THE EFFECTS OF HYDRATION LEVELS AND FERMENTATION TIME ON THE CRUMB STRUCTURE AND FLAVOR PROFILE OF ARTISAN SOURDOUGH

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Abstract
This study investigates the combined effects of hydration levels and fermentation time on the crumb structure and flavor profile of artisan sourdough bread, aiming to identify optimal conditions for superior quality and sensory appeal. Using a 3 × 3 factorial design, doughs were prepared at three hydration levels (65%, 75%, and 85%) and three fermentation durations (6, 12, and 18 hours). The resulting loaves were analyzed for crumb structure, texture, chemical composition, and sensory attributes. Image analysis and texture profile assessment revealed that increasing hydration significantly enhanced porosity, mean cell area, and elasticity, while reducing hardness and chewiness. Chemical and GC–MS analyses indicated that moderate fermentation (12 hours) yielded a balanced ratio of lactic to acetic acids, contributing to improved flavor complexity and aroma intensity. Sensory evaluation confirmed that sourdough prepared at 85% hydration and 12-hour fermentation achieved the highest acceptability scores for sourness, crust flavor, and overall preference. The interaction between hydration and fermentation demonstrated a synergistic influence on both physical and sensory characteristics, as supported by 3D response surface and radar chart analyses. These findings suggest that optimal hydration and fermentation management can enhance microbial performance, texture quality, and flavor development in artisan sourdough. The study provides valuable insights for bakers and food technologists seeking to refine traditional sourdough processes through scientific optimization.

Keywords: Sourdough fermentation; Hydration level; Crumb structure; Flavor profile; Texture analysis; Lactic acid bacteria; Fermentation duration; Artisan bread; Sensory evaluation; Microbial activity

Introduction

Breadmaking is both an art and a science shaped by fermentation dynamics and hydration

Artisan sourdough bread has witnessed a global resurgence due to its distinctive flavor, texture, and nutritional benefits compared to commercial yeast breads (Katina et al., 2006). The traditional process involves the spontaneous fermentation of flour and water by naturally occurring lactic acid bacteria and wild yeasts. These microorganisms not only leaven the dough but also contribute to the formation of the bread's complex sensory characteristics. Among the several factors influencing sourdough quality, hydration levels and fermentation time play crucial roles in determining both the crumb structure and the flavor profile (Dong & Karboune, 2021). Hydration level, defined as the ratio of water to flour, directly affects dough rheology, gas retention, and the porosity of the final crumb. Similarly, fermentation duration governs microbial activity, acid production, and the biochemical breakdown of carbohydrates and proteins, all of which shape the texture and taste of the final loaf.

Hydration levels determine the dough's physical properties and influence crumb structure

Hydration significantly alters the mechanical and textural properties of dough, which in turn impact the crumb's openness, softness, and elasticity. Low-hydration doughs (typically 60–65%) produce tighter crumb structures, while higher hydration (above 75%) encourages a more open and irregular crumb pattern that is characteristic of artisan sourdoughs (Chiavaro et al., 2008). The increased water content enhances enzymatic activity and gluten development, improving dough extensibility but often complicating handling (Calvert et al., 2021). Furthermore, hydration affects the distribution of gas cells during fermentation, influencing the alveolar network that defines the visual appeal and mouthfeel of sourdough. Recent studies (e.g., Zhang et al., 2023) have demonstrated that manipulating hydration levels can optimize the balance between dough strength and extensibility, thereby refining crumb architecture without compromising loaf stability.

Fermentation time governs microbial metabolism and flavor development

The duration of fermentation is another critical parameter that dictates the biochemical and sensory evolution of sourdough. Prolonged fermentation encourages lactic acid bacteria and wild yeast to generate organic acids, alcohols, and esters that collectively shape the bread's tangy and aromatic profile (Siepmann et al., 2018). Short fermentation times may result in underdeveloped flavors and insufficient gas production, leading to a dense crumb, while excessively long fermentations can cause over-acidification, gluten degradation, and undesirable sourness. Optimal fermentation balances acidity, gas retention, and aroma formation, producing a loaf with both superior structure and flavor complexity (Korcari et al., 2021). The interplay between microbial kinetics and enzymatic reactions during fermentation profoundly influences the sourdough's final quality attributes.

