of carob flour from 10 to 15%. Also a significant increase in Newtonian viscosity (η_0) was observed ($p < 0.05$) as the amount of carob flour increased from 10% to 20%.

Table 4. Parameters of Burgers model for creep and recovery phase as a function of carob flour and dried sourdough amount.

Independent Variable	$J_{\max}$ ($10^{-4} \cdot \text{Pa}^{-1}$)	J_0 ($10^{-4} \cdot \text{Pa}^{-1}$)	J_1 ($10^{-4} \cdot \text{Pa}^{-1}$)	η_0 ($10^5 \cdot \text{Pa} \cdot \text{s}$)	λ (s)	R^2
Creep phase						
10% carob flour						
0% dried sourdough	8.11 ± 0.12^a	2.25 ± 0.18^{ab}	2.68 ± 0.13^{ab}	4.08 ± 0.10^a	143.7^a	0.9956
5% dried sourdough	10.69 ± 0.66^c	3.40 ± 0.10^a	3.53 ± 0.11^b	3.10 ± 0.21^d	143.8^a	0.9953
10% dried sourdough	12.67 ± 0.37^b	4.10 ± 0.15^d	4.18 ± 0.13^c	2.61 ± 0.12^c	143.8^a	0.9933
15% carob flour						
0% dried sourdough	7.77 ± 0.40^a	1.66 ± 0.01^c	2.56 ± 0.02^{ab}	4.26 ± 0.09^{ab}	143.8^a	0.9977
5% dried sourdough	8.02 ± 0.06^a	2.14 ± 0.12^{ab}	2.65 ± 0.10^{ab}	4.12 ± 0.14^{ab}	143.8^a	0.9979
10% dried sourdough	9.84 ± 0.28^b	2.59 ± 0.02^{ab}	3.25 ± 0.01^b	3.96 ± 0.35^a	143.8^a	0.9961
20% carob flour						
0% dried sourdough	7.49 ± 0.35^a	1.69 ± 0.13^c	2.47 ± 0.11^{ab}	4.42 ± 0.15^b	143.8^a	0.9968
5% dried sourdough	7.74 ± 0.09^a	2.12 ± 0.01^{ab}	2.66 ± 0.02^{ab}	4.27 ± 0.21^{ab}	143.8^a	0.9975
10% dried sourdough	8.05 ± 0.13^a	2.17 ± 0.01^{ab}	2.55 ± 0.03^{ab}	4.11 ± 0.19^{ab}	143.8^a	0.9993
Recovery phase						
10% carob flour						
0% dried sourdough	N/A	5.62 ± 0.12^{ab}	0.94 ± 0.18^b	2.73 ± 0.13^{cd}	339.5	0.9560
5% dried sourdough	N/A	7.23 ± 0.18^c	1.28 ± 0.12^d	2.01 ± 0.03^c	339.7	0.9921
10% dried sourdough	N/A	8.85 ± 0.20^d	1.68 ± 0.10^c	1.53 ± 0.01^b	339.7	0.9472
15% carob flour						
0% dried sourdough	N/A	6.39 ± 0.05^b	2.22 ± 0.20^e	1.16 ± 0.01^a	339.6	0.9755
5% dried sourdough	N/A	5.86 ± 0.02^{ab}	1.60 ± 0.01^c	1.61 ± 0.00^b	339.7	0.9966
10% dried sourdough	N/A	7.38 ± 0.15^c	2.17 ± 0.10^e	1.19 ± 0.12^a	339.7	0.9954
20% carob flour						
0% dried sourdough	N/A	5.68 ± 0.08^{ab}	1.64 ± 0.12^c	1.57 ± 0.16^b	339.5	0.9884
5% dried sourdough	N/A	6.19 ± 0.11^b	1.79 ± 0.01^c	1.44 ± 0.20^b	339.6	0.9924
10% dried sourdough	N/A	4.99 ± 0.02^a	0.96 ± 0.10^b	2.69 ± 0.11^d	339.7	0.9955

J_0 —instantaneous compliance, J_1 —viscoelastic compliance, $J_{\max}$ —maximum creep compliance, η_0 —Newtonian viscosity, λ —retardation time, R^2 —the coefficient of determination. Mean $\pm$ SD ($n = 3$); values in rows marked with different letters are statistically significantly different ($p < 0.05$).

