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ORIGINAL RESEARCH PAPER

INFLUENCE OF THE ADDITION OF WAXY WHEAT FLOUR ON THE BEHAVIOR OF BAKERY YEAST IN FROZEN MINIBAGUETTE DOUGH

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Abstract: The present study investigates the influence of partial substitution of wheat flour with waxy wheat flour (10 %, 15 %, and 20 %) on the behavior of baker's yeast and on the final quality of mini baguettes obtained from frozen dough, stored for up to 56 days. Yeast activity was evaluated after 60 and 120 minutes of fermentation, being correlated with the specific volume, textural properties, and overall acceptability of the finished products. The samples with the addition of waxy wheat flour showed a better-preserved fermentative activity, especially at the substitution levels of 15 % and 20 %, both at 60 and 120 minutes. This higher yeast activity was directly reflected in higher specific volume values, indicating a better gas retention capacity in the dough. Textural analysis revealed an increase in hardness and gumminess during storage, along with a decrease in cohesiveness and resilience, but these changes were attenuated in the case of samples with waxy flour. Also, samples with higher yeast activity presented a more aerated and less dense texture, an aspect reflected in higher overall acceptability scores. In conclusion, the use of waxy wheat flour contributes to maintaining yeast activity in frozen dough, positively influencing the specific volume, texture, and sensory acceptability of mini baguettes. The results support the potential of this raw material in optimizing the quality of frozen bakery products.

Keywords: *frozen dough, waxy wheat flour, yeast activity, fermentation, texture, viability, specific volume*

INTRODUCTION

Recently, modern scientific literature has paid attention to the study of the properties of waxy wheat flour and the possibility of its use in the manufacture of food products. Most researchers have noted that waxy wheat flour, compared to classical wheat flour, has smaller particle sizes, contains a slightly lower amount of protein and a higher amount of arabinoxylan, and a higher content of damaged starch. Waxy wheat starch also has lower stability to mechanical processing compared to soft or durum wheat [1] as well as higher α-amylase activity [2]. Among the main characteristics of waxy wheat flour is a very low value of the falling index. Also, in the case of waxy wheat starch, a reduced gelatinization temperature and an increased dough viscosity can be noted, characteristics that are associated with the peculiarities of the amylopectin structure [3]. Iorgachova *et al*. (2018) demonstrated, in a series of studies, the increased capacity for sugar formation and carbon dioxide gas fermentation in the case of waxy wheat flour compared to classic bakery flour [4]. According to the results of farinograms, waxy wheat flour has a 10 - 15 % higher water absorption capacity, a 30 - 50 % increase in dough development time, elasticity and stability indicators almost halved and a dough softening index approximately 30 % higher [5]. In this regard, most researchers do not recommend using waxy wheat flour alone for the manufacture of bakery products, although in the case of adding waxy wheat flour in an amount of 10 - 20 % of the bakery flour, it is possible to obtain an improved quality of bakery products. Regarding the specific volume, researchers observed an increase in it with the addition of waxy wheat flour and a higher porosity and a fresher crumb during storage [6].

Hexaploid wheat (*Triticum aestivum* L.) is a widely cultivated variety that contains 70 - 75 % of the dry weight of starch stored in the endosperm [3]. 43 countries consume wheat-based starchy foods, representing 35 % of the total world population [7]. This makes wheat a highly valuable food ingredient globally from a nutritional point of view. Being rich in fiber and carbohydrates, it is recommended in balanced diets in different contexts [8, 9].

To improve the stability of wheat starch and flour, various methods have been studied to stabilize or modify their functionality to meet the desired quality standard. In this regard, several methods have been studied, such as the use of hydrocolloids [10], chemical methods using oxidizing and reducing agents [3, 11,12], and physical methods using heat and pressure [13–15]. Mixing different types of starch and flour is a form of modification widely used in food systems [16].

Waxy wheat was first produced in Japan by Hoshino *et al*. (2010) using the traditional hybridization method [17]. Like other types of starches and waxy flours, waxy wheat starch also contains an amylose content of up to 1 %. Amylose/amylopectin ratios and granule structure influence the physicochemical and processing properties of starch [18, 19]. Due to the lack of amylose, waxy wheat starch has a reduced interaction with starch lipids, which leads to a subsequent loss of amylose-lipid inclusion complexes, thus affecting water binding capacity. However, waxy wheat effectiveness in frozen dough systems remains insufficiently explored [7].

The literature suggests multiple uses for waxy wheat, including blending with conventional wheat flour to improve the texture of bakery products during shelf life, processing, and quality of the finished product [17]. The presence of null alleles influences the physicochemical and functional properties of waxy wheat, and therefore, the quality of waxy wheat flour cannot be determined solely by the quality and quantity of proteins, but by the interaction of proteins with amylose, amylopectin, and damaged starch [20]. Compared with common wheat flour, waxy wheat flour has lower protein and amylases, and higher crude starch content, thus presenting better processing characteristics such as shorter dough development time and extensibility [7]. A study by Bhattacharya *et al*. (2002) suggests that substituting 20 % of white wheat flour with waxy wheat flour can improve crumb softness and delay staling [21].