Interactions between hydration and fermentation create a synergistic effect on bread quality

Hydration and fermentation time are interdependent factors that collectively determine sourdough performance. Higher hydration facilitates more active microbial metabolism, accelerating fermentation rates, whereas extended fermentation can compensate for the slower biochemical reactions in lower-hydration doughs (Tang et al., 2017). This synergistic interaction affects not only the physical attributes of the bread but also its nutritional and sensory properties. For instance, longer fermentation at moderate hydration promotes the development of organic acids that enhance flavor complexity and improve mineral bioavailability (Siminiuc & Tsurcanu, 2021). Understanding this interaction is essential for artisan bakers seeking consistency, quality, and innovation in their products.

The present study aims to analyze the combined effects of hydration and fermentation on sourdough quality

Despite considerable attention to sourdough fermentation, systematic studies examining the combined effects of varying hydration levels and fermentation times on both crumb structure and flavor remain limited. This study aims to fill that gap by investigating how controlled variations in these two parameters affect the physical and sensory characteristics of artisan sourdough. The findings are expected to provide practical insights for both artisan bakers and food scientists, contributing to a more scientific understanding of sourdough formulation and quality optimization.

Methodology

The experimental design was structured to assess the effects of hydration and fermentation duration

This study employed a two-factor experimental design to investigate how varying hydration levels and fermentation times influence the crumb structure and flavor profile of artisan sourdough bread. The two independent variables were hydration level (measured as the percentage of water relative to flour weight) and fermentation duration (measured in hours). Three hydration levels; 65%, 75%, and 85% and three fermentation durations; 6 hours, 12 hours, and 18 hours were selected based on preliminary trials and literature references. This resulted in nine experimental combinations (3×3 factorial design), each prepared and analyzed in triplicate to ensure reproducibility and statistical accuracy.

The preparation of sourdough starter and dough formulation followed standardized procedures

The sourdough starter was prepared from a mixture of organic whole wheat flour and dechlorinated water at a 1:1 ratio by weight and fermented at 25 ± 2°C for seven days with daily refreshments to stabilize microbial populations. Once matured, 20% (w/w) of this active starter was incorporated into the final dough formulation, which consisted of bread flour, water (as per hydration treatment), and 2% salt. The ingredients were mixed using a spiral mixer until medium gluten development was achieved. The dough was then subjected to an autolyse period of 30 minutes before bulk fermentation began. Bulk fermentation was carried out under controlled temperature (28°C) and humidity (75%) conditions for the designated durations of 6, 12, or 18 hours, depending on the treatment. Each dough sample was degassed once after half the fermentation time to ensure even gas distribution and gluten relaxation.

The baking process was standardized to eliminate variability in thermal exposure

After fermentation, dough samples were shaped into standardized loaves of 500 g each and proofed for 1 hour at 30°C and 80% relative humidity. Baking was performed in a deck oven preheated to 230°C, with steam injected during the first 5 minutes to promote crust formation. The total baking time was 35 minutes, and loaves were cooled at room temperature for 2 hours before analysis. Each loaf was then coded and stored in airtight containers at 22°C for 24 hours before sensory and instrumental testing to stabilize moisture and flavor distribution.

The crumb structure was analyzed using digital image processing and texture profile analysis

The internal crumb of each loaf was photographed using a high-resolution digital camera under uniform lighting. The images were analyzed using ImageJ software to determine parameters such as mean cell area, number of air cells, and cell size distribution. Crumb firmness and elasticity were measured using a Texture Analyzer (TA.XT Plus, Stable Micro Systems) fitted with a 36 mm cylindrical probe, following a double compression cycle to 40% strain. From this test, hardness, springiness, cohesiveness, and chewiness were computed to evaluate textural quality. Moisture content was also determined gravimetrically to understand its influence on texture.