The introduction of dried sourdough into dough with carob flour changed its rheological properties. For each carob flour level, $J_{\max}$ increased as the proportion of dried sourdough increased (Table 4), indicating that the dough became softer and more susceptible to deformation under applied stress [41]. Additionally, dried sourdough decreased the viscosity of dough samples. The mentioned results are consistent with the empirical measurements reported by Zahorec et al. [23], which confirmed that the addition of sourdough causes a decrease in dough resistance and the resistance-to-extensibility ratio (R/E), indicating improved handling properties of such dough.

However, the positive effect of the dried sourdough on dough rheological properties was reduced by increasing the amount of carob flour. In samples containing 10% carob flour, the addition of 5% and 10% dried sourdough significantly increased $J_{\max}$ ($p < 0.05$). In contrast, in dough with 15% carob flour, only 10% dried sourdough had a significant effect, while in samples with 20% carob flour, no significant change was observed (Table 4). Similarly, the viscosity of dough with 10% carob flour decreased significantly by 24–36% alongside an increase in the amount of dried sourdough ($p < 0.05$). However, at higher

carob flour levels (15% and 20%), the viscosity reduction with increasing dried sourdough content was much less evident (only 3–7%) and not significant ($p > 0.05$). Presented results indicate the presence of factor interaction, that is, the combined effect of carob flour and dried sourdough on both creep parameters, $J_{\max}$ and η . Statistical analysis of the two-way ANOVA confirmed that the influence of both factors, as well as the their interaction, is statistically significant ($p < 0.05$).

All of the above effects can be attributed to the synergistic effects of various organic acids (acetic acid and lactic acid), pH reduction, and enzymes produced during sourdough fermentation [42]. The acidification resulting from microbial fermentation activates cereal proteases and increases prolamin solubility [43]. Lactic acid bacteria (LAB) were reported to induce changes in the secondary structure of gluten proteins. Gluten network was partially depolymerized into fibril- and laminar-like microstructures associated with antiparallel β -sheets and parallel β -sheets, respectively [44]. Overall, this process weakens the gluten network, leading to more stable and less elastic dough with improved extensibility [42].

3.2. Bread Quality Parameters

High-quality bread should have a well-developed internal structure, manifested by high crumb porosity [45]. To obtain data on the crumb structure of the examined bread samples, digital image analysis of the bread crumb was performed, and the results are summarized in Table 5. The presented results show that the number of pores per cm^2 increased, while the average pore area decreased with the increasing proportion of carob flour. Specifically, samples containing 15% carob flour without dried sourdough and all samples containing 20% carob flour had the lowest values of average pore area. These data indicate that the substitution of higher proportion of wheat flour with carob flour results in bread with a compact crumb and dense, small pores. Such negative impact may be attributed to the dietary fiber present in carob flour on the gluten network structure [46].

Table 5. Dependence of crumb pore parameters on the amount of carob flour and dried sourdough.

Independent Variables	Pore Density ($1/\text{cm}^2$)	Average Pore Surface Area (mm^2)	Proportion of Pore Surface Area (%)	Proportion of Pore Walls Surface Area (%)
10% carob flour				
0% dried sourdough	17.0	3.02	51.35	48.65
5% dried sourdough	13.0	3.86	49.88	50.12
10% dried sourdough	11.8	4.15	54.59	45.41
15% carob flour				
0% dried sourdough	25.0	1.62	37.36	62.64
5% dried sourdough	20.8	4.28	47.93	52.07
10% dried sourdough	19.8	4.97	48.46	51.54
20% carob flour				
0% dried sourdough	27.0	0.88	23.64	76.36
5% dried sourdough	12.5	2.07	43.03	56.97
10% dried sourdough	10.5	2.17	42.85	57.15

The effect of dried sourdough addition on pore parameters followed the opposite trend. The most pronounced impact was observed when increasing the dried sourdough content from 0 to 5% (Table 5). Similar findings were observed by Naji-Tabasi et al. [47] who investigated the effect of sourdough in whole wheat and whole barley bread. It was reported that bread porosity increased with increasing proportions of sourdough, although

the rate of this increase became less pronounced at higher sourdough levels, which is in accordance with our findings.

The highest increase in average pore surface area with the addition of 5–10% dried sourdough was observed in the sample containing 15% carob flour (Figure 4). It is also evident that increasing the content of dried sourdough increased the percentage of pores and decreased the proportion of pore walls in bread samples with equivalent content of carob flour. These parameters are closely related to the fineness of crumb structure. Pore size and structure greatly influence the tactile sensation of the crumb, whether felt between the fingers or in the mouth—thin-walled, uniformly sized cells produce a soft and elastic bread texture, which is generally appreciated by consumers [45]. It can therefore be expected that samples with a lower proportion of pore walls will have a finer crumb structure. Conversely, the addition of higher levels of carob flour to bread formulation is expected to negatively affect these sensory parameters.