Waxy wheat has a different starch ratio compared to conventional wheat flour. The amylose-amylopectin ratio varies depending on the starch, but typical amylose-amylopectin ratios are 25 - 28 % and 72 - 75 %, respectively. Waxy wheat grains (without amylose) have an amylose content of less than 5 %. This different amylose-amylopectin ratio leads to different starch granule structures, different physicochemical properties, and influences the quality of the final products.

The ratio of amylopectin to amylose contributes to the properties of flour and influences the texture, viscosity, and stability of processed foods made from this flour.

Several researchers have reported that waxy wheat starch and waxy wheat flour have different properties compared to conventional wheat flour [22]. Waxy wheat starch exhibited higher initial and peak gelatinization temperatures, gelatinization enthalpy, and degree of crystallization. Products made with waxy wheat starch also exhibited higher refrigeration and freeze-thaw stability than those made with non-waxy starches. There are also studies showing that bread containing waxy wheat flour has a longer shelf life due to reduced rates of stalling [21]. It has been suggested that waxy wheat flour could replace 10 - 25 % of regular wheat flour in bread, tortillas, pancakes, cakes, and pastries with a positive effect on softness, improved freshness, and increased shelf life. Due to its effect on softness, waxy wheat flour can be used to replace some of the fatty or oily ingredients in a food, thereby reducing calories [23]. The use of waxy wheat flour to produce frozen dough has not been fully studied to date. In frozen dough, structural changes in the gluten network occur during freezing and storage, and yeast activity is often low.

The quality of bread made from frozen dough is diminished by the changes that occur during freezing. New varieties of waxy wheat flour containing less than 2 % amylose offer unique properties to produce bakery products: the first seems to be related to freezing and water migration during freezing, the second to damage to yeast cells due to ice and the concentration of solutes upon freezing. In practice, the detrimental effects can be mitigated by adding dough treatment agents, increasing protein or yeast levels, or modifying processing conditions to limit initial yeast activity. This study aims to evaluate the effect of partial substitution of wheat flour (10 - 20 %) with waxy wheat flour on yeast fermentative activity and the quality of frozen minibaguette dough during storage.

MATERIALS AND METHODS

For the study tests, white wheat flour 650 made by SC SAPTE SPICE SA was used (Iași, Romania). The wheat flour used in this study was analyzed in accordance with Romanian and international standard methods, according to the International Association for Cereal Science and Technology – ICC, and presented the following characteristics: moisture - 14.1 % (ICC 110/1); ash - 0.65 % (ICC 104/1); wet gluten - 29.2 % (ICC 106/1); falling number - 416.5 s (ICC 107/1); deformation index - 2 mm (SR 90-2007). For this study,

the behavior of fresh baker's yeast in compressed form and packaged in 500 g packages, marketed by SC ROMPAK SRL (Pașcani, Romania), was analyzed. The baker's yeast was analyzed according to Romanian and international standard methods, having the following characteristics: dry matter - 33.34 %, protein content in dry matter - (N x 6.25) 43.375 %, fermentative activity after 60 minutes - 799 mL CO_2, fermentative activity after 120 minutes - 920 mL CO_2, trehalose content - 18.6 %. The waxy wheat flour Innosense Wheat 11402 (Limagrain, France) was used for the tests. It is a heat-treated wheat flour that does not show the retrogradation phenomenon, having a high viscosity and high water-binding capacities. It also shows very good stability to *p*H variations and temperature variations, including freeze-thaw stress. Waxy wheat flour Innosense Wheat 11402 has, according to the technical specification, a viscosity value of 1300 cP. For the tests, extrafine recrystallized, iodized salt from the manufacturer Ginavidor was used, with a sodium chloride content of 99.5 %.
Drinking water from the mains was used, with a hardness of 22 °dH (ISO 6059:1984). Commercial ice cubes were used for the tests. The tests used the Eka Excel Fresh bakery improver, composed of the following ingredients: enzymes - fungal alpha-amylase, fungal xylanase, bacterial xylanase, and lipase - and ascorbic acid, intended to correct the rheological parameters of the flour used, the improver produced and marketed by SC ROMPAK SRL (Pașcani, România).

Manufacturing recipe

Mini baguettes of 72 g of dough were made according to the manufacturing recipe described in Table 1.