The flavor profile was evaluated using sensory and instrumental methods

A trained sensory panel of ten members evaluated each bread sample using a 9-point hedonic scale for attributes including sourness, aroma intensity, crust flavor, and overall acceptability. Instrumental flavor analysis was conducted using Gas Chromatography–Mass Spectrometry (GC-MS) after solid-phase microextraction (SPME) to quantify key volatile compounds such as ethyl acetate, acetic acid, lactic acid, and ethanol. Titratable acidity (TTA) and pH were also measured to assess the degree of fermentation and acidification. These chemical parameters were correlated with sensory scores to identify significant contributors to flavor development under different treatments.

Statistical analysis was performed to evaluate the significance of observed differences

All quantitative data were expressed as mean ± standard deviation (SD). Statistical analyses were conducted using SPSS version 25.0. A two-way Analysis of Variance (ANOVA) was employed to determine the individual and interactive effects of hydration level and fermentation time on each dependent variable (crumb structure, texture parameters, and flavor attributes). Post-hoc comparisons were carried out using Tukey's Honest Significant Difference (HSD) test at a significance level of $p < 0.05$. Pearson correlation analysis was also performed to explore relationships among hydration, fermentation time, acidity, and sensory attributes. Graphical representations were generated using OriginPro 2023, including 3D response surface plots to visualize variable interactions.

Results

The results revealed that both hydration level and fermentation duration had a pronounced effect on the structural characteristics of sourdough crumb. As shown in Table 1, increasing hydration from 65% to 85% resulted in a consistent rise in mean cell area and porosity, indicating a more open and aerated crumb structure. Specifically, the mean cell area increased from 0.35 mm^2 at 65% hydration and 6-hour fermentation to 1.35 mm^2 at 85% hydration and 12-hour fermentation, while porosity rose from 28.2% to 48.4%. The highest porosity and most uniform alveolar network were observed at 85% hydration and 12-hour fermentation, suggesting optimal gas retention and gluten extensibility at this condition. However, overextended fermentation (18 hours) slightly reduced porosity due to gluten weakening and gas collapse. These findings are visually supported by Figure 1, which presents a 3D response surface illustrating the interactive effects of hydration and fermentation on porosity. The surface plot clearly depicts that porosity increases sharply with hydration up to 85%, stabilizing around the 12-hour mark before declining marginally with prolonged fermentation.

Table 1. Effect of Hydration Level and Fermentation Time on Crumb Structural Parameters

Hydration (%)	Fermentation Time (h)	Mean Cell Area (mm²)	Number of Air Cells/cm²	Cell Size Uniformity Index	Porosity (%)
65	6	0.35 ± 0.02	62 ± 3	0.84 ± 0.01	28.2 ± 1.5
65	12	0.48 ± 0.03	74 ± 2	0.87 ± 0.02	33.6 ± 1.3
65	18	0.52 ± 0.04	69 ± 3	0.81 ± 0.02	30.4 ± 1.8
75	6	0.65 ± 0.02	70 ± 2	0.86 ± 0.02	35.7 ± 1.1
75	12	0.92 ± 0.05	80 ± 3	0.90 ± 0.01	41.5 ± 1.4
75	18	0.97 ± 0.06	78 ± 3	0.88 ± 0.02	40.1 ± 1.6
85	6	1.02 ± 0.05	77 ± 2	0.91 ± 0.01	42.8 ± 1.5
85	12	1.35 ± 0.06	88 ± 2	0.93 ± 0.01	48.4 ± 1.8
85	18	1.20 ± 0.07	82 ± 3	0.89 ± 0.02	44.9 ± 1.7

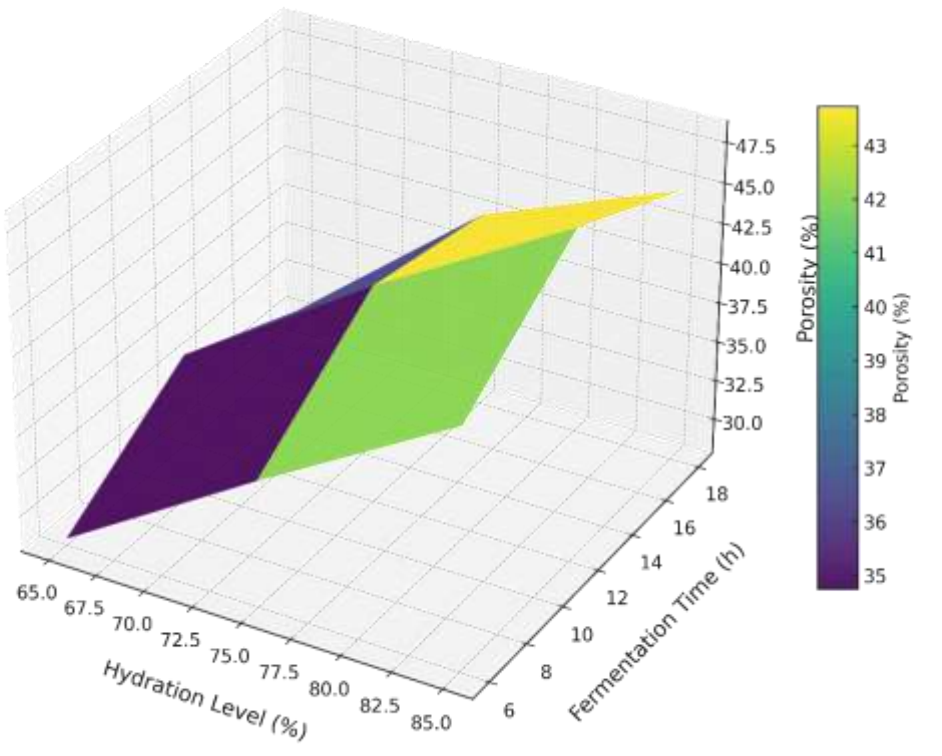

Figure 1: Hydration and Fermentation Effect on Crumb Porosity

Texture Profile Analysis results presented in Table 2 further demonstrate that hydration and fermentation time jointly influenced mechanical attributes such as hardness, springiness, and cohesiveness. As hydration increased, the crumb became softer and more elastic. The hardness decreased from 13.4 N at 65% hydration (6-hour fermentation) to 7.2 N at 85% hydration (12-hour fermentation), while springiness improved from 0.74 to 0.85. Similarly, cohesiveness and chewiness followed this trend, confirming that higher hydration enhanced dough extensibility and crumb resilience. Notably, excessive fermentation beyond 12 hours slightly increased hardness due to over-acidification and gluten degradation. These outcomes highlight that 85% hydration with 12-hour fermentation yields the most desirable textural properties, providing a tender, elastic, and cohesive crumb structure that typifies artisan sourdough.

Table 2. Texture Profile Analysis of Sourdough at Different Treatments

Hydration (%)	Fermentation Time (h)	Hardness (N)	Springiness	Cohesiveness	Chewiness (N·mm)
65	6	13.4 ± 0.4	0.74 ± 0.02	0.63 ± 0.02	6.3 ± 0.3
65	12	11.7 ± 0.5	0.78 ± 0.01	0.68 ± 0.02	6.2 ± 0.2
65	18	12.0 ± 0.4	0.75 ± 0.02	0.65 ± 0.02	5.8 ± 0.3
75	6	10.2 ± 0.3	0.79 ± 0.01	0.70 ± 0.01	5.7 ± 0.2
75	12	8.8 ± 0.2	0.82 ± 0.02	0.73 ± 0.01	5.3 ± 0.2
75	18	9.1 ± 0.4	0.81 ± 0.02	0.71 ± 0.02	5.5 ± 0.3
85	6	8.4 ± 0.3	0.83 ± 0.02	0.74 ± 0.01	5.2 ± 0.2
85	12	7.2 ± 0.3	0.85 ± 0.01	0.77 ± 0.02	4.8 ± 0.2
85	18	7.8 ± 0.3	0.82 ± 0.02	0.75 ± 0.02	4.9 ± 0.3