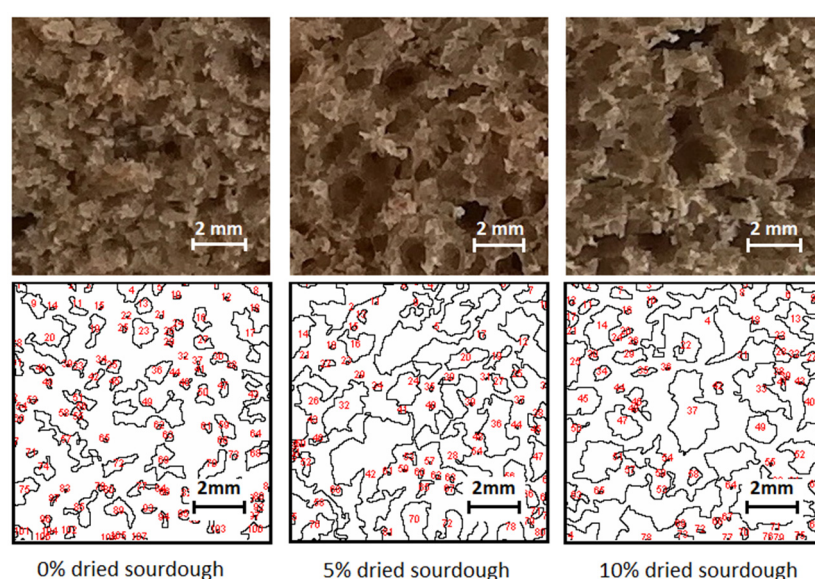


Figure 4. Original and digitally processed images (2×2 cm; 1 cm = 79 px) for pore size distribution analysis of bread crumbs with 15% carob flour and varying dried sourdough levels.

In the development of a product with acceptable sensory quality, texture should be taken into account, as textural parameters are closely related to sensory quality attributes [48]. Based on the results presented in Table 6, an increase in carob flour was associated with an increase in crumb hardness ($p < 0.05$). The incorporation of 5–10% dried sourdough in bread with 15% carob flour resulted in a significant reduction in hardness of up to 40% ($p < 0.05$). In bread containing 20% carob flour, hardness decreased by approximately 30%, and a statistically significant difference ($p < 0.05$) was observed only when 10% dried sourdough was added, compared to the corresponding sample without the improver. Crumb hardness is strongly influenced by crumb porosity. The reduction in the force required to compress the sample occurs as a result of a better-developed bread structure, due to an increase in total pore surface area [49,50].

Springiness is a measure of the crumb's ability to return to its original shape after compression, while resilience is the measure of its ability to retain shape after deformation [51]. Statistical analysis of the obtained results confirmed that differences in crumb springiness and resilience values for most examined samples were not statistically significant ($p < 0.05$). The only significant differences in resilience were observed for the sample with 20% carob flour without dried sourdough, which had the lowest recorded value (0.33), and for the sample with 10% carob flour and 10% dried sourdough, which showed

the highest value (0.46). Cohesiveness, which indicates the degree of crumb structural disruption during compression, showed a somewhat-decreasing trend with increasing carob flour content. The addition of dried sourdough did not have a significant effect on this parameter ($p > 0.05$). The changes in chewiness followed the same trend as hardness, which was expected since chewiness is obtained as a result of hardness, springiness, and cohesiveness of the bread crumb [52].

Table 6. The influence of carob flour and dried sourdough on texture properties of bread.

