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REVIEW

Cryoprotectants for Frozen Dough: A Review

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Abstract

Dough is the first step to create baked goods that are known for their variety of presentations, textures, and flavors, divided into different groups such as bread, cakes, cookies, pizza, and puff pastries, among others. These products are mainly made from cereals or cereal-based flours. Particularly, starch and gluten from wheat help develop the characteristic textures of these products. Since the ingredients used to make these products are susceptible to damage during storage, alternatives such as freezing have been sought. However, storage at temperatures below the freezing point of water often affects the sensory quality of the final product, especially by minimizing the development of the texture after baking, resulting in a food with a limited volume because of the reduction of the number of viable yeast cells, or by the presence of overlapping layers which do not develop in the baking stage of the puff pastry because of fat syneresis. To mitigate the negative effects of low temperatures, the application of cryoprotectants has been investigated in the industry to improve the quality of frozen dough. In consequence, this review analyzes the relevant advances for the frozen storage of dough for baked products based on the use of additives such as cryoprotectants and the scientific evidence available to date to indicate the perspectives toward improving dough in aspects related to the development of sensory attributes, their technological feasibility, and shelf life.

Keywords Food quality · Frozen dough · Ice crystallization inhibitors · Food storage

Introduction

Baked goods made from grains have been an important source of food for humans. For example, the consumption of bread has been increasing over time, making it a basic food in the diet. Only for the year 2021, this industry has accumulated about $117.65 billion in revenue globally [1]. Therefore, this sector can be considered one of the most important in the food industry in the world [2]. Preservative agents are included in dough, generally synthetic, whose use is sought to be reduced or eliminated, as clean labels have surged as a global concern [3]. On the other hand, baked products are known for their characteristic texture, which can be hard for products such as cookies, soft and crunchy for bread, or with greater volume and laminated such as puff pastries, according to the manufacturing process of each one [3].

Within the conservation of bakery dough, it is known that freezing temperatures help preserve the product for longer periods, ensuring a long shelf life. One of the critical points that must be controlled is the temperature fluctuation because storage cause increased rates of quality deterioration particularly due to changes in the structure of ice crystals and recrystallization. Moreover, there can be increased moisture loss leading to a reduction of quality and accelerated loss of acceptance by the final consumer [4]. Moisture is involved in the aging process of the food since the availability of water can migrate and cause dehydration of the gluten and starch network, which is responsible for developing the final structure [5].

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In addition, dough can present damage to their structure and final quality since the storage time and temperature can generate mechanical damage due to the formation of ice crystals [6]. The freezing process for bakery dough begins when the food is exposed to low temperatures, usually below − 18 °C, and depends on the rate of formation of ice crystals; if small size crystals are formed, the integrity of the cell wall is not affected due to a growth in an orderly manner, on the contrary, large size crystals grow in a disorderly manner damaging the structure of the product. Besides, when obtaining a frozen dough, the water absorption index of wheat flour starch should be considered since this determines its capacity to retain water and the effect on the texture of the matrix [7].

To mitigate the effects linked to storage at low temperatures, various types of cryoprotectants have been found, aimed at protecting the viability of yeast cells and the structure of the baked product, creating a synergy between the cell wall and the cryoprotectant molecule. Some of the additives used in the industry are DATEM (Diacetyl Tartaric Acid Esters of Mono and Diglycerides) and CSL (Calcium stearyl lactate), which have a multiple mode of action related to (i) the delay of starch retrogradation caused by the effect of freezing, and (ii) an inhibition of moisture migration from dough network to exterior which helps decrease water absorption by the interaction between starch and lipid to reduce surface tension in gas bubbles. Likewise, applications of hydrocolloids, proteins, nucleating agents, and enzymes can be found on the market to preserve the integrity of dough network, control the rheology of the dough, and protect the cells during freezing. Some applications of natural additives are known in the baking industry, specifically glycerol, proline, and trehalose molecules in kneaded and baked products are reported [8, 9].

Considering the above, the objective of this review is to discuss the application of cryoprotection additives in kneaded products in the industry and the perspectives on this technology. This article is arranged as follows: initially, the characteristics and types of baked products will be presented, followed by an explanation of the freezing process and frozen dough. Subsequently, the use of cryoprotective additives used in frozen dough for baked products will be analyzed, and finally, some conclusions and future perspectives will be established. This technology is expected to have great potential to improve the losses generated in the product manufacturing process.