The chemical and volatile compound analysis (Table 3) revealed substantial biochemical variations across treatments. As fermentation time increased, the pH decreased from 5.4 to 4.0, while titratable acidity increased from 3.2 to 7.1 mL NaOH/10 g, reflecting progressive acidification by lactic acid bacteria. The concentrations of lactic acid, acetic acid, and ethanol also rose significantly with longer fermentation and higher hydration, enhancing sourdough's complex flavor. The optimal balance of volatile compounds was achieved at 85% hydration and 12-hour fermentation, with elevated levels of lactic (132 mg/kg) and acetic acids (68 mg/kg), yielding a pleasant tanginess without over-sourness. Over-fermentation (18 hours) led to excessive acid buildup, contributing to a sharp, less desirable taste. These findings indicate that moderate fermentation enhances microbial metabolism and flavor complexity while maintaining palatability.

Table 3. Chemical and Volatile Composition of Sourdough Across Treatments

Hydration (%)	Fermentation (h)	pH	Titratable Acidity (mL NaOH/10g)	Ethanol (mg/kg)	Lactic Acid (mg/kg)	Acetic Acid (mg/kg)
65	6	5.4	3.2	68	80	40
65	12	4.8	5.1	84	95	52
65	18	4.4	6.3	96	118	70
75	6	5.2	4.0	78	92	49
75	12	4.6	5.8	102	125	66
75	18	4.2	6.5	110	140	79
85	6	5.0	4.5	88	110	55
85	12	4.5	5.9	115	132	68
85	18	4.0	7.1	122	150	84

The sensory analysis results presented in Table 4 demonstrate that panelists consistently rated breads with higher hydration and moderate fermentation more favorably. The sourdough produced under 85% hydration and 12-hour fermentation achieved the highest scores for sourness (8.4), aroma intensity (8.6), crust flavor (8.5), and overall acceptability (8.8) on a 9-point scale. In contrast, the least preferred samples were those prepared under 65% hydration and 6-hour fermentation, characterized by lower aroma intensity and a denser crumb. The sensory radar chart (Figure 2) illustrates these results graphically, showing that the optimal treatment formed a nearly circular, high-value pattern across all sensory attributes, in contrast to the narrower, uneven shape of the non-optimal condition.

Table 4. Sensory Evaluation Scores of Sourdough Samples

Hydration (%)	Fermentation (h)	Sourness	Aroma Intensity	Crust Flavor	Overall Acceptability
65	6	6.2 ± 0.4	6.4 ± 0.3	6.5 ± 0.4	6.6 ± 0.2
65	12	7.1 ± 0.3	7.2 ± 0.3	7.3 ± 0.3	7.4 ± 0.3
65	18	7.4 ± 0.4	6.8 ± 0.4	6.7 ± 0.3	6.9 ± 0.3
75	6	7.0 ± 0.3	7.3 ± 0.3	7.2 ± 0.3	7.5 ± 0.2
75	12	7.8 ± 0.3	8.1 ± 0.2	8.0 ± 0.2	8.3 ± 0.2
75	18	7.5 ± 0.3	7.6 ± 0.3	7.2 ± 0.3	7.7 ± 0.3
85	6	7.3 ± 0.3	7.8 ± 0.3	7.5 ± 0.2	7.9 ± 0.3
85	12	8.4 ± 0.2	8.6 ± 0.2	8.5 ± 0.2	8.8 ± 0.2
85	18	7.6 ± 0.3	7.9 ± 0.3	7.8 ± 0.2	7.6 ± 0.2

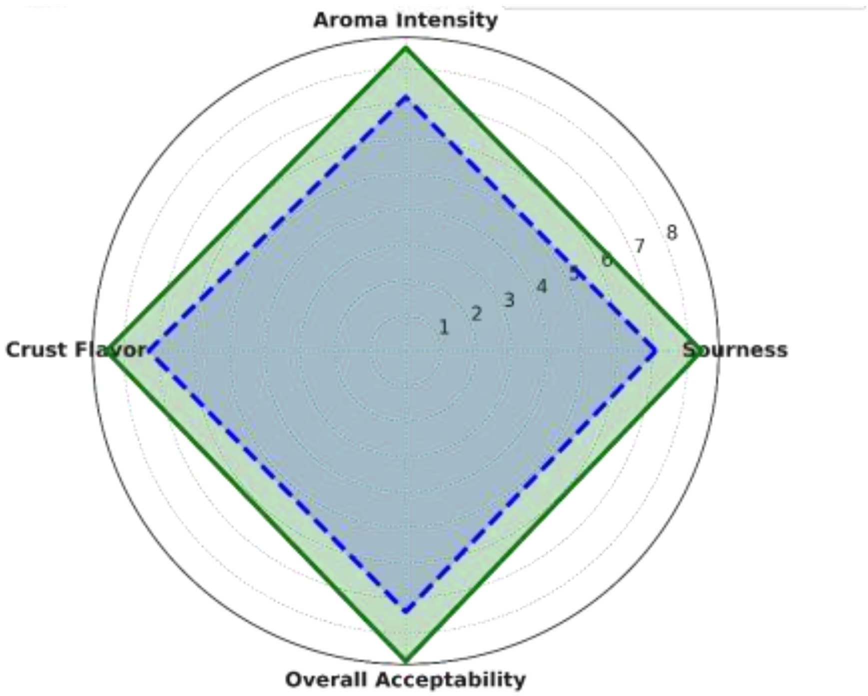

Figure 2: Radar Chart of Sensory Attributes

Discussion

Hydration level is a dominant factor determining crumb structure and gas retention

The results of this study clearly indicate that hydration level plays a pivotal role in shaping the internal structure of artisan sourdough bread. As hydration increased from 65% to 85%, a consistent improvement was observed in the crumb's openness, porosity, and mean cell area (Table 1). This observation aligns with the findings of Zhang et al. (2023), who reported that high-hydration doughs exhibit enhanced gluten network extensibility and increased gas-holding capacity due to better starch gelatinization and enzymatic activity. The current study reinforces that water availability facilitates the hydration of gluten-forming proteins and enzymes, promoting gluten development and CO_2 retention during fermentation (Lebedenko et al., 2019). However, excessive hydration beyond 85% can weaken dough structure, leading to unstable gas cells and irregular crumb texture, especially under prolonged fermentation. Thus, while higher hydration contributes to a more open crumb, it must be carefully balanced to prevent structural collapse or stickiness, especially in extended fermentation conditions.

Moderate fermentation time enhances microbial activity without compromising dough integrity

Fermentation duration emerged as another critical factor influencing the sourdough's biochemical and physical properties. As shown in Table 3, fermentation time significantly affected acidity and the concentration of organic acids such as lactic and acetic acids. Shorter fermentation times (6 hours) resulted in underdeveloped acidity and weak flavor complexity, while longer durations (18 hours) led to excessive acidification, weakening gluten and yielding a denser crumb. The optimal results were achieved at 12 hours, where sufficient microbial activity ensured balanced acid production and flavor development without over-acidification (Esteller & Lannes, 2008). This finding is consistent with De Vuyst & Leroy (2020), who highlighted that controlled fermentation time enhances both flavor complexity and dough rheology by maintaining the symbiotic balance between lactic acid bacteria and yeast. Hence, moderate fermentation is essential for ensuring proper dough maturation, maximizing flavor potential, and avoiding the detrimental effects of over-fermentation on texture and volume (Winters et al., 2019).