Independent Variables	Hardness (kg)	Springiness	Resilience	Cohesiveness	Chewiness (kg)
10% carob flour					
0% dried sourdough	0.94 ± 0.29^{abc}	0.61 ± 0.09^a	0.41 ± 0.03^{ab}	0.83 ± 0.02^{bcd}	0.48 ± 0.19^{ab}
5% dried sourdough	0.50 ± 0.06^a	0.60 ± 0.17^a	0.43 ± 0.06^{ab}	0.81 ± 0.03^{abcd}	0.24 ± 0.07^a
10% dried sourdough	0.77 ± 0.18^{ab}	0.60 ± 0.16^a	0.46 ± 0.07^b	0.85 ± 0.03^{cd}	0.41 ± 0.16^a
15% carob flour					
0% dried sourdough	1.75 ± 0.29^{ef}	0.76 ± 0.10^a	0.36 ± 0.03^{ab}	0.75 ± 0.04^{ab}	1.00 ± 0.21^c
5% dried sourdough	1.04 ± 0.18^{abcd}	0.76 ± 0.08^a	0.40 ± 0.03^{ab}	0.76 ± 0.03^{ab}	0.59 ± 0.13^{ab}
10% dried sourdough	1.10 ± 0.18^{bcd}	0.67 ± 0.16^a	0.42 ± 0.06^{ab}	0.76 ± 0.06^{abc}	0.58 ± 0.19^{ab}
20% carob flour					
0% dried sourdough	2.11 ± 0.60^f	0.64 ± 0.10^a	0.33 ± 0.05^a	0.76 ± 0.07^{abc}	1.02 ± 0.31^c
5% dried sourdough	1.55 ± 0.25^{def}	0.71 ± 0.09^a	0.35 ± 0.03^{ab}	0.73 ± 0.04^a	0.80 ± 0.14^{bc}
10% dried sourdough	1.51 ± 0.26^{cde}	0.71 ± 0.10^a	0.38 ± 0.04^{ab}	0.75 ± 0.05^{ab}	0.79 ± 0.17^{bc}

Mean $\pm$ SD (n = 5); different superscript letters in columns represent statistically significant difference ($p < 0.05$).

Based on the literature, the metabolic products of certain lactic acid bacteria include various types of exopolysaccharides, which behave similarly to hydrocolloids in dough systems [53]. It has been reported that the application of sourdough fermentation leading to exopolysaccharide formation in buckwheat bread resulted in improved bread texture, primarily through reduced hardness [54].

The characteristics of functional products often differ from those of traditional products, therefore it is essential that changes in parameters defining sensory quality remain within acceptable limits, ensuring consumer acceptability across a broad population and promoting the intake of functional components in the daily diet. In our previous publication it was reported that overall sensory quality of carob-enriched breads was enhanced by adding dried sourdough, placing samples with 10–15% carob flour in the quality category comparable to or higher than wheat bread without additives [23]. It was also observed that increasing carob flour proportion in bread formulation generally decreased taste scores, while the addition of dried sourdough mitigated this effect and improved the mouth-feel [23]. Apart from taste, the sensory attribute most affected by the addition of tested ingredients was the bread crumb structure. Accordingly, its detailed evaluation by QDA was performed, given its close relationship with physical parameters analyzed in this study. The assessed parameters included crumb development, pore fineness, elasticity, crumbliness, and color uniformity.

As shown in the results presented in Figure 5, the increase in the proportion of carob flour caused a negative effect in all evaluated parameters. In contrast, the addition of dried sourdough exhibited a significant positive effect on the observed parameters, justifying its use as a bread improver in this study. Maximum crumb development scores were recorded for samples containing 10% carob flour, regardless of the content of dried sourdough, as well as for the sample with 15% carob flour and maximum amount of dried sourdough.

Half-point lower scores were observed for the sample with maximum amount of both investigated ingredients. All other samples exhibited less developed, compact crumb structure with small pores. These results are in agreement with those obtained from digital image analysis of the bread crumb (Table 5).

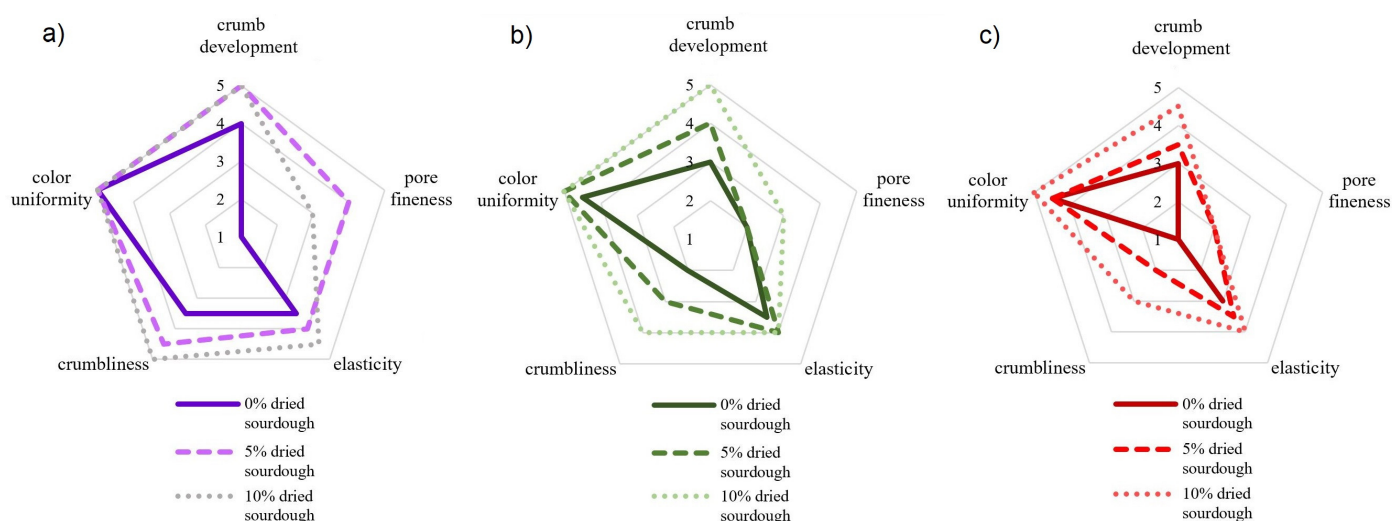


Figure 5. Crumb quality depending on the amount of dried sourdough in bread with (a) 10% carob flour, (b) 15% carob flour, and (c) 20% carob flour. Numbers 1–5 indicate sensory scores (1 = poorest; 5 = best).

The pore fineness of the sample with 10% carob flour and 5% dried sourdough was described as fine (4.0). Samples containing 15% and 20% carob flour and 10% dried sourdough scored one point lower in pore fineness. The pore fineness of the remaining samples was rated as slightly coarse and coarse (<2.0). Furthermore, QDA diagrams show that the elasticity of samples without dried sourdough was lower than that of samples with 5% or 10% dried sourdough. The negative effect of carob flour and the mitigating influence of dried sourdough on structural deterioration in bread containing 10%, 15%, and 20% carob flour were most evident in crumb crumbliness (Figure 5). Lakić and Grubačić [55] reported a similar effect in wheat bread with added sourdough, showing both decreased crumbliness and slower crumb degradation over storage. This may be attributed to the effect of sourdough on the inhibition of amylopectin recrystallization [56]. No significant deviations were found in crumb color uniformity among the samples. Although closely related to crumb development, the results showed that the cross-section color remained fairly uniform even in carob flour bread with a less developed crumb.

Summarizing the results of physical properties, textural characteristics, and sensory analysis, the findings confirm the assumptions derived from rheological measurements, highlighting the beneficial effects of dried sourdough addition in the production of carob-enriched bread. The demonstrated approach supports the production of functional bakery products with improved quality and consumer appeal, while maintaining a clean-label formulation. However, this study was conducted under laboratory-scale conditions, and if industrial-scale application were to be considered, further research would be required to optimize the process and evaluate associated costs. Additionally, it should be noted that each functional ingredient behaves differently within the dough matrix, requiring further investigation to fully understand these effects. Moreover, as various types of dried sourdoughs with distinct microbial compositions and flavor profiles are available, their selection can be tailored to specific product types and desired characteristics, offering additional formulation flexibility without the need for starter maintenance.

4. Conclusions

Based on the results of this study, it can be concluded that the use of dried sourdough in the production of carob-enriched bread represents a promising approach. The incorporation of dried sourdough positively influenced the rheological behavior of the dough during bread-making, as well as the final product quality, including improved crumb porosity, reduced hardness, and enhanced sensory characteristics. Involving the use of dried sourdough as a dough improver aligns with current trends in functional foods and clean-label products, as it may successfully replace chemical improvers. Consequently, dried sourdough could also be applied to the production of other value-added breads of lower quality, contributing to their overall quality improvement.

Further research is needed to evaluate its effects on shelf life, nutritional properties, and the cost implications of producing such specialty products. Overall, dried sourdough represents a versatile and effective ingredient for the development of high-quality, consumer-acceptable breads enriched with functional ingredients such as carob flour, offering both technological and sensory benefits.

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Appendix A

Table A1. Bread crumb quality scoring scale with descriptors for quantitative descriptive analysis.

Attribute	Descriptive Scores				
	1	2	3	4	5
Crumb development	very dense crumb	rather dense crumb	slightly dense crumb	moderately developed crumb	well-developed crumb
Pore fineness	coarse pores	slightly coarse pores	nearly fine pores	fine pores	spongy pores
Elasticity	unsatisfactory elasticity	satisfactory elasticity	good elasticity	very good elasticity	excellent elasticity
Crumbliness	extremely crumbly	rather crumbly	partly crumbly	slightly crumbly	not crumbly
Color uniformity	non-uniform color	rather non-uniform color	partly uniform color	fairly uniform color	uniform color

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