Freezing

Freezing is considered an ancient preservation method in the food industry. This process occurs when the food matrix is exposed to a temperature below the freezing point of water. This favors a significant decrease in the rate of microbial growth that induces food deterioration and affects its organoleptic quality. Additionally, this decrease in temperature reduces the enzymatic and oxidative activity of the dough due to the formation of ice crystals, which modifies the availability of water present in the product and prevents it from interfering with the deterioration reaction [10]. A reduction in the final texture can occur in the process of ice crystal formation. In addition, some storage conditions must be controlled such as exposure time and freezing rate. For instance, quick freezing is characterized by the development of small ice crystals in the food matrix and a freezing time of four to six hours. On the other hand, slow freezing is characterized by the development of large and heterogeneous ice crystals, which can damage the matrix and its freezing time can be up to 24 h. Based on the previous information, quick freezing is a technique that promotes the formation of small crystals within the product's structure, resulting in minimal mechanical damage. As a result, it is widely considered the most recommended process for the food industry. On the other hand, in slow freezing, the crystals that are formed may cause ruptures in the cell walls of the product, leading to a loss in food quality. This is because ice growth occurs in a disorderly manner, resulting in the formation of large crystals [10, 11]. Also, the gassing power in frozen dough is dependent on various factors, including the number of yeast cells and their activity prior to storage, as well as the level of fermentable sugar present. When the dough is frozen and thawed, there can be a loss of fermentative activity, but a higher population of microorganisms can compensate for this loss during the fermentation cycle. Therefore, it is important to consider these factors when freezing dough to ensure optimal fermentation and gassing power [12].

According to [11] the freezing process in foods is developed in several stages: pre-cooling, nucleation, and tempering. The pre-cooling stage starts from the initial temperature of the food, which is gradually reduced until it reaches the freezing point to continue decreasing, but without producing physical changes in the matrix. Then, nucleation starts, where the food matrix spontaneously forms ice nuclei in its structure with the available water and causes the temperature to rise and reach its stable freezing point. Finally, in tempering, the matrix manages to stabilize in the time/rate of freezing and storage until reaching the final established temperature.

In the bakery industry, the procedure to obtain frozen dough involves kneading the ingredients, as reflected in the standardization of the production process of fresh products and then portions are formed according to the established requirements. Then, the dough is exposed to low temperatures in a freezing system until the center reaches an internal temperature of -18 °C and, by the exchange of specific heat of the matrix, completes its frozen state. For bakery products that require proofing of the dough, it is possible to modify at which point in the process the product should be frozen, for example, after the kneading stage, after proofing the dough or the partially baked product, also, the formation of intracellular ice alters the structure and can present consequently a limitation in the survival of the yeast [6, 13, 14], evaluated the use of sourdough in frozen bread dough technology with the inclusion of fructose and glucose, cryoprotectants such as guar gum, DATEM, honey, and a cryoprotective solution based on skimmed milk, sucrose, and trehalose. The results obtained showed that the control treatment had the best performance in terms of dough quality. After 50 days of frozen storage, the fermentation time needed by the doughs after the thawing cycle was 14 h at a temperature of 4 °C. Furthermore, it is crucial to establish the time-temperature conditions for freezing the dough at the lowest possible level. This is to prevent vapor condensation on the cold surface of the dough, which could affect the quality of the bread during the baking process. Additionally, proper freezing conditions will ensure that the bread is evenly baked, preventing scenarios where the surface of the bread is overcooked while the center remains undercooked [6]. The best yield was obtained when a cryoprotective solution (skim milk and sucrose) with a concentration of 4% trehalose was used to preserve yeast cells. On the other hand, the characterization of bread indicated that the control treatment with 30% sourdough, frozen and without additives, presented the highest hardness value due to the lack of presence of cryoprotectants additives, while the bread frozen with the addition of honey presented 60% less hardness than control.

Additionally, [15] studied the effect of pectin as a cryoprotectant in bread dough. For the development of the study, they carried out a bread dough control and three treatments using different cryoprotectants for each case: pectin, sorbitol, and fructose at a fixed concentration of 1.5%. Then, the samples were stored at -24 °C for a month and thawed by two methods, traditional for two hours at room temperature and by microwave for 30 min. Finally, the pieces were baked at 220 °C for 15 min. According to the results obtained, the best method to carry out the defrosting cycle was in a microwave, which reduced the defrosting time by 75%. In addition, the yeast in the dough containing pectin showed a survival of 98% meanwhile the control had 80%. It can be concluded that the function of pectin as a cryoprotectant for bread dough stored at freezing temperature by the slow method, ensured the protection of the gluten-starch network and yeast cells, which translates into obtaining a better texture in the final product. Similar results can be seen in the study conducted by [16] on the effects of freezing rate and firmness by analyzing yeast viability and thermal properties of frozen croissant dough, where the optimal freezing rate was 3.19 °C per minute and the initial temperature of the piece to start the freezing process was 20 °C.

Consequently, it is considered freezing is a determining factor to control the size of the crystals since it affects the viability of the yeast, the specific volume, and the firmness of the final product. For example, when the dough is frozen, the rate at which the process will be carried out must be considered. If it is slow, the ice crystals formed in the matrix will be of irregular size and shape, affecting the integrity of the cells and causing a possible migration of moisture in the thawing cycle. In addition, the temperature fluctuation during storage can lead to an increase in ice crystal size, generating irreversible damage to yeast [17]. Therefore, to obtain a good quality baked product, quick-freezing must be done to maintain the intracellular water of the yeast above the crystallization point.

The effects of frozen storage on the structure of the dough and the quality of the final product are evaluated from physicochemical and textural properties. Besides, the industry tends to improve quality by avoiding secondary effects on the organoleptic properties after baking. Among the possible changes that can occur in the food are related to fermentation, as well as derived from gluten and starch structure stability.

Effects of Freezing on Fermentation

In general, baker's yeast, Saccharomyces cerevisiae, is the main starter for frozen dough [18]. In the process of dough making, there are changes in the production of carbon dioxide (CO_2) which determine the final volume of the baked product.

In addition, the result in the final product depends on the fermentation potential of the yeast chosen for the process, the number of viable cells, and their ability to adapt to freezing temperatures, which in turn is determined on the type of strain and physiological state. Likewise, several factors help maintain or improve the matrix so that the yeast adapts to the freezing conditions, such as the temperature during the preparation of the dough, the rate of freezing of the matrix, the osmotic pressure during the concentration of solutes in storage, the presence or absence of ice crystallization inhibitors for yeast protection and the availability of fermentable sugars [8]. The tolerance of yeast to low temperatures is very limited since it is likely that subjecting the dough to freezing temperatures is more harmful than freezing the yeast directly, this is because the viable cells would suffer direct stress due to the freezing and thawing cycles, changes in osmotic pressure and oxidative stress [19]. In addition, the retention capacity of carbon dioxide (CO_2) produced by the yeast depends on the stability of the bubble walls and the interaction between gluten, starch, and water. Considering the above, the gas bubbles generated in the fermentation before freezing tend to let the gas produced escape, and consequently the volume of the bread decreases during baking [8, 20].

The protein and the cell membrane suffer damage under stress conditions, which leads to the inhibition of cell growth and, therefore, its fermentation viability [21, 22] evaluated two types of bread dough, one with the addition of single yeast and the other with double yeast. To determine the quality of the product, they evaluated the gassing power and the volume of the dough during fermentation. The results obtained showed that the longer the storage time, the greater the decrease in the quality of the frozen dough. During the frozen storage period, the yeast cells may be damaged by the mechanical effects caused by the formation of ice crystals in the dough. This can result in the release of glutathione, which can weaken the dough by adhering to the disulfide bonds present in gluten. Accordingly, yeast freeze damage is considered the main factor affecting dough quality.

Effects on Gluten

The gluten network is made up of glutenin and gliadin. When intertwined, these proteins develop viscoelastic properties in the dough, producing a balance between extensibility and elasticity. Another characteristic property of gluten is that it allows the dough to spread out to trap the gas produced by the fermentation of the yeast and thus achieves that once baked the product retains a spongy texture. For frozen doughs, the damage in the freezing stage is observed in the changes that the rheological properties have through the interruption of the protein chains by the formation of ice crystals, this is attributed to dehydration of the gluten because of redistribution of the available water and ice recrystallization. This disruption of the crosslinking between gliadins and glutenins facilitates the loss of gas produced by viable yeast cells. An important factor is the size of the protein polymers in the dough to be able to determine the damage caused during storage at frozen temperatures because the main function is the formation of structure in the dough, which must protect the integrity of the product in the freezing process avoiding moisture loss [8]. In relation to storage time, the airstream at freezing temperature and temperature fluctuation affects the hydrophobicity of the gluten surface. At the molecular level, stable disulfide and non-covalent bonds are involved in rearranging the gluten structure and exposing the hydrophobic phase of the protein molecule. The exposure of this phase increases the fluidity of the water which correlates with the decrease in the rate of water absorption of the proteins. The cycles that occur in freezing storage and thawing can accelerate the breakdown of the gluten network cross-linking, weakening the cell wall, which interferes with the quality of the product [23].

Additionally, [24] evaluated the effect of freezing rate and frozen storage on the rheological properties and protein structure of unfermented doughs. The results showed that a faster freezing rate had a positive effect on the water retention, elasticity, and hardness of the dough. However, a slower freezing rate produced more extensible doughs. Regarding frozen storage, it was observed that the stability of the protein structure decreased after four weeks of storage, which led to a reduction in the elasticity and strength of the dough.

Overall, the study suggests that freezing rate and frozen storage can have significant effects on the rheological properties and protein structure of unfermented doughs. These results can be useful to improve the quality of bakery products that are stored frozen and [25] investigated the effect of different frozen storage conditions on the functional properties of wheat gluten protein in unfermented dough. The results showed that freezing at -18 °C for 60 days and freezing at -80 °C for 30 days significantly affected gluten protein solubility, water-holding capacity, and dough elasticity. In addition, frozen storage also affected the gluten protein structure, leading to a decrease in free amino acid content and an increase in oxidized amino acid content. Overall, the results indicate that frozen storage conditions can significantly affect the functional properties of the gluten protein, which can have a negative impact on the quality of the dough and the resulting bakery products.

Moreover, [26] evaluated the effect of freezing rate and storage time on the solubility of gluten proteins. According to the results obtained, the content of insoluble polymeric protein in the mass decreased significantly, reporting 7.46% in slow freezing rate, while in fast freezing it decreased by 3.73%, indicating a weakening of the gluten network throughout the storage time. Also, they observed a gradual increase in the proportion of soluble polymeric protein in slow freezing. In addition, the proportion of gliadins increased significantly after 14 days of storage in the slow freezing process, showing that the presence of protein peptides separated by the effect of freezing is derived from the decomposition of glutenins, which means that there was a deterioration in the protein polymer and, consequently, a weakening in the network of gluten.

Also, [27] studied the structure of frozen sweet dough at -20 °C, -30 °C, and −40 °C and were evaluated for structural and rheologic properties by Fourier transform infrared (FTIR), rheologic measurements, and differential scanning calorimetry (DSC). The authors observed that the effect of low freezing rates resulted in an elasticity reduction of 8.6% and 12% at -30 °C and – 40 °C, respectively. This result can be attributed to the dehydration of the dough network and, also, starch retrogradation. In addition, during the freezing storage, temperature, pH, and high ionic strength influenced dehydration and protein denaturation due to competition with electrostatic bonds, lipid oxidation, and enzymatic reactions due to the ice structure.

In conclusion, that freezing can negatively affect the gluten network that is formed to maintain a food system in optimal conditions and, therefore, obtain products with a limited quality after the baking stage. This can occur mainly when the slow freezing method is used, in which ice nuclei of heterogeneous shape and size and without apparent order are generated, causing mechanical damage to the cells that make up the structure. Therefore, there may be a limitation in the specific volume of the baked pieces and, in the dough, an increase in viscosity after thawing.

Effects of Freezing on Starch

Starch is composed of amylopectin and amylose. Each granule is found in different sizes ranging between average diameter of A-, B-, and C-granules among different starches varied between 23.0 and 28.5, 10.0 and 12.0, and 2.3 and 2.7 µm, respectively [28] and can affect the quality of the dough according to its behavior. There are three possible factors to evidence the behavior of starch in the dough: the small granules exude less amylose during the baking stage and, therefore, the hardening of the gluten-starch network formed will be reduced. Furthermore, small starch granules have a higher lipid content than large granules, being able to: (i) decrease the firmness of the matrix, and (ii) increase the moisture retention of the food given its high swelling power [7]. One of the main damages in starch from freezing may depend on the storage time, if it is slow, it can cause the formation of ice nuclei with a higher density producing mechanical damage and extracting the amylose when thawing. In the case of the gluten-starch bond, it is reduced in the cycle of freezing and thawing while the starch content increases in relation to the amylose solution. The size of starch granules and their susceptibility to the freezing and thawing cycle can be influenced by the content of amylose and amylopectin. Larger starch granules typically have a higher content of amylose, which makes them more susceptible to the effects of freezing and thawing. Type B granules, which are larger in size compared to Type A, may undergo greater starch degradation due to their high content of amylopectin, making them more sensitive to the freezing process [7, 29, 30] studied the impact of the inclusion of whole wheat starch and its type A and B granules, in a frozen dough composed of wheat flour, water, sugar, and salt. Regarding the image analysis of the structure, it was observed that type A starch granules had a regular disc-shaped morphology while type B granules recorded a diversity of ellipsoid shapes with a degree of damage after freezing, such as irregularities on the edges, which indicated that type B granules were susceptible to the fluctuation of the medium where they were found [31] indicated that the thermal transition, the amylose, and amylopectin ratio were associated, and gelatinization occurred in wide temperature ranges for type B granules 72.5 °C although, after frozen storage, these ranges proved to be wider since more energy was needed to interrupt the chains formed by amylose-amylose and amylose-amylopectin.

Freezing can cause a decrease in protein and lipid contents and the ratio of amylose to amylopectin, as well as an increase in ice nuclei in starch granules. In addition, type B granules undergo most changes during storage, which makes them more sensitive to sub-zero temperatures. The effect of dough storage at low temperatures on the thermodynamic properties of starch is attributed to an increase in the stability and the order of crystallization in the starch structure. Therefore, the baked product made from frozen dough presented a smaller volume and an increase in the hardness compared to a baked product made from fresh dough [7].

Similarly, [32] studied the particle size distribution of wheat starch granules fractionated into types A and B and subjected to storage in freezing for three cycles for 22 h at -34 °C and then thawing at 25 °C for three hours. The freezing treatment did not cause apparent damage to type A starch granules, contrary to type B, since this exposure facilitated the leaching of amylose, proteins, and lipids. Additionally, when the thawing cycle was carried out, the temperature helped increase the gelatinization, enthalpy of fusion, and dough viscosity. On the other hand, type B granules were more sensitive to frozen storage, facilitating structural changes in bread dough, for which it is advisable to increase the content of type A starch granules to improve the quality of the final product [33] evaluated the effects of freezing rate and storage time on starch properties in frozen dough. The freezing process was carried out at a fast rate of 1.75 °C/min and a slow rate of 0.14 °C/min, finding that the maximum viscosity occurred at the slow rate of freezing and the enthalpy of fusion of the starch granules increased gradually during storage and was lower in the slow rate frozen dough. In this way, the structural properties decreased since the network that was formed together with the gluten suffered mechanical damage due to the growth of the ice crystals, changing the microstructure of the dough. The foregoing shows that, to obtain frozen dough for baked products, it is advisable to do it at a fast rate, since in this way negative effects on the integrity of the structure are avoided. Moreover, [34] indicated that quick freezing temperature had a significant impact on starch retrogradation and ice crystal formation in oatmeal rolls. Quick freezing at -80 °C resulted in increased starch stability and a decrease in the number and size of ice crystals, compared to quick freezing at -20 °C. Furthermore, the formation of large and small ice crystals in steamed oat rolls was correlated with increased starch retrogradation and decreased quality of the final product.

In summary, the study suggests that quick freezing at low temperatures can improve product quality and reduce starch retrogradation in steamed oat rolls.

Therefore, it can be inferred that the starch gelatinization slightly changes at the baking stage and influences the rate of amylopectin retrogradation. On the other hand, a determining factor to consider in the preparation of the frozen dough is the rate of the process, since the lower it is, there is a greater risk of the formation of large and random ice nuclei, which harms the starch granules found in the matrix, generating a breakdown of the cell wall, thus, facilitating the migration of amylose. Likewise, this exposure to low temperature increases the enthalpy of fusion and dough viscosity, and consequently, the final texture of the product is modified.

Compounds to Protect the Quality of Frozen Dough

Freezing technology in the baking industry can affect the quality of products made from frozen dough. To achieve partial control of the formation of ice nuclei and recrystallization during storage at low freezing temperatures, the addition of cryoprotective additives is suggested, which helps to improve the quality of the final product.

There are emulsifying additives in the industry such as DATEM and CSL (calcium stearyl lactate) having different modes of action such as (i) Delay of retrogradation of starch because of freezing, (ii) Inhibition of moisture migration between starch and gluten which helps decrease the water absorption caused by starch, and (iii) The interaction of lipids to reduce the surface tension in gas bubbles [8, 9]. To improve the quality of a baked product made from frozen dough, certain parameters must be considered in the production process such as freezing and thawing rates, mixing time, and storage [35]. The possible effects that freezing have on frozen doughs are related to a reduction in the viscoelastic behavior and may represent a decrease in the volume of the food. Meanwhile, the gluten network is weakened by the reduction of substances such as glutathione released by yeast, as well as a loss of gas-holding capacity may occur due to the ice crystallization of water molecules [36].

Some of the inhibitors useful for the inhibition of ice crystallization in frozen dough are:

Hydrocolloids

These additives can control the rheology and texture of food matrices. During the storage time, the properties of the frozen mass and its instability are related to the recrystallization of ice while the fluctuation and adequacy of the freezing temperature occur. Among the most used hydrocolloids in the industry are carboxymethylcellulose (CMC), hydroxypropylmethylcellulose (HPMC), guar gum, xanthan gum, carrageenan, among others [37]. Hydrocolloids manage to form interactions with the gluten and water network, and as a result, help increase the water retention capacity, affecting the moisture content and, in turn, decreasing the damage generated by the formation of ice crystals in the gluten. In addition, the interaction of hydrocolloids with the macronutrients of the dough such as water, starch, and protein differ according to its nature since greater mobility of the molecules of the gluten-water network can be found with the addition of xanthan gum or lower mobility with pectin [9] [37] investigated the influence of guar and xanthan gums and their combined use on the dough fermentation rate, using differential scanning calorimetry at 7, 14, 21, and 28 days of storage. The addition of guar and xanthan gum was found to reduce the enthalpy of fusion by 5.3% compared to the control by day 28 of storage. This reduction in ice crystal formation can help the dough matrix maintain its organoleptic properties, as it can allow for faster baking of the bread dough, leading to better development of the crumb and crust structure. This can ultimately result in a bread product with desirable sensory attributes. In all treatments, the fermentation rate after the storage time and the thawing cycle decreased considerably compared to the not frozen dough, which indicated that the freezing process influenced the viability of yeast cells, limiting their ability to produce and maintain the gas in the structure. It must be considered that the efficiency of the addition of inhibitors can be affected by factors such as the amount added, solubility, water retention capacity, the effect on the interaction with the components of the food and the storage time, as well as and the rheological properties of the matrix [9] [38] studied the physical properties of bread with the addition of xanthan gum, guar gum, and HPMC at a concentration of 0.2% and 0.4%. Regarding the textural characteristics of the crust, the results showed that the color and moisture content were affected by the addition of xanthan gum since they were darker than the other samples. The highest yield was obtained with the partially baked, interrupted in the baking process when completed 60% of the cooking. Likewise, differences were observed in the specific volume obtained from the samples according to the added concentration of hydrocolloid, being the best result when concentrations of up to 0.4% were used. On the other hand, bread stored at -20 °C had a more plastic and deformable crust compared to the control, thanks to a higher moisture content.

Hydrocolloids such as gums are substances commonly used in frozen dough for baked products. Thanks to their interaction with the gluten network, they manage to stabilize the moisture content by protecting the structure in the nucleation stage. An advantage is the value of the concentration required to ensure its effectiveness, since it does not exceed 1% with respect to the flour content [39]. Besides, it is important to consider the solubility, the ability to retain moisture, and the rheological properties of the matrix. Thus, the industry can make these additions a technological challenge in terms of improving the texture and increasing the shelf life of baked products. The feasibility of this technology is usually conditioned according to the desired characteristics to be modified in the food and it does not mean that any hydrocolloid will work successfully if the possible effects that may arise are not further investigated. Similarly, it can be considered to combine them with other types of inhibitors such as polyalcohols, to know if the matrix can improve its final quality.

Polyols

Also known as sugar alcohols and/or sugar substitutes, are carbohydrates with low sweetening power and classified into monosaccharides such as erythritol, mannitol, sorbitol, and xylitol, and polysaccharides such as isomaltitol, lactitol, maltitol, and trehalose. These compounds are found naturally in fruits, but in the industry, they are manufactured from other carbohydrates such as starch, sucrose, and glucose. In addition, they have a lower calorie content than sucrose, therefore, their glycemic response is lower because they are not completely absorbed in the small intestine. Thanks to this attribute, it is known that in the baking industry these compounds are frequently added to cakes, cookies, bread, etc. In addition, the inclusion of these polyalcohols can mitigate the effects of dough freezing for baked products, in which the quality of the final product is affected by the effects of low temperatures [40].

The trehalose can improve dough behavior under freezing conditions in terms of bread volume and texture characteristics [41]. Also, [42] studied the effects of trehalose content and freezing rate on the characteristics of frozen dough and bread quality. According to the study's findings, the qualities of the frozen dough and the bread's quality were significantly influenced by the rate of freezing. Bread quality was worse and gas loss was higher in dough that was frozen at a slower rate.

But in every one of the analyzed freezing situations, trehalose was added to the frozen dough, improving the bread's quality. Additionally, it was discovered that 2.5% of the flour's weight was the ideal trehalose content. On the other hand, [43] investigated how the addition of trehalose and maltodextrin affected the physical characteristics of Chinese steamed bread manufactured from frozen doughs. Considering these findings, it may be concluded that adding maltodextrin and trehalose to frozen dough improved the steamed bread's quality. The inclusion of trehalose improved the texture and softness of the steamed bread, whereas the addition of maltodextrin increased the frozen dough's ability to hold water. Additionally, it was discovered that adding maltodextrin and trehalose together improved the steamed bread's quality. The study's findings imply that trehalose and maltodextrin can greatly enhance the physical characteristics of steamed Chinese bread manufactured from frozen dough.

Moreover, [44] investigated the effects of trehalose on the mechanical, thermal, and rheological properties of wheat flour dough and water distribution in bread. The presence of trehalose reduced the notable gluten film in the dough and decreased the staling rate constant in bread, indicating an inhibitory effect on the firming process. Trehalose was also found to retain water by hindering the interaction among water molecules, gluten, and starch, thus improving the water-holding capacity. Overall, trehalose was found to be an improver in dough and bread-making performance, as well as an antistaling agent in bread. Furthermore, [35] analyzed the effects of various additives, including ready to use bakery products, on the crumb structure and specific volume of baked savory Danish dough and adding this compound, can improve the volume and crumb structure of the product baked from frozen dough can be achieved.

In addition, trehalose was found to have a protective effect on the structure of the bread, preventing the formation of ice crystals during freezing and thawing, which improved the texture and softness of the bread. It was also observed that trehalose reduced the mobility of water in dough and bread, resulting in better retention of bread freshness [44].

In conclusion, the study suggests that the addition of trehalose in wheat flour dough can significantly improve the textural, rheological, thermal, microstructural, and water mobility properties of the dough and the resulting bread. Additionally, trehalose can protect the structure of the bread during the freezing and thawing process, resulting in a better final product [45] conducted a similar study for frozen pizza dough to evaluate the effects on rheological and sensory parameters, by using mannitol and sorbitol as additives with concentrations of 0.1%, 0.5%, 1.0%, 1.5% and 2.0% in relation to wheat flour and monitored on days 0, 15, 30, 45 and 60 through sensory evaluation. It was found the water absorption increased by 8% and 6.8%, respectively, when 2% of either mannitol or sorbitol was added. This shows that the cryoprotection behavior of polyalcohols is based on maintaining the moisture in the structure to achieve constant hydration of the dough.

In this regard, the redistribution of the water contained in products made from frozen dough is due to its migration and mobility during the formation of ice crystals in the freezing process. It is observed that polyols such as mannitol and sorbitol had good water retention capacity and their wetting behavior helped the gel formation in the dough making process. This behavior manages to strengthen the gluten-starch network that is formed, improving the texture and crunch of the dough through an increase in volume and caramelization of the crust.

The latter forIce Structural Proteinscome from sources such as plants and microorganisms that enhance freezing tolerance in the matrix. An example of these additives is the oat extract (*Avena sativa* L.) which showed an ability to reduce the water content and formation of ice crystals in frozen dough, improving the final quality of the baked product. The viability of the yeast cells and the gas retention capacity were improved in the presence of these proteins, and the damage to the gluten network was considerably reduced in the cycle of freezing and thawing [9]. Changes in thawed dough include loss of liquid and fermentation time and a decrease in the ability to retain carbon dioxide and in the specific volume. In turn, during prolonged storage in freezing and thawing cycles, ice recrystallization can contribute to the weakening of the gluten network and result in a decreased quality of the final product after the baking stage [46]. Among other effects reported by [9], from protein isolated from barley, are the increase in the apparent specific heat of the dough after freezing and the decrease in the range of the enthalpy of fusion of ice. Finally, the presence of wheat proteins increased the water retention capacity and the specific volume [47] studied the effect of barley protein as a cryoprotective agent in dough and bread during freeze-thaw cycles. Some positive changes in the structure were found since the damage caused by the ice formation was minimized. In this way, the water content, its mobility in the structure, and its final distribution intervened in the protection generated by the addition of the protein. The damaging effect of temperature was found to be greater for glutenins than for gliadins and this influenced ice formation, resulting in inhibition of recrystallization during treatment at low temperatures. Additionally, fermentation times were longer for frozen dough that did not contain barley protein inclusion, but the specific volume after baking was lower compared to a fresh product [48] analyzed the cryoprotective effects of carrot proteins in bread dough. The frozen dough limited the increase in freezable water content, and this effect reduced the damage caused by the formation of ice crystals and helped improve the specific volume and texture of the product at the end of the baking stage.

Finally, the cryoprotective properties of ice structural proteins help maintain the fermentation activity of viable yeast cells, preventing the formation of ice crystals which can weaken the structure of the gas cells formed during fermentation, with a consequent adverse effect on the specific volume of the finished product. In addition, the quality of the matrix in terms of its microstructure depends on factors such as the amount of water and the storage time at low temperatures, which have a negative effect on the viscosity of the dough. An advantage of antifreeze proteins is that they can control up to 73% of the variation in the volume of the ice obtained, limiting the increase in the freezable water content, and generating a product with better volume and low viscosity [49–52].

Like trehalose, glycerol exhibits cryoprotective properties. The possibility for employing intracellular-glycerol-enriched cells in frozen dough is suggested by the improvement of dough leavening capacity, decreased proof time after first freezing and thawing, and enhanced freeze thaw stress tolerance following the addition of glycerol to baker's yeast.

investigated the effects of glycerol on the amount of ice in unfrozen and frozen steamed bread dough, as well as the quality of unfrozen and frozen steamed bread. The results showed that glycerol prevented ice crystal formation during freezing and maintained the quality of steamed bread made from prefermented frozen dough for up to 30 days. The addition of 2% glycerol was found to be the most effective. Additionally, the quality of the bread was affected by prefermenting conditions, with the best results obtained at 32 °C and 85% relative humidity for 40 min [53]. Also, [54] investigated how the qualities of dough and white bread were affected by the addition of polyols, particularly glycerol and sorbitol. The rigidity of the dough was reduced by both polyols, according to rheology experiments. Since glycerol can hold more water than sorbitol, more water is absorbed into the surface of the gluten-starch system. When glycerol or sorbitol was added in amounts lower than 8%, the qualities of the dough and bread were improved, including the moisture content and water activity. The gluten strength of the dough decreased when more than 8% of glycerol or sorbitol was added, making shaping, and proving challenging and lowering the quality of the white bread. Additionally, [45] claim that glycerol plays a significant part in the development of ice crystals during freezing and frozen storage mode, maintaining the bread's quality. Finally, [55] on the quality and shelf life of Barbari bread, it was investigated how part-baking technology, freezer storage, the usage of glycerol, and ascorbic acid affected it. The effects of adding glycerol and ascorbic acid to the bread formulation at various concentrations (0, 0.5, and 1% for glycerol and 0, 75, and 100 ppm for ascorbic acid) on the bread's rheological and sensory characteristics were assessed. They discovered that adding 0.5% glycerol and 150 ppm ascorbic acid to bread during frozen storage caused it to become less hard while increasing its specific volume, porosity, and sensory quality.

The Fructooligosaccharides compounds can make the dough softer, reduce dough hardness, and improve baking quality of bread [56] and [57] claim the best result was found with 6% addition which presented the highest volume after baking, and the color of the bread crust was darker, but the crumb was moister and softer. Additionally, [58] have shown plausible applications as dough improvers in frozen dough baking or related applications [59] studied the impact of fructooligosaccharides (FOS) and soy protein hydrolysates (SPH) on the technical excellence of functional bread and dough rheology. The rheological characteristics of premixes with various degrees of SPH and FOS were assessed using Mixolab. To choose two premixes appropriate and unsuitable for baking bread, surface response methodology (SRM) and desirability methodology were used, and they were compared to control bread made exclusively with wheat flour (WF). The findings demonstrated that Mixolab characteristics and statistical techniques like CCD and desirability were suitable for predicting the replacement levels of WF by SPH and FOS for generating functional bread with comparable specific volume and firmness to control bread.

Also, guar gum, was investigated by [60] and the effect of hydrocolloids such as guar and xanthan gums and their combination with amylase and lipase can improve the quality of part baked frozen bread. The results indicated the guar gum had better effect when combination whit enzymes (amylase and lipase). In addition, [37] the quality and stability of the dough after freezing storage showed significant improvement in volume, porosity, moisture content, hardness, and sensory properties. On the other hand, [61] assessed the impact of adding guar gum to gluten-free cheese bread made with chilled and frozen dough. Three different levels of guar gum were tested, and sensory analysis was conducted on samples with the closest texture and specific volume to the control dough. Results showed that samples processed using freezing treatment with 3,5% of guar gum had lower consumer acceptance due to a light salty taste even the purpose of cryoprotection was good.

Cryoprotectants are categorized as intracellular and extracellular compounds. Intracellular cryoprotectants are able to permeate the cell wall and impact colligative properties, resulting in a decrease in solute concentration and a less harmful environment for yeast cells. This behavior reduces the amount of water available for the freezing process by reducing the mobility of water molecules, caused by the solution's viscosity, and lowering the freezing point. In contrast, extracellular cryoprotectants induce osmolarity in the environment, promoting the outflow of water from the inside of the cell to the outside to prevent the formation of ice crystals during the freezing cycle. The mechanism of action of these compounds is particularly suited to protecting yeast cells, as they can coat the entire outer surface of the cell wall, forming a viscous layer that stabilizes the cell and reduces damage caused by nucleation of ice at freezing temperatures [62].

The development of baked products that incorporate cryoprotectants is based on the specific qualities that each cryoprotectant presents, in order to report the specific needs required. Polyols included in frozen dough have the advantage of supporting the gluten, starch, and yeast network, as they act as protectors for viable cells during freezing, which is reflected in the development of the dough's structure. On the other hand, hydrocolloids, such as gums, can retain moisture in the structure, preventing the thawing cycle from negatively affecting the dough and causing leaching of available water in the matrix. This results in a moist and stable product with minimal porosity. The most promising compounds used in the industry are hydrocolloids and polyalcohols, as they provide protection for yeast cells to ensure the presence of gas and generate the specific volume characteristic of baked products. Consequently, the market acceptability of baked goods increases, and a considerable number of investigations have been conducted on different matrices. Finally, this illustrates how the bakery industry is adapting to market trends and creating technological challenges to improve the quality of frequently consumed foods.

Current trends try to find the combination of ice formation inhibitors as an alternative to adapt and improve the organoleptic properties of foods. For this reason, it is recommended to carry out further research on the combination of antifreeze proteins and other cryoprotective compounds such as hydrocolloids, polyalcohols, and [41][35][44][53][54][45][55][56][57][58][59][60][37][61] enzymes, among others, and thus identify which of these mixtures could be more promising for the bakery industry.

Challenges and Future work

The use of cryoprotective substances in frozen dough is a technological advancement that aims to mitigate the potential negative effects of frozen storage and ensure the stability of the dough structure. Furthermore, these substances are being considered for the development of new baked products that have an extended shelf life while maintaining the industry's characteristic textural properties. One of the challenges faced by the industry is understanding how these compounds interact with various additives that are used to improve the palatability of the dough matrix. It is essential to understand if these products affect the behavior of cryoprotectants in frozen dough. Another challenge is the effect of individual or combined cryoprotectants on ice crystallization, which can impact the quality of the final product. Establishing a product with satisfactory physicochemical, microbiological, and sensory attributes is a significant challenge in the bakery industry. Researchers must determine the stability between the freezing process and the protective compounds to ensure efficient processing of baked goods.

The differential approach of cryoprotectant compounds for frozen dough in baked goods today is to carefully balance the need to protect the dough during the freezing process with the need to maintain the quality and taste of the final product. Future perspectives in research on cryoprotectant compounds for frozen dough in baked goods can focus on finding more efficient, sustainable, and environmentally friendly solutions to improve the quality and shelf life of these products.

Conclusion

When preparing frozen dough for bakery products, mechanical damage occurs, which significantly impairs the quality of the final product by reducing specific volume and organoleptic properties. Starch retrogradation proceeds rapidly, causing an increase in hardness, viscoelasticity, and dough expansion. To control the problems associated with storing frozen dough, additives have been included in the production process to improve or preserve the dough quality at the baking stage and prolong the shelf life of bakery dough. Hydrocolloids, ice structural proteins, and polyols are used as additives in the industry, with polyols being the most promising cryoprotectants due to their protective action and integration with the gluten network and starch granules present in the dough. The production of frozen dough is a challenge for food science and technology, offering an opportunity to improve the process and develop research and innovation.

Including additives helps ensure greater product stability over time, even at increased cost, and reformulating raw materials can guarantee technological development in the industry. Thawing technology has led pastry chefs, bakers, and researchers to consider cryoprotection a viable alternative to maintain dough structure integrity and ensure yeast cell viability, resulting in characteristic volume when processed without freezing. Ice crystallization has different applications in relation to baked products, its main advantage being the protection of matrix integrity. The industry must continue to study cryoprotective compounds to understand their effects and behaviors with different food matrices or their synergy with other food additives.

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Declarations

Competing Interests The authors declare no competing interests.

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