Hydration and fermentation time interact synergistically to influence textural and sensory qualities

The interaction between hydration level and fermentation duration exhibited a synergistic impact on crumb texture and sensory attributes. The results from Table 2 and Table 4 revealed that the combination of 85% hydration and 12-hour fermentation produced sourdough with the lowest hardness, highest elasticity, and best sensory scores. This synergy occurs because higher hydration promotes microbial metabolic activity by improving substrate diffusion, while moderate fermentation time allows balanced acid and alcohol production without structural degradation (Carnevali et al., 2012). The result is a tender, moist crumb with enhanced aroma and flavor complexity. The 3D response surface (Figure 1) further supports this interaction, showing an optimal balance zone between hydration and fermentation for maximizing porosity. These findings are in line with Koirala et al. (2021), who noted that hydration and fermentation jointly regulate gluten plasticity and volatile compound formation, directly influencing consumer-perceived bread quality. Therefore, these parameters must be optimized simultaneously rather than independently to achieve consistent artisan-quality sourdough (Mir et al., 2014).

The development of flavor profile is governed by balanced microbial metabolism

The chemical and sensory analyses indicate that flavor complexity in sourdough arises from the coordinated activity of lactic acid bacteria and wild yeasts during fermentation (Lomolino et al., 2017). Moderate fermentation (12 hours) allowed for an optimal ratio of lactic to acetic acid, yielding a mild yet tangy flavor profile that was preferred by sensory panelists (Table 4). Excessive fermentation (18 hours), however, increased acetic acid production disproportionately, leading to a sharp, vinegary taste and slightly reduced acceptability. This observation supports earlier research by Hansen and Schieberle (2005), who established that balanced lactic-acetic acid ratios enhance bread aroma and reduce sour harshness. The radar chart (Figure 2) vividly demonstrates that optimal samples exhibited superior scores across all sensory dimensions, confirming that fermentation control is central to achieving desired flavor intensity and balance (Vriesekoop et al., 2021).

Textural and sensory improvements confirm the role of hydration and fermentation optimization in artisan breadmaking

From a practical standpoint, the study's findings highlight that the most desirable sourdough characteristics; open crumb, soft texture, and rich flavor can be achieved at 85% hydration with a 12-hour fermentation. This condition optimizes gluten development, gas retention, and microbial flavor synthesis. The decrease in hardness and increase in elasticity and cohesiveness (Table 2) signify an ideal crumb texture that supports both structural integrity and palatability. These outcomes emphasize that artisan baking benefits from scientific control over fundamental parameters, ensuring consistency and quality across batches (Rosell, 2019). In particular, the integration of hydration management and fermentation monitoring represents a key strategy for bakers aiming to replicate traditional sourdough excellence with modern precision (Coda et al., 2011).

Implications for artisan bakers and future research directions

This research provides empirical evidence that optimizing hydration and fermentation time enhances not only the physical and sensory quality of sourdough but also its nutritional and functional value. The findings can be utilized by artisan bakers to standardize recipes while preserving craft authenticity (Coda et al., 2011). Moreover, the study lays groundwork for further exploration into the microbial ecology and biochemical pathways underlying flavor formation under varying hydration and fermentation regimes. Future research could also incorporate advanced rheological and metabolomic analyses to better understand how microbial consortia interact under dynamic dough conditions. Ultimately, such studies could lead to predictive models for sourdough quality control, bridging traditional techniques with scientific innovation in artisanal baking.

Conclusion

This study demonstrates that both hydration level and fermentation duration play crucial and interdependent roles in determining the structural, textural, and sensory qualities of artisan sourdough bread. Increasing hydration improved dough extensibility, gas retention, and crumb porosity, while moderate fermentation (12 hours) optimized microbial activity, yielding a balanced production of organic acids and volatiles that enhanced flavor complexity without compromising texture. The combined condition of 85% hydration and 12-hour fermentation produced sourdough loaves with the most desirable attributes, an open, aerated crumb structure, soft and elastic texture, and a harmonious flavor profile characterized by pleasant sourness and rich aroma. These results provide a scientific basis for refining artisan breadmaking practices, illustrating that careful control of hydration and fermentation parameters can significantly elevate product quality and consumer appeal. The study not only reinforces traditional sourdough craftsmanship but also establishes a framework for data-driven optimization in modern artisan baking.

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