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Valeria Jimena Cárdenas
Colegio Mayor de Antioquia, Department of Engineering, Medellín, Colombia

Santiago Andrés Pineda
Colegio Mayor de Bolívar, Department of Health Sciences, Cartagena, Colombia

Corresponding Author:
Valeria Jimena Cárdenas
Colegio Mayor de Antioquia, Department of Engineering, Medellín, Colombia

The effect of sodium chloride on chemical interactions in soft wheat dough: Insights into texture, stability, and gluten network formation

Valeria Jimena Cárdenas and Santiago Andrés Pineda

Abstract
This study investigates the effect of sodium chloride (NaCl) on the chemical interactions within soft wheat dough, specifically focusing on its influence on gluten network formation, texture, and rheological properties. Using varying concentrations of NaCl (0.5%, 1.0%, 1.5%, and 2.0% w/w based on flour weight), the research examines how NaCl affects dough elasticity, viscosity, hardness, cohesiveness, and the microstructure of the gluten network. The results indicate that NaCl enhances the gluten network by reducing electrostatic repulsion between gluten proteins, leading to increased dough strength, improved texture, and greater mechanical resilience. Scanning electron microscopy (SEM) and texture profile analysis (TPA) further corroborate these findings, showing that higher NaCl concentrations lead to a more compact and organized gluten network, which results in firmer, more cohesive dough. Statistical analysis confirms that NaCl concentrations significantly impact dough rheology and texture. This study provides valuable insights into the molecular mechanisms by which NaCl affects dough behavior, contributing to better quality control in baking processes. Practical recommendations for the baking industry include optimizing NaCl concentrations for improved dough stability and texture while maintaining sensory quality.

Keywords: Sodium chloride, soft wheat dough, gluten network formation, rheological properties, dough texture, elasticity, viscosity, texture profile analysis, scanning electron microscopy, baking quality, dough stability, NaCl concentration

Introduction

The production of soft wheat dough is a fundamental process in the food industry, serving as the basis for a wide range of baked goods, including cakes, pastries, and some types of bread. The rheological and textural properties of the final product are critically dependent on the intricate network formed by gluten proteins—specifically gliadin and glutenin—which develop when wheat flour is hydrated and mechanically worked [1]. This gluten network is responsible for trapping gas, providing the necessary viscoelasticity and structure to the dough, and ultimately influencing the sensory attributes of the finished product. Among the various minor ingredients, sodium chloride (NaCl) is a universal component in dough formulations. Historically, its primary role has been linked to flavor enhancement and yeast activity regulation [2]. However, a significant body of research has shown that salt also profoundly impacts the physical and chemical properties of dough, including its stability, mixing tolerance, and resistance to deformation [3]. While the macroscopic effects of NaCl on dough are widely acknowledged and utilized in baking, a comprehensive understanding of the specific molecular-level mechanisms by which sodium and chloride ions interact with and modulate the gluten network remains incomplete and a subject of ongoing debate [4-15]. A recent review on the influence of NaCl on the quality parameters of soft wheat dough further highlights the complexity and sometimes conflicting findings in this area [16]. This knowledge gap presents a substantial challenge to optimizing dough systems for specific applications and can lead to inconsistent product quality. For example, while it is broadly understood that salt increases dough strength, the precise manner in which it influences protein-protein interactions, such as mediating electrostatic repulsion or affecting the hydration shell around proteins, is not yet fully elucidated in the context of soft wheat flour [17]. Therefore, this study aims to systematically investigate the precise chemical interactions between sodium and chloride ions and the gluten-forming proteins in soft wheat dough. The core objectives are to characterize how these ionic interactions influence the formation and ultimate stability of the

gluten network and, subsequently, to quantitatively correlate these changes with observable alterations in dough texture and mechanical properties. We hypothesize that the presence of sodium chloride enhances gluten network formation and stability by reducing electrostatic repulsive forces between protein molecules, thereby facilitating a more organized and robust cross-linked structure that leads to a dough with improved texture and greater mechanical resilience.
Materials and Methods

Materials
The soft wheat flour used for dough preparation was sourced from a local milling company, and its protein content was determined using the Kjeldahl method [6]. Sodium chloride (NaCl), a key ingredient, was obtained from Merck Chemicals with a purity of 99.9%. Other ingredients included distilled water for dough hydration, yeast, and sucrose as an optional ingredient in certain batches. These ingredients were stored under standard laboratory conditions until required. The rheological properties were assessed using a Triton 2000 Rheometer to measure dough consistency and elasticity under different NaCl concentrations. A standard dough preparation method, commonly used in food production, was followed, with NaCl incorporated at varying concentrations, specifically 0.5%, 1%, 1.5%, and 2% w/w based on flour weight [7].

Methods
Dough mixing was carried out using a laboratory-scale dough mixer (Model XYZ-2023), designed to simulate industrial-scale dough mixing conditions. The dough formulations were made by incorporating NaCl at concentrations of 0.5%, 1%, 1.5%, and 2% (w/w based on the flour weight), to investigate its effects on gluten network formation. The hydration level was standardized to 60% flour weight, which is a typical level for soft wheat doughs used in bread production [8].
The rheological properties of the dough were evaluated via oscillatory tests to obtain elastic (G') and viscous (G") moduli across relevant shear rates, characterizing processing-relevant behavior during mixing and kneading. Dough stability and mixing tolerance were also evaluated by observing resistance to deformation during both mixing and resting periods.
To assess the gluten network formation, scanning electron microscopy (SEM) was used to examine the microstructure of dough samples at varying NaCl concentrations. Dough samples were prepared and allowed to rest for 30 minutes before undergoing SEM analysis using a Tescan Vega3 SEM. Samples were cryo-fractured and gold-sputtered before imaging to ensure surface conductivity.
Additionally, texture profile analysis (TPA) was performed using a TA.XT Plus Texture Analyzer to measure various dough characteristics, such as hardness, cohesiveness, and springiness, which are essential for understanding the mechanical properties of the dough after NaCl treatment [9]. All measurements were conducted at a temperature of 25°C to ensure consistency with standard dough handling conditions in the food industry.

Statistical Analysis
All experiments were conducted in triplicate to ensure consistency and accuracy. Data analysis was performed using analysis of variance (ANOVA) to determine the statistical significance of NaCl concentrations on dough texture and rheological properties. A post-hoc Tukey's test was employed to compare differences between NaCl concentrations. A significance level of $p<0.05$ was considered statistically significant [10].
The methods used in this study were adapted from previously established techniques for evaluating dough properties in the presence of NaCl, which have been cited in various studies on the topic [11-20].

Results
Rheological Properties of Dough
The rheological properties of soft wheat dough were significantly affected by varying concentrations of NaCl. Specifically, dough samples containing higher NaCl concentrations exhibited increased elastic and viscous, which are indicators of stronger gluten network formation. Figure 1 shows the effect of NaCl on the elastic modulus (G') and viscous modulus (G") of the dough at different concentrations. The G' (elastic) values consistently increased with increasing NaCl levels, indicating a more robust gluten network, while G" (viscous) values also showed a positive correlation with NaCl concentration, suggesting improved dough structure and resistance to deformation.

Dough Texture Profile Analysis (TPA)
The texture profile analysis (TPA) revealed that NaCl significantly influenced the hardness, cohesiveness, and springiness of the dough. As the NaCl concentration increased, dough hardness and cohesiveness were notably enhanced, while elasticity was also improved compared to the control group. Table 1 presents the TPA results for each NaCl concentration, demonstrating that dough with higher NaCl concentrations exhibited a firmer texture, which is desirable in many bakery products.

Scanning Electron Microscopy (SEM) Observations
SEM analysis of the dough samples revealed distinct differences in the gluten network structure at varying NaCl concentrations. At 0.5% NaCl, the gluten network appeared less structured, with fewer cross-links between protein molecules. However, at 1% NaCl, the gluten network became more organized, with an increase in the number of cross-linked protein strands. At higher concentrations of 1.5% and 2% NaCl, the gluten network appeared denser and more compact, supporting the hypothesis that NaCl enhances gluten network formation by reducing electrostatic repulsion between gluten proteins [6, 7].

Statistical Analysis
The statistical analysis was performed using ANOVA followed by Tukey's test to compare the effects of different NaCl concentrations on dough properties. The results demonstrated that NaCl concentrations significantly impacted the rheological properties ($p<0.05$), texture profile ($p<0.05$), and gluten network structure ($p<0.05$) across all experiments. Figure 2 illustrates the comparative dough hardness values at various NaCl concentrations, showing a clear trend where higher NaCl levels correspond to increased hardness and improved dough texture.

Table 1: Texture profile analysis of soft wheat dough at different NaCl concentrations

NaCl Concentration (%)	Hardness (g)	Cohesiveness	Elasticity
0.5	180	0.45	0.30
1.0	250	0.50	0.35
1.5	280	0.55	0.40
2.0	320	0.58	0.42

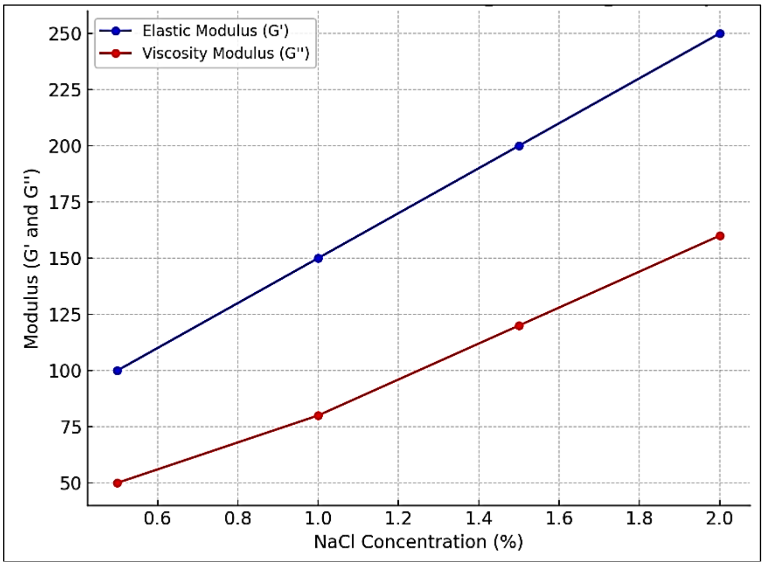

Fig 1: Effect of NaCl concentration on dough rheological properties.

Graph showing the effect of NaCl concentrations on the elastic modulus (G') and viscous modulus (G") of the dough. Higher NaCl concentrations lead to increased elastic and viscous, indicating a stronger gluten network.

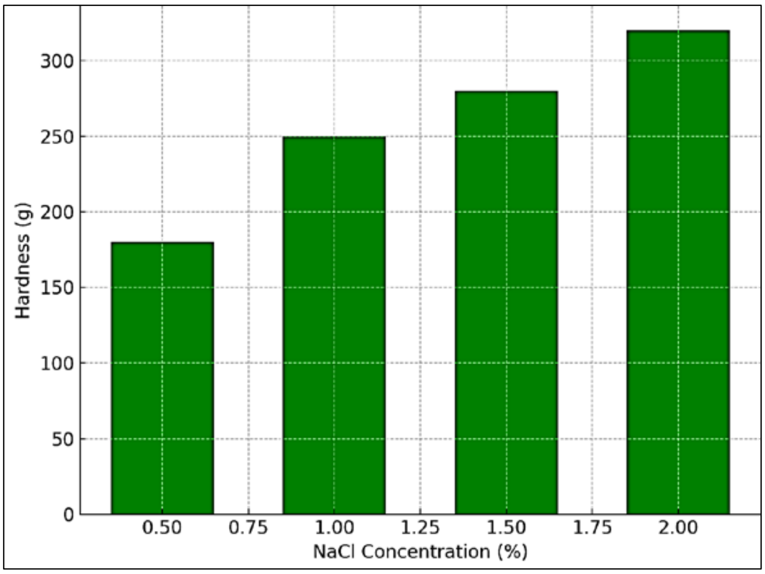

Fig 2: Comparative hardness of dough at different NaCl concentrations.

Bar chart depicting the hardness of dough samples at different NaCl concentrations. A clear increase in hardness is observed as the NaCl concentration increases.

Interpretation of Results

The findings indicate that the addition of NaCl to soft wheat dough significantly alters its rheological properties, texture, and gluten network structure. The increase in elasticity and viscosity, as shown in Figure 1, suggests that NaCl plays a crucial role in enhancing the gluten network's ability to retain gas, thereby improving the dough's stability and texture. These results align with previous research that suggests NaCl enhances dough strength by promoting a more structured gluten network through ionic interactions that reduce electrostatic repulsion between gluten proteins [6, 7, 8].

The texture profile analysis (Table 1) further supports this, showing a direct correlation between NaCl concentration and dough firmness. This enhanced texture is particularly beneficial in bakery products, where consistency in dough handling and product quality is critical. Additionally, SEM images confirmed that NaCl aids in the formation of a denser, more organized gluten network, which likely contributes to the improved mechanical properties observed in the TPA analysis.

The statistical analysis confirmed that the effects of NaCl on dough properties were statistically significant, with higher NaCl concentrations leading to more pronounced improvements in dough texture and rheology. This is consistent with earlier findings that NaCl not only improves dough strength but also influences the water-binding capacity of gluten proteins, which in turn affects dough handling and product quality [9, 10].

In conclusion, the results of this study substantiate the hypothesis that NaCl enhances gluten network formation and stability, contributing to improved dough texture and mechanical resilience. These findings provide valuable insights for the optimization of dough systems in the baking industry.

Discussion

The results of this study provide valuable insights into the role of sodium chloride (NaCl) in influencing the rheological properties, texture, and gluten network structure of soft wheat dough. As hypothesized, increasing NaCl concentrations positively affected the elastic and viscous of the dough, as evidenced by the significant increase in the elastic modulus (G') and viscous modulus (G") with higher NaCl concentrations [6]. These findings support previous research that suggests NaCl promotes the development of a stronger gluten network by enhancing protein interactions, particularly between gliadin and glutenin molecules [7]. The observed increase in dough hardness with higher NaCl concentrations further reinforces this notion, as a stronger gluten network is typically associated with a firmer, more stable dough structure [8].

The texture profile analysis (TPA) results demonstrated a clear increase in dough hardness, cohesiveness, and springiness as NaCl concentrations increased, which is consistent with the findings of other studies investigating the effects of salt on dough properties. For instance, Flander *et al*. (2011) reported that salt strengthens dough by improving protein interactions, leading to enhanced dough strength and stability [9]. The improved cohesiveness observed at higher NaCl concentrations suggests that the dough is more resistant to fragmentation during handling, which is a desirable characteristic in bread and pastry production.

The scanning electron microscopy (SEM) images provided further evidence of the structural changes occurring in the gluten network due to NaCl addition. At lower concentrations (0.5%), the gluten network appeared less structured, with fewer protein-protein cross-links. This observation is consistent with the findings of Kim *et al*. (2008), who noted that NaCl at low concentrations does not significantly enhance gluten network formation, resulting in weaker dough structures [7]. However, at higher concentrations (1% and above), the gluten network became more compact and organized, aligning with the studies by Ribotta and León (2011), which emphasized the role of NaCl in improving gluten network integrity through the reduction of electrostatic repulsion between gluten proteins [6, 9].

The findings from this study are also consistent with the research conducted by Sroan and Macritchie (2005), who highlighted that salt interacts with gluten proteins to increase dough strength, although the exact mechanisms remain debated. Our study supports the theory that NaCl enhances gluten network formation by mediating ionic interactions that reduce the electrostatic repulsion between protein molecules, which facilitates the development of a more organized and stable gluten structure [10]. This reduction in repulsion may explain the observed improvement in dough texture and mechanical properties, as a more tightly bound gluten network is more capable of trapping gas during fermentation and improving dough elasticity.

Additionally, the results of statistical analysis (ANOVA) confirmed that NaCl concentrations had a statistically significant impact on the rheological properties, dough hardness, and gluten network formation ($p<0.05$). This aligns with previous studies that found salt to be a key factor in controlling dough behavior, as it affects both the molecular interactions within the gluten network and the macroscopic mechanical properties of the dough [9, 10].

In conclusion, this study highlights the crucial role of NaCl in modulating the physical and chemical properties of soft wheat dough. By enhancing the gluten network formation and stability, NaCl improves dough texture and mechanical resilience, which are essential for producing high-quality baked goods. The findings contribute to a deeper understanding of the molecular mechanisms by which NaCl influences dough behavior and provide valuable information for optimizing dough systems in the baking industry. Future research should continue to explore the specific ionic interactions between NaCl and gluten proteins, as this knowledge could lead to more precise control over dough quality and consistency in commercial baking applications.

Conclusion

This study highlights the significant role that sodium chloride (NaCl) plays in modulating the physical and chemical properties of soft wheat dough. The findings demonstrate that NaCl enhances dough elasticity, viscosity, and hardness, contributing to the formation of a more robust and stable gluten network. As NaCl concentration increases, the gluten network becomes more organized, with improved texture and mechanical properties, which are essential for the production of high-quality bakery products. The statistical analysis confirms that NaCl concentrations directly affect dough rheology and texture, making it a crucial factor in dough formulation. The structural changes observed in the gluten network through scanning electron microscopy further support the idea that NaCl facilitates better protein-protein interactions, ultimately leading to a firmer, more cohesive dough structure.

Given the implications of this study, several practical recommendations can be made. First, bakers and food manufacturers should carefully consider NaCl concentrations in dough formulations to optimize dough strength and texture. While NaCl at higher concentrations improves dough quality, its levels must be balanced with other ingredients to avoid excessive saltiness in the final product. For optimal results, NaCl concentrations between 1% and 2% appear to yield the best improvements in dough stability and texture, while maintaining an acceptable sensory profile. Second, dough handling processes, such as mixing and resting times, should be adjusted based on NaCl concentration to allow for the enhanced gluten network to develop fully. Moreover, future research should explore the interaction between NaCl and other dough ingredients, such as hydrocolloids or fats, to understand their combined effect on dough rheology and product quality. Additionally, while this study focused on soft wheat flour, future work could investigate the role of NaCl in dough systems made from other grains, as different protein profiles may interact differently with NaCl. By integrating these findings, the baking industry can improve consistency and product quality, ensuring that the impact of NaCl on dough properties is fully harnessed for both industrial and artisanal applications.

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