Table 1. *Manufacturing recipe for mini baguettes*

Material	A1		A2		A3		A4	
	Quantities for 1000 g of dough							
Wheat flour 650 [g]	620.35	100%	558.32	90%	527.3	85%	496.28	80%
Fresh yeast [g]	24.81	4%	24.81	4%	24.81	4%	24.81	4%
Salt [g]	12.41	2%	12.41	2%	12.41	2%	12.41	2%
Bread improver [g]	1.24	0.2%	1.24	0.2%	1.24	0.2%	1.24	0.2%
Water [mL]	206.79	33%	206.79	33%	206.79	33%	206.79	33%
Ice [g]	134.4	22%	134.4	22%	134.4	22%	134.4	22%
Waxy wheat flour [g]	-	-	62.03	10%	93.05	15%	124.07	20%

The raw materials were weighed, dosed and kneaded for five minutes at low speed and another five minutes at high speed of the mixer (Esmach S.p.a., Italy).
At the end of the kneading stage, the temperature of the dough was measured, taking care that it was between 19 and 20 °C. No variations in the addition of ice water were necessary, so that the temperature remained within the mentioned range.
The dough thus prepared was divided into 56 pieces of 72 g of dough each. The dough pieces were automatically shaped in the form of minibaguettes on the MANU/FFBT/M750 shaper (Esmach S.p.A., Italy).
300 g samples of dough were also prepared to determine the yeast activity.
The freezing of the samples was carried out in an EVCO Group thermal shock freezer with a capacity of four trays at a temperature of -35 °C.

The freezing time was 45 minutes. The temperature of the minibaguettes in the thermal center at the end of freezing was -15 °C.
The storage of the frozen dough samples and the frozen finished products was carried out in a Criocabin EF1216VT01 cold room at a temperature of -18 °C for a period of eight weeks. The samples were taken and analyzed weekly.
The storage of the frozen dough samples and the frozen finished products was carried out in a Criocabin EF1216VT01 cold room at a temperature of -18 °C for a period of eight weeks. The samples were analyzed over a period of 56 days. The analyses were performed after 7, 14, 28, 42, and 56 days of storage, respectively.
Thawing of the dough samples and finished products took place in a refrigerator whose temperature was set at 8 °C. The defrosting time in the refrigerator was 90 minutes. After defrosting in the refrigerator, the samples were subjected to defrosting at ambient temperature, 22 °C, for 30 minutes.
Fermentation of the minibaguettes was performed in a proofer (Miwe, Germany), whose temperature was set at 35 °C and humidity at 75%, for 50 minutes.
Baking of the minibaguettes was performed in a ventilated Aero e+ oven (Miwe, Germany), with ventilation set at level 4, at a temperature of 230 °C, for 10 minutes, with 120 ml of steam at the beginning of baking. The technological parameters of the analyzed samples are presented in Table 2, where:

- **A1** - control sample, without the addition of waxy wheat flour;
- **A2** - sample of mini baguettes with the substitution of 10 % wheat flour with waxy wheat flour in the recipe;
- **A3** - sample of mini baguettes with the substitution of 15 % wheat flour with waxy wheat flour in the recipe;
- **A4** - sample of mini baguettes with the substitution of 20 % of the white wheat flour in the recipe with waxy wheat flour.

Table 2. *Technological parameters of minibaguette samples subjected to variations in freeze-thaw parameters*

Sample	Dough temp [°C]	Kneading time [min]	Freezing time [min]	Defrosting time at 8 °C	Defrosting time at 22°C	Fermentation time [min]	Baking time [min]	Oven temp [°C]
A_1	19.8	10	45	90	30	50	6	230
A_2	19.8	10	45	90	30	50	6	230
A_3	19.8	10	45	90	30	50	6	230
A_4	19.9	10	45	90	30	50	6	230

Analysis methods. Dough rheological properties analysis

Parameters such as water absorption, dough development time, dough stability during kneading, and dough softening index during kneading were analyzed using the Brabender farinograph according to the standard SR EN ISO 5530-1:2025 Part 1: Determination of water absorption and rheological properties using a farinograph. The rheological properties of the dough, such as strength, extensibility, strength-to-extensibility ratio, and energy, were determined with the Brabender extensograph. The determinations were carried out according to the standard SR EN ISO 5530-1:2025 Part 2: Determination of rheological properties using an extensograph. The value of the falling number, which is an indicator of α-amylase activity in wheat flour, was determined with the Falling Number equipment (PerkinElmer, Hägersten, Sweden) according to the standard method ICC 107/1: 2024. The rheological kneading and viscosity properties of the dough were determined with the Mixolab equipment (Chopin, Tripette, and Renaud, Paris, France) according to ICC 173/1: 2011. The parameters analyzed were flour hydration capacity (WA), dough formation time (DT), dough stability (ST), dough softening due to proteins (C2), starch gelatinization (C3), stability of the starch gel formed (C4), and starch retrogradation during the cooling phase (C5).

Analysis of quality parameters of mini baguettes

The obtained mini baguettes were analyzed for their physical, textural, color, and sensory characteristics. The physical characteristics of the bread (specific volume of the bread, porosity, and elasticity) were determined according to the Romanian standard method SR 91: 2007. The specific volume of the finished product samples was determined using the TexVol Instrument BVM apparatus. The textural parameters of the finished product samples (firmness, gumminess, cohesiveness, and resilience) were determined using the TVT-6700 textural analyzer (Perten Instruments, Hägersten, Sweden) equipped with a 10 kg load cell. The 50 mm wide test samples were subjected to two compression cycles up to 20 % of their original height using a 45 mm cylinder at a speed of 1.0 mm/s, a trigger force of 5 g, and a recovery period between compressions of 15 s. The sensory analysis was performed using a 9-point hedonic scale (where 1 represents “dislike extremely” and 9 represents “like extremely”) using a panel of 10 semi-trained evaluators. The following sensory characteristics of the finished product were evaluated: appearance, aroma, taste, color, texture, smell, and overall acceptability

Analysis of yeast activity in mini baguette dough after thawing
Determination of baker's yeast activity

Yeast activity was measured using a Y55 gastograph (Yucebas Machinery Analytical Equipment Industry, Turkey). Yeast fermentation performance analysis evaluates CO_2 production during the fermentation of a dough sample under standardized conditions of formulation, temperature, and humidity. The method determines the total or cumulative gas production over a predetermined time at a controlled temperature, expressed in mL.

Figure 1. *Gastograf Y55 Yucebas Machinery*

RESULTS AND DISCUSSION

Influence of the addition of waxy wheat flour on the rheological and technological properties of the dough

The results of the analyses are summarized in Table 3.

Table 3. *Technological properties of dough samples*

Sample	Hydration capacity [%]	Development time [min]	Stability [min]	Softening index UF
A_1	60.3	2.5	9.8	33
A_2	60.3	3.4	7.9	68
A_3	60.2	5.0	6.2	98
A_4	61.1	4.5	6.5	107

The addition of waxy wheat flour has a clear effect on the rheological properties of the dough by increasing the hydration capacity, which indicates that waxy flour, rich in amylopectin, has a higher water retention capacity, prolonging the dough development time, lower dough stability, which thus becomes less resistant to kneading and mechanical stress, but also increasing its softening during kneading. The enhanced water interaction of waxy wheat flour arises from the highly branched structure of amylopectin, whose abundant hydroxyl groups and open molecular conformation promote hydrogen bonding with water, facilitate granule swelling, and reduce chain reassociation after gelatinization.

Influence of waxy wheat flour addition on biaxial stretching rheological properties

The results of the analysis are summarized in Table 4.

Table 4. *Biaxial tensile rheological properties of dough samples*

Sample	R [BU]	E [mm]	Energy [cm^2]	R/E
A_1	231	159.6	67.2	1.45
A_2	218	110.6	40.0	1.96
A_3	228	105.9	37.4	2.15
A_4	205	102.5	30.5	2.01

The addition of waxy wheat flour weakens the gluten network, with values decreasing as the percentage of white wheat flour in the recipe is replaced with waxy wheat flour. A decrease in energy values is also observed, indicating a lower stability to deformation with the increase in the amount of waxy wheat flour. The weakening of the gluten network with increasing waxy wheat flour substitution can be explained by the unique starch composition of waxy wheat, which is composed almost entirely of amylopectin. The highly branched amylopectin structure has numerous hydrophilic sites and exhibits high water-binding capacity, causing strong competition between starch and gluten proteins for available water. Reduced protein hydration limits gluten unfolding and decreases the formation of intermolecular interactions such as disulfide bonds, hydrogen bonds, and hydrophobic interactions that are necessary for a cohesive gluten matrix. In addition, starch-protein interactions may hinder gluten aggregation and reduce high-molecular-weight gluten polymer formation, resulting in a weaker and less deformation-resistant gluten network [24]

Influence of the addition of waxy wheat flour on the rheological kneading and viscosity properties of the dough

The rheological properties of the dough determined with the Mixolab apparatus are presented in Table 5.

Table 5. *Rheological kneading and viscosity properties of dough when analyzed on Mixolab*

Sample	WA [Nm]	ST [min]	C2 [Nm]	C3 [Nm]	C4 [Nm]	C5 [Nm]
A_1	1.082	9.1	0.484	2.028	1.978	2.783
A_2	1.153	6.4	0.399	1.657	1.545	2.180
A_3	1.264	5.2	0.389	1.509	1.369	1.940
A_4	1.420	3.7	0.390	1.408	1.296	1.875

WA, hydration capacity of wheat flour; opposite moment of dough: C2, measures the softening of the dough due to proteins; C3, measures the gelatinization of starch; C4, measures the stability of the starch gel formed; C5, measures the retrogradation of starch during the cooling phase.

Influence of waxy wheat flour addition and storage time on yeast activity

In the experiments, data from the specialized literature and from previous own research were used to choose the freezing-thawing parameters. Also, the choice of the type of baker's yeast was carried out from own research, which concluded that the best type of baker's yeast for frozen dough is compressed baker's yeast. The results obtained regarding the fermentative activity of baker's yeast by analysis with the Gastograf are summarized in Tables 6 and 7.

Table 6. *Yeast fermentative activity, after 60 minutes of analysis, in frozen mini baguette dough during storage (mL CO_2)*

Frozen dough sample	Storage time of frozen dough, [days]					
	0	**7**	**14**	**28**	**42**	**56**
A1	624	618	600	571	519	472
A2	614	608	590	562	511	473
A3	623	621	602	574	531	483
A4	633	626	608	579	526	478

Based on the data presented in Tables 6 and 7, yeast fermentative activity in frozen mini-baguette dough progressively decreased with increasing storage time in all formulations. This reduction is consistent with previous reports showing that prolonged frozen storage negatively affects yeast functionality due to ice crystal formation, osmotic stress, and damage to cellular membranes, resulting in reduced metabolic activity and gas production [25].

Table 7. *Yeast fermentative activity, after 120 minutes of analysis, in frozen mini baguette dough during storage (mL CO_2)*

Frozen dough sample	**Storage time of frozen dough, [days]**					
	0	**7**	**14**	**28**	**42**	**56**
A1	779	771	748	713	660	600
A2	779	763	727	694	630	583
A3	854	845	804	767	695	633
A4	857	840	815	777	705	685

Although all samples exhibited a gradual decline in CO_2 production during storage, formulations containing higher levels of waxy wheat flour (A3 and A4) tended to maintain greater fermentative activity, particularly after the longer fermentation period (120 min). Similar observations have been reported for frozen dough systems containing waxy wheat flour, were moderate incorporation levels improved dough performance during frozen storage [26].
The observed behaviour may be associated with the high amylopectin content of waxy wheat flour, which has been reported to increase water absorption and modify water distribution within the dough matrix. Improved water retention may reduce localized dehydration during freezing and help maintain a more favourable microenvironment for yeast cells. In addition, waxy wheat flour has been shown to reduce water redistribution and limit structural changes occurring during frozen storage, contributing to better preservation of dough properties.
However, previous studies also indicate that excessive waxy wheat flour incorporation may weaken gluten structure and alter gas retention properties, suggesting that the effects of waxy flour in frozen dough depend on the balance between improved hydration characteristics and maintenance of structural integrity [26].
Overall, the present results suggest a tendency for formulations containing 15 - 20 % waxy wheat flour to better maintain fermentative activity during frozen storage; however, additional investigations are needed to confirm the mechanisms involved.

Influence of waxy wheat flour addition and storage time on the physical characteristics of mini baguettes. Influence of waxy wheat flour addition and storage time on the specific volume of mini baguettes

The variation in the specific volume of mini baguettes with different levels of waxy wheat flour addition is presented in Figure 2. Initially, the specific volume increased with the addition of waxy wheat flour, and this trend was also maintained after 7 days of storage. This behavior may be related to the high amylopectin content of waxy wheat flour, which enhances water absorption and availability within the dough system, potentially supporting yeast activity and promoting gas cell expansion during fermentation. Furthermore, the delayed starch retrogradation associated with amylopectin-rich systems may contribute to a more extensible dough structure during the early stages of storage. However, after 14 days of frozen storage, a general decrease in specific volume was observed for all samples, with a more pronounced reduction at higher substitution levels. Sample A4 reached a specific volume of 3.94 $cm^3 \cdot g^{-1}$ compared to 4.13 $cm^3 \cdot g^{-1}$ for A1. This behavior suggests that although moderate levels of waxy wheat flour may initially favor dough expansion, higher substitution levels can progressively weaken the gluten network due to starch-protein interactions and competition for water. During frozen storage, structural damage caused by ice crystal formation and reduced gluten integrity may impair gas retention capacity, resulting in a greater loss of specific volume. Therefore, the initial beneficial effect on dough expansion appears to be counterbalanced by reduced structural stability under prolonged freezing conditions.

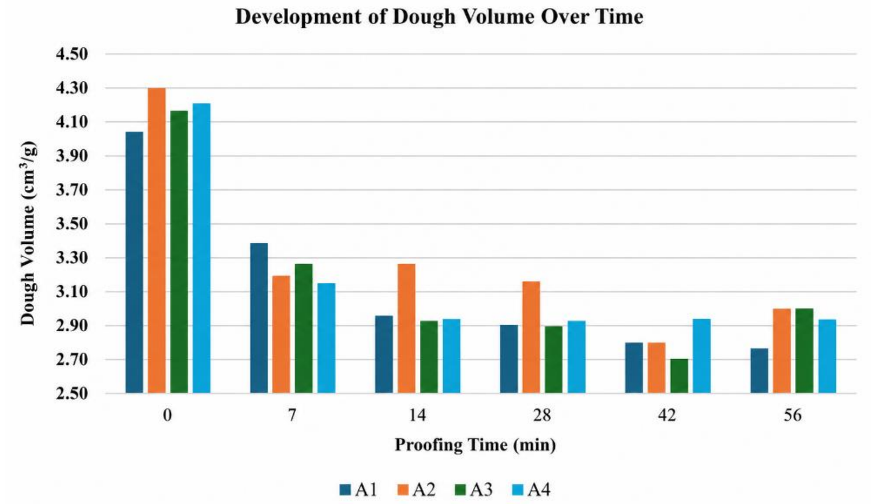

Figure 2. *Effect of storage time on the specific volume of mini baguettes*

At 28 and 42 days of storage, respectively, sample A3 presents the best specific volume values, a result that suggests the existence of an optimal level of substitution (15 %) that confers structural stability and a good CO_2 gas retention capacity during storage. After 56 days of storage at -18°C, all samples register decreases in specific volume, but the differences become more evident: sample A3 maintains a high value, 4.52 $cm^3 \cdot g^{-1}$, while the specific volumes of the mini-rods corresponding to samples A1, A2 and A4 decrease to 3.83 $cm^3 \cdot g^{-1}$; 3.96 $cm^3 \cdot g^{-1}$ and 3.81 $cm^3 \cdot g^{-1}$, respectively, which demonstrates that 15 % substitution of white wheat flour with waxy wheat flour ensures the best stability during long-term storage, while a 20 % substitution percentage negatively affects the specific volume of the mini baguettes.

Influence of waxy wheat flour addition and storage time on the texture of mini baguettes

The analysis of the textural parameters of the mini baguettes revealed that both frozen storage duration and the level of substitution of white wheat flour with waxy wheat flour significantly influenced product quality (Figures 3-6). Across all formulations, hardness generally increased during storage, reflecting starch retrogradation and structural reorganization associated with bread aging. However, the magnitude of these changes differed among samples. The control sample (A1) exhibited the greatest increase in hardness, indicating a higher susceptibility to staling and freshness loss. In contrast, waxy wheat-containing samples (A2 - A4) showed a slower evolution of texture parameters, with the effect becoming more pronounced as substitution level increased. Sample A4 (20 % substitution) displayed the best preservation of a softer and more stable texture throughout the 56-day storage period, suggesting that waxy wheat flour effectively reduced structural deterioration during frozen storage.

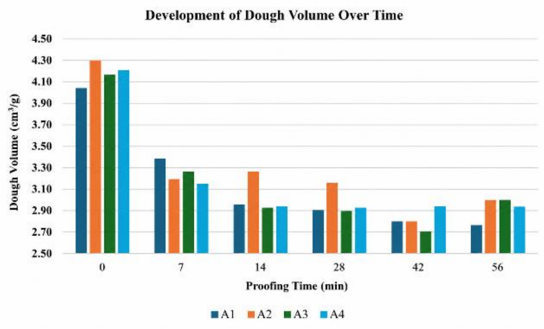

Figure 3. Influence of storage time on the hardness of mini baguettes

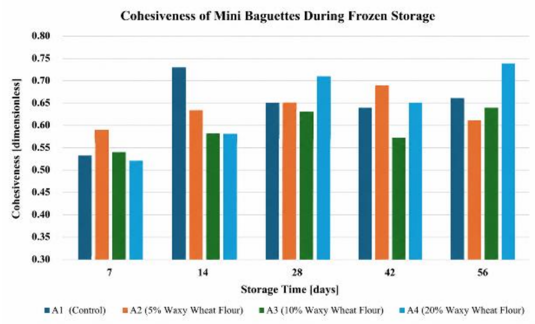

Figure 4. Influence of storage time on the cohesiveness of baguettes

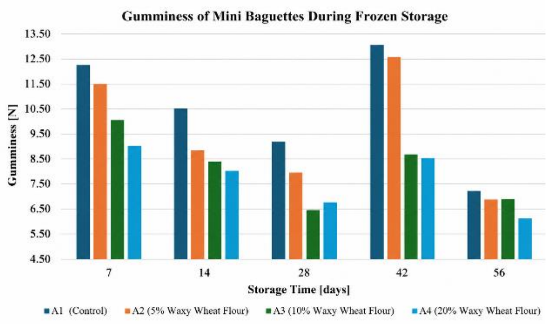

Figure 5. Influence of storage time on the gumminess of mini baguettes

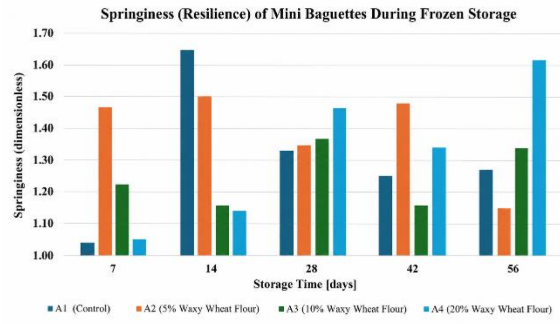

Figure 6. Influence of storage time on the resilience of mini baguettes

The evolution of cohesiveness indicates a gradual decrease over time, suggesting a weakening of the internal structure of the core. However, the samples with waxy flour maintain higher values compared to the control, which indicates a more stable structure and a better ability to resist deformation. This behavior suggests a favorable interaction between the starch fractions and the gluten network in the presence of waxy flour.

Regarding gumminess, it follows a similar trend to hardness, with increasing values during storage, reflecting a denser and less sensorially pleasant texture. However, samples A3 and A4 present lower gumminess values compared to A1, which indicates a positive effect of waxy flour in limiting textural degradation.

Resilience, as an indicator of the product's ability to return to its original shape after deformation, progressively decreases in all the variants analyzed. However, samples with higher substitution levels (A3 and A4) show a slight decrease, suggesting better preservation of elasticity during frozen storage of the samples. Overall, the results demonstrate that the addition of waxy wheat flour has an improving effect on the textural properties of frozen mini baguettes, reducing the negative impact of long-term storage. The effect is concentration-dependent, with the 20 % substitution level (A4) being the most effective in maintaining an optimal texture, characterized by reduced hardness, high cohesiveness, and better resilience.

These observations confirm that waxy wheat flour can be used as a functional ingredient in frozen bakery products, contributing to slowing down the aging processes and maintaining textural quality during storage of up to 56 days.

Influence of variations in freezing-thawing parameters and storage time on the sensory characteristics of mini baguettes

The results obtained highlight that the partial substitution of white wheat flour with waxy wheat flour significantly influences the evolution of the overall acceptability of mini baguettes obtained from frozen dough, during storage (Table 8). The control sample (A1) presented a constant decrease in sensory scores, from 8.67 at the initial time to 7.00 after 56 days, confirming the negative impact of frozen storage on sensory quality, in the absence of functional ingredients. This behavior is consistent with the observations reported by Ronda *et al*. (2015), which highlight the progressive degradation of sensory properties in frozen bakery products [27]. In the case of the substituted samples, a progressive improvement in sensory stability is observed in proportion to the increase in the level of waxy flour (10 - 20 %). Thus, sample A2 (10 %) shows a slower reduction in acceptability compared to the control, while samples A3 (15 %) and A4 (20 %) maintain higher values throughout the analyzed period, with A4 recording the highest final score (7.83). These results are supported by studies conducted by Hung et al. (2007), which demonstrated that the use of waxy flours contributes to improving the texture and acceptability of bakery products [28].

Table 8. *Overall acceptability of minibags during storage*

Frozen dough sample	Storage time of frozen dough, [days]					
	0	**7**	**14**	**28**	**42**	**56**
A1	8.67	8.17	8.17	7.50	7.33	7.00
A2	8.67	8.50	8.33	8.0	7.83	7.17
A3	8.33	8.50	8.50	8.0	7.83	7.67
A4	8.33	8.50	8.50	8.2	8.0	7.83

The favorable effect of waxy wheat flour can be explained by the structural peculiarities of starch, characterized by a high amylopectin content and a low level of amylose. According to Gray & Bemiller (2003), starch rich in amylopectin shows a reduced tendency to retrograde, a phenomenon responsible for the hardening of the crumb and the loss of freshness in bakery products [29]. This phenomenon is considered the main mechanism of bread staleness. The observed behavior can also be correlated with changes in the rheological properties of the dough. Studies by Rosell *et al*. (2001) show that changes in starch composition influence the water retention capacity and the stability of the gluten network, essential aspects for maintaining the quality of frozen products [30]. In addition, Angioloni & Collar (2009) demonstrated that functional ingredients can slow down the aging processes by modifying starch-water-gluten interactions [31]. Synthesis of sensory results for mini baguette samples analyzed according to the storage duration of the frozen dough are presented in Figure 7.

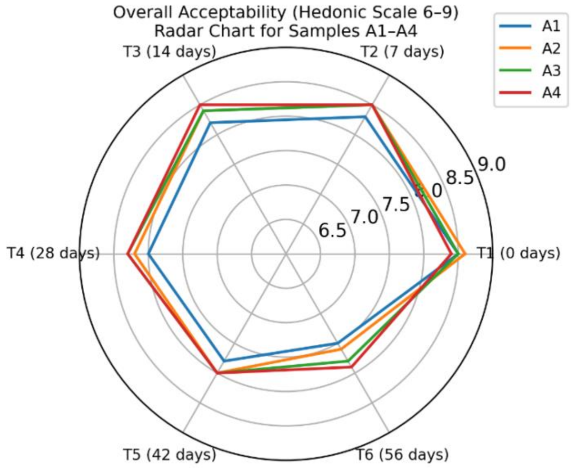

Figure 7. *Synthesis of sensory results for mini baguette samples analyzed according to the storage duration of the frozen dough*

Overall, the results confirm that, although all samples show a gradual decrease in acceptability with increasing storage time, the amplitude of this decrease is significantly reduced in the case of samples with higher substitution levels. This aspect emphasizes the role of waxy flour as a functional ingredient in the formulation of frozen bakery products. In conclusion, the substitution of white wheat flour with waxy wheat flour, in proportions of up to 20 %, represents an effective strategy for improving the sensory stability of mini baguettes during frozen storage. The results obtained support the use of this raw material in the development of bakery products with extended shelf life, by limiting starch retrogradation phenomena and maintaining the quality perceived by the consumer.

Correlations between yeast fermentative activity and the specific volume of mini baguettes

After 56 days of frozen storage, descriptive statistical analysis revealed moderate variations in specific volume and yeast activity between the analyzed samples (Table 9). The samples with waxy wheat flour addition (A3 and A4) showed higher mean values of fermentative activity, especially at 120 minutes, compared to the control sample, indicating better yeast viability in the modified systems.

Table 9. *Influence of frozen storage duration on yeast fermentative activity and specific volume of the finished product*

Frozen dough sample	Specific volume [$cm^3 \cdot g^{-1}$]	Yeast activity after 60 minutes [mL CO_2]	Yeast activity after 120 minutes [mL CO_2]
A1	3.15 ± 0.47	567.3 ± 60.47	711.8 ± 70.02
A2	3.29 ± 0.51	559.7 ± 56.73	696.0 ± 76.77
A3	3.16 ± 0.49	572.3 ± 55.69	766.3 ± 87.36
A4	3.19 ± 0.44	575.0 ± 61.45	779.8 ± 71.29

Anova analysis (p-value): Specific volume p = 0.963; yeast activity 60 minutes p = 0.970; yeast activity 120 minutes p = 0.199

The results of the ANOVA analysis did not reveal statistically significant differences between the samples ($p > 0.05$), suggesting that the observed variations may be associated with both formulation composition and the effects of frozen storage. Although no significant differences were detected, descriptive analysis indicated trends toward changes in fermentative behavior and specific volume with increasing levels of waxy wheat flour substitution. Samples A3 and A4 showed relatively higher yeast activity values at 120 minutes, which coincided with slightly greater specific volume values and a more aerated crumb structure. These observations may suggest that waxy wheat flour influences dough behavior and fermentation characteristics; however, due to the lack of statistical significance, these tendencies should be interpreted cautiously and cannot be considered conclusive evidence of improved fermentative performance or gas retention capacity.

CONCLUSIONS

The results of the study highlight that the activity of baker's yeast is a determining factor in establishing the final quality of mini baguettes obtained from frozen dough, being strongly influenced by both the storage time and the composition of the recipe. As the storage time increased up to 56 days, a progressive reduction in yeast fermentative activity was observed, evaluated at 60 and 120 minutes, a phenomenon associated with freezing-induced stress on yeast cells. This decrease in activity was directly correlated with the reduction in specific volume and the deterioration of textural characteristics, especially in the case of the control sample (A1). The substitution of white wheat flour with waxy wheat flour had a positive effect on maintaining yeast activity, an effect that intensified with increasing substitution level. Samples A3 (15 %) and A4 (20 %) showed the highest yeast activity values after both 60 and 120 minutes of fermentation, suggesting better viability of yeast cells and a superior gas production capacity. This improved fermentative activity was reflected in higher specific volume values, indicating a more porous structure and an increased gas retention capacity in the dough. At the same time, samples with high yeast activity showed a more favorable texture, characterized by reduced hardness, higher cohesiveness and superior resilience, compared to the control sample. The overall acceptability followed the same trend, with waxy flour samples, especially A4, recording the highest sensory scores throughout the entire storage period. This correlation confirms that maintaining yeast activity directly contributes to improving the sensory perception of the finished product. In conclusion, the addition of waxy wheat flour represents an effective strategy for protecting yeast activity in frozen dough, contributing to the maintenance of specific volume, textural properties and sensory acceptability. The optimal substitution level identified in this study is 20 %, which ensures the best results under medium-term frozen storage conditions.

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