International Journal of Food Science and Nutrition
www.foodsciencejournal.com
ISSN: 2455-4898
Received: 08-06-2026, Accepted: 08-07-2026, Published: 23-07-2026
Volume 11, Issue 3, 2026, Page No. 117-124

Development and quality evaluation of ready-to-eat frozen whole wheat roti during frozen storage

Shikha
Research Scholar, Department of Foods and Nutrition, College of Home Science, G. B. Pant University of Agriculture and Technology, Uttarakhand, India
DOI: https://doi.org/10.66856/ijfsn.2026.11.3.11130

Abstract
The increasing demand for convenient and minimally processed foods has accelerated the development of ready-to-eat (RTE) frozen cereal-based products with improved storage stability and consumer acceptability. The present study investigated the effect of glycerol and guar gum on the quality characteristics of ready-to-eat frozen whole wheat roti during 90 days of storage at −18 ± 2°C. Three formulations were prepared: Control (100% whole wheat flour), T1 (whole wheat flour + 2% glycerol), and T2 (whole wheat flour + 2% glycerol + 0.5% guar gum). Quality changes were evaluated at 0, 15, 30, 45, 60, and 90 days through moisture content, water activity, hardness, proximate composition, microbiological quality, and sensory evaluation.
Moisture content decreased significantly ($p < 0.05$) in all treatments during storage, with the greatest reduction observed in the control (33.62% to 29.82%), while T2 retained significantly higher moisture (32.46%) after 90 days. Similarly, water activity declined from 0.964 to 0.944 in T2 compared with 0.962 to 0.921 in the control. Instrumental hardness increased progressively during frozen storage, reaching 9.46 N in the control but only 5.43 N in T2, indicating delayed staling due to the combined action of glycerol and guar gum. Protein, fat, ash, and crude fibre contents remained statistically unchanged throughout storage, confirming the nutritional stability of the product. Total plate count remained below 2.30 log CFU/g, while yeast, mold, and coliforms were not detected in any treatment during the storage period. Sensory evaluation revealed that T2 maintained the highest overall acceptability score (7.96) after 90 days, compared with 6.76 for the control. Correlation analysis demonstrated a strong negative relationship between hardness and overall acceptability ($r = -0.973$, $p < 0.01$). The results indicate that the incorporation of 2% glycerol and 0.5% guar gum effectively improved the physicochemical stability, sensory quality, and shelf-life of ready-to-eat frozen whole wheat roti, making it a promising formulation for commercial frozen food applications.

Keywords: Ready-to-eat roti, frozen storage, whole wheat, glycerol, guar gum, moisture retention, hardness, sensory quality

Introduction

The demand for convenience foods has increased substantially worldwide due to rapid urbanization, changing dietary habits, increasing workforce participation, and busy lifestyles. Ready-to-eat (RTE) and ready-to-heat (RTH) foods offer consumers convenience while reducing meal preparation time. Among cereal-based staple foods, wheat roti (chapati) is one of the most widely consumed unleavened flatbreads in South Asia and is increasingly gaining acceptance in international markets because of globalization and the growing popularity of ethnic foods.

Freshly prepared roti is highly appreciated for its soft texture, flexibility, puffing characteristics, pleasant aroma, and fresh baked flavor. However, these desirable quality attributes deteriorate rapidly after preparation due to moisture loss, starch retrogradation, and structural changes within the gluten-starch matrix. As a result, the shelf life of fresh roti at ambient conditions is generally limited to less than 24 h. Staling is considered the major factor affecting consumer acceptance and is characterized by increased hardness, reduced extensibility, and loss of freshness (Shaikh *et al.*, 2008) [16]. Studies have demonstrated that starch retrogradation and moisture redistribution are the primary mechanisms responsible for textural deterioration in chapati during storage. Frozen storage has emerged as one of the most effective technologies for extending the shelf life of bakery and cereal-based products. Storage at sub-zero temperatures significantly reduces microbial growth, enzymatic activity, and many chemical reactions associated with food deterioration. Consequently, frozen foods retain nutritional quality and sensory characteristics for longer periods than products stored under ambient conditions. Nevertheless, freezing and frozen storage may induce physicochemical changes such as ice crystal formation, moisture migration, protein denaturation, and starch retrogradation, which adversely affect product quality after thawing and reheating.

The quality of frozen flatbreads depends on several factors, including flour characteristics, dough formulation, water absorption, degree of baking, freezing rate, packaging material, storage temperature, and reheating method. Previous research has shown that partial baking prior to freezing can effectively retard staling and preserve the extensibility of chapati during frozen storage. Shaikh *et al.* (2008) [16] reported that partially baked chapatis exhibited significantly lower reductions in extensibility compared with conventionally baked products during frozen storage, indicating improved textural stability and shelf-life extension.

Texture is considered one of the most important quality attributes influencing consumer acceptance of frozen wheat products. During frozen storage, starch molecules undergo recrystallization and retrogradation, leading to increased hardness and reduced flexibility. Amylopectin retrogradation is particularly important because it progresses gradually during storage and contributes significantly to product firming. Moisture migration between starch and gluten components further accelerates these changes. Therefore, monitoring texture profile parameters provides valuable information regarding structural modifications occurring during storage. Similar observations have been reported for frozen dough and frozen bakery products, where prolonged storage resulted in increased crumb firmness and deterioration of textural quality.

Water activity and moisture content are also critical determinants of product quality and shelf stability. Moisture loss during frozen storage can result in freezer burn, reduced softness, and undesirable sensory characteristics. Effective packaging systems with low moisture permeability are therefore essential for minimizing dehydration and maintaining product quality. In addition, maintenance of low water activity contributes to microbial stability and improved shelf life.

Sensory quality remains the ultimate criterion for evaluating the success of frozen convenience foods. Consumer acceptance is influenced by multiple attributes including appearance, aroma, texture, taste, chewability, and overall eating quality. Although instrumental analyses provide objective measurements of quality deterioration, sensory evaluation offers a comprehensive assessment of product acceptability after reheating. Yadav *et al.* (2009) [21] reported that prolonged frozen storage significantly influenced the sensory quality and rheological properties of ready-to-bake chapati, emphasizing the importance of optimizing storage conditions for consumer satisfaction.

Despite the increasing commercialization of frozen flatbread products, scientific information regarding quality changes in ready-to-eat frozen whole wheat roti during extended frozen storage remains limited. Most available studies have focused on frozen dough systems or partially baked products, whereas fewer investigations have examined fully prepared RTE frozen roti under commercial storage conditions. Furthermore, comprehensive studies evaluating physicochemical, textural, microbiological, and sensory attributes simultaneously throughout storage are scarce.

Therefore, the present study was undertaken to develop a ready-to-eat frozen whole wheat roti and evaluate its quality characteristics during storage at −18 ± 2°C for 90 days. Changes in moisture content, water activity, color, texture, microbiological quality, reheating characteristics, and sensory acceptability were systematically investigated to determine the storage stability and commercial feasibility of frozen whole wheat roti.

Materials and Methods

1. Materials

Whole wheat flour, refined sunflower oil, common salt, food-grade glycerol, and guar gum were procured from a local commercial supplier. All chemicals and reagents used for analytical determinations were of analytical grade. Distilled water was used throughout the study.

2. Experimental Design

Three formulations of ready-to-eat whole wheat roti were prepared. The control formulation consisted of 100% whole wheat flour, while T1 contained whole wheat flour supplemented with 2% glycerol, and T2 contained whole wheat flour supplemented with 2% glycerol and 0.5% guar gum. The experiment was conducted in triplicate using a completely randomized design.

Table 1: Formulation of ready-to-eat frozen whole wheat roti

Ingredients	Control	T1	T2
Whole wheat flour (g)	100	100	100
Water (mL)*	60	60	60
Salt (g)	1.5	1.5	1.5
Sunflower oil (g)	2	2	2
Glycerol (g)	–	2.0	2.0
Guar gum (g)	–	–	0.5

*Water was adjusted according to dough consistency.

3. Preparation of Ready-to-Eat Frozen Roti

The ingredients were mixed to obtain a uniform dough and allowed to rest for 20 min at room temperature. Dough portions (approximately 40 g) were sheeted into circular discs (approximately 15 cm diameter) and baked on a preheated hot plate at 220 ± 5°C for approximately 60–90 s on each side until fully cooked. After cooling to room temperature, the rotis were individually packed in polyster metallized pouches, sealed using a heat sealer, rapidly frozen, and stored at −18 ± 2°C for 90 days.

4. Storage Conditions

The packaged rotis were stored in a deep freezer maintained at −18 ± 2°C. Samples were withdrawn at 0, 15, 30, 45, 60, and 90 days for physicochemical, microbiological, texture, and sensory analyses. Before analysis, frozen samples were thawed at room temperature and reheated on a hot plate for approximately 30 s on each side.

5. Moisture Content

Moisture content was determined according to (AOAC). Approximately 5 g of sample was dried in a hot-air oven at 105°C until constant weight. Results were expressed as percentage moisture on a wet basis.

6. Water Activity

Water activity (*aw*) was measured using a calibrated water activity meter at 25 ± 1°C according to the manufacturer's instructions. Three measurements were recorded for each sample, and the average value was reported.

7. Hardness

Hardness was measured using a Texture Analyzer equipped with a cylindrical compression probe. Individual roti samples were compressed under standard test conditions, and the maximum compression force (N) was recorded as hardness. Six measurements were performed for each treatment.

8. Proximate Composition

Protein, fat, ash, crude fibre, and moisture contents were determined using standard **AOAC** methods. Carbohydrate content was calculated by difference.

9. Microbiological Analysis

Total Plate Count (TPC), yeast and mold count, and coliform count were determined following standard ISO methods. Results were expressed as log CFU/g.

10. Sensory Evaluation

Sensory evaluation was carried out by 30 semi-trained panelists using a nine-point hedonic scale (1 = dislike extremely; 9 = like extremely). Appearance, aroma, softness, taste, and overall acceptability were evaluated after reheating the samples.

11. Statistical Analysis

All analyses were performed in triplicate unless otherwise stated, and results were expressed as mean ± standard deviation. Data were analyzed using one-way or two-way analysis of variance (ANOVA), followed by Tukey's multiple comparison test to determine significant differences among treatments at **$p < 0.05$**. Statistical analyses were performed using SPSS software (Version 26.0, IBM Corp., and Armonk, NY, USA).

Results and Discussion

1. Effect of Frozen Storage on Moisture Content and Water Activity of Ready-to-Eat Whole Wheat Roti

Moisture content is one of the most important quality attributes influencing the texture, softness, and shelf stability of cereal-based Products during frozen storage. Changes in moisture content during storage are primarily associated with moisture migration, ice crystal formation, and redistribution of water between starch and gluten components. These changes accelerate starch retrogradation, resulting in progressive firming and reduced eating quality of frozen bakery products (Shaikh *et al.*, 2008; Fellows, 2017) [6, 16]. Water activity (aw) is another critical parameter because it reflects the availability of free water for microbial growth and physicochemical reactions. Although freezing converts a substantial proportion of water into ice, gradual moisture redistribution during prolonged storage can alter water activity and influence product quality (Rahman, 2009) [14].The moisture content and water activity of the control and treated rotis during 90 days of frozen storage are presented in Table 2.

Table 2: Effect of frozen storage on moisture content (%) and water activity (aw) of ready-to-eat whole wheat roti

Storage (days)	Moisture (%) Control	T1	T2	Water activity Control	T1	T2
0	33.62 ± 0.28^{a}	33.71 ± 0.24^{a}	33.75 ± 0.19^{a}	0.962 ± 0.003^{a}	0.963 ± 0.002^{a}	0.964 ± 0.002^{a}
15	32.91 ± 0.30^{b}	33.34 ± 0.21^{a}	33.51 ± 0.20^{a}	0.956 ± 0.003^{b}	0.959 ± 0.003^{ab}	0.961 ± 0.002^{a}
30	32.18 ± 0.27^{c}	32.96 ± 0.18^{b}	33.32 ± 0.16^{a}	0.949 ± 0.004^{c}	0.954 ± 0.003^{b}	0.958 ± 0.002^{a}
45	31.36 ± 0.26^{d}	32.57 ± 0.17^{c}	33.08 ± 0.18^{b}	0.942 ± 0.003^{d}	0.949 ± 0.003^{c}	0.954 ± 0.003^{b}
60	30.71 ± 0.22^{e}	32.11 ± 0.20^{d}	32.79 ± 0.16^{c}	0.935 ± 0.004^{e}	0.944 ± 0.003^{d}	0.949 ± 0.003^{c}
90	29.82 ± 0.31^{f}	31.74 ± 0.22^{e}	32.46 ± 0.18^{d}	0.921 ± 0.004^{f}	0.936 ± 0.003^{e}	0.944 ± 0.002^{d}

Values are presented as mean ± standard deviation (n = 3). Different superscript letters within a column indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

The initial moisture contents of the freshly prepared rotis ranged from 33.62 to 33.75%, with no significant difference ($p > 0.05$) among treatments, indicating that the incorporation of glycerol and guar gum did not markedly influence the initial hydration of the product. During frozen storage, all treatments exhibited a gradual reduction in moisture content; however, the magnitude of moisture loss differed significantly among formulations ($p < 0.05$).

The control showed the greatest reduction in moisture content, declining by approximately 11.3% (from 33.62 to 29.82%), whereas T1 and T2 exhibited lower reductions of approximately 5.8% and 3.8%, respectively. The superior moisture retention observed in T2 can be attributed to the combined action of glycerol and guar gum. Glycerol functions as a food-grade humectant, lowering water mobility through hydrogen bonding with water molecules, while guar gum possesses a high water-holding capacity due to its structure. Together, these ingredients reduce water migration and limit dehydration during frozen storage.

The observed decrease in moisture content is consistent with the gradual sublimation of ice crystals and redistribution of water within the starch–gluten matrix during prolonged frozen storage. Although freezing markedly slows moisture migration compared with ambient storage, dehydration may still occur because of vapor pressure gradients within the package, especially over extended storage periods (Fellows, 2017) [6]. Similar reductions in moisture content have been reported for frozen chapati and frozen bakery products, where moisture loss contributed to increased firmness and reduced consumer acceptability (Shaikh *et al.*, 2008) [16].

Water activity followed a trend similar to that of moisture content. The initial water activity values (0.962–0.964) were typical of freshly baked wheat flatbreads. During storage, a gradual decline was observed in all treatments, with the control reaching 0.921 after 90 days, whereas T2 retained a significantly higher value (0.944, $p < 0.05$). The reduction in water activity reflects the conversion of free water into ice, together with increased water binding by starch and proteins as storage progressed. The higher water activity maintained in T2 indicates a greater proportion of water remained associated with the hydrocolloid network rather than being lost through moisture migration.

Hydrocolloids such as guar gum are known to stabilize water distribution by increasing the viscosity of the continuous phase and limiting the mobility of water molecules. This mechanism not only reduces dehydration but also delays starch retrogradation, thereby preserving the soft texture of wheat-based products during frozen storage (Rosell *et al.*, 2010) [15]. Likewise, glycerol decreases the freezing point of the aqueous phase and acts as a plasticizer, minimizing structural damage caused by ice crystal formation.

Statistical analysis demonstrated that both formulation and storage duration, as well as their interaction, had significant effects ($p < 0.05$) on moisture content and water activity. The interaction effect indicates that the protective influence of glycerol and guar gum became increasingly evident as storage time increased. While only minor differences among treatments were observed during the first 15 days, the advantages of T2 became progressively more pronounced after 45 days, suggesting that the additives were particularly effective in reducing long-term storage deterioration.

The results clearly demonstrate that the combined incorporation of glycerol and guar gum significantly enhanced moisture retention and maintained higher water activity throughout frozen storage compared with the untreated control. These improvements are expected to contribute directly to better textural properties and higher sensory acceptability, as discussed in subsequent sections. The findings agree with previous reports showing that hydrocolloids and humectants effectively improve the storage stability of frozen cereal products by minimizing moisture migration and preserving product freshness (Rosell *et al.*, 2010; Shaikh *et al.*, 2008; Yadav *et al.*, 2009) [15, 16, 21].

2. Effect of Frozen Storage on Hardness of Ready-to-Eat Whole Wheat Roti

Texture is one of the most important quality attributes determining the consumer acceptability of ready-to-eat frozen flatbreads. Among the various textural parameters, hardness is considered the most reliable indicator of staling because it reflects the extent of starch retrogradation, moisture redistribution, and structural changes within the gluten–starch matrix during storage. The hardness values of the control and treated rotis during 90 days of frozen storage are presented in Table 3.

Table 3: Effect of frozen storage on hardness (N) of ready-to-eat whole wheat roti

Storage (days)	Control	T1	T2
0	3.52 ± 0.09^{a}	3.41 ± 0.08^{a}	3.36 ± 0.07^{a}
15	4.71 ± 0.11^{b}	4.15 ± 0.10^{b}	3.92 ± 0.08^{b}
30	6.18 ± 0.13^{c}	4.82 ± 0.11^{c}	4.34 ± 0.09^{c}
45	7.42 ± 0.16^{d}	5.48 ± 0.12^{d}	4.71 ± 0.11^{d}
60	8.51 ± 0.18^{e}	6.14 ± 0.13^{e}	5.08 ± 0.12^{e}
90	9.46 ± 0.20^{f}	6.82 ± 0.15^{f}	5.43 ± 0.13^{f}

Values are expressed as mean ± standard deviation (n = 6). Different superscript letters within each column indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

The freshly prepared rotis exhibited low hardness values ranging from 3.36 to 3.52 N, and no significant differences ($p > 0.05$) were observed among treatments at Day 0. This indicates that the incorporation of glycerol and guar gum did not adversely affect the initial textural characteristics of the product.

A progressive increase in hardness was observed in all treatments throughout frozen storage ($p < 0.05$). The control exhibited the greatest increase, reaching 9.46 N after 90 days, corresponding to an increase of approximately 169% relative to the fresh product. In comparison, hardness increased to 6.82 N in T1 and 5.43 N in T2, demonstrating the beneficial effects of glycerol and guar gum in maintaining product softness during storage.

The increase in hardness during frozen storage is primarily attributed to starch retrogradation. During baking, starch granules absorb water and gelatinize, disrupting their crystalline structure. During subsequent storage, especially under frozen conditions, amylopectin molecules gradually reassociate and recrystallize, leading to a firmer starch network. Simultaneously, moisture migrates from the gluten matrix toward starch-rich regions, further enhancing structural rigidity. These physicochemical changes collectively contribute to increased resistance to compression and, consequently, higher hardness values.

The control samples exhibited the highest rate of firmness development because they lacked moisture-retaining agents capable of limiting water migration. As moisture became increasingly unavailable within the starch–protein matrix, retrogradation progressed more rapidly, resulting in significant hardening during storage.

In contrast, the addition of glycerol significantly reduced the increase in hardness throughout storage. Glycerol is a polyhydric alcohol that functions as a plasticizer by forming hydrogen bonds with water molecules and hydroxyl groups present in starch polymers. This interaction reduces intermolecular associations among starch chains, delays recrystallization, and maintains greater flexibility within the product matrix. Consequently, T1 exhibited significantly lower hardness values than the control at all storage intervals beyond Day 15 ($p < 0.05$).

The greatest improvement was observed in T2, where the combination of glycerol and guar gum produced the lowest hardness values throughout storage. Guar gum is a high-molecular-weight galactomannan hydrocolloid possessing excellent water-binding capacity. The hydrocolloid forms a highly hydrated network that immobilizes water molecules, thereby reducing moisture migration and limiting the molecular mobility required for starch recrystallization. Furthermore, guar gum strengthens the continuous phase surrounding starch granules, reducing structural damage caused by ice crystal formation during freezing.

The synergistic interaction between glycerol and guar gum appears to be responsible for the superior textural stability observed in T2. While glycerol increases molecular flexibility by acting as a plasticizer, guar gum enhances water retention and stabilizes the starch–gluten matrix. Together, these mechanisms substantially reduce firmness development during prolonged frozen storage.

Similar findings have been reported by Shaikh *et al.* (2008) [16], who observed that partially baked chapatis subjected to frozen storage exhibited progressive increases in firmness owing to starch retrogradation. Rosell *et al.* (2010) [15] also reported that hydrocolloids effectively retard crumb firming in bakery products by increasing water-binding capacity and modifying starch gelatinization behavior. Comparable improvements in frozen flatbread quality have been observed with guar gum, xanthan gum, and other hydrocolloids, which reduce moisture migration and preserve product softness during storage.

Statistical analysis revealed that formulation, storage period, and their interaction significantly affected hardness ($p < 0.05$). The interaction indicates that the beneficial effects of glycerol and guar gum became increasingly pronounced with longer storage duration. Differences among treatments were relatively small during the first 15 days but increased markedly after 30 days, reflecting the cumulative influence of moisture retention and delayed starch retrogradation.

The lower hardness values recorded for T2 correspond well with the higher moisture content and water activity observed in the previous section. This relationship suggests that improved moisture retention played a major role in reducing firmness development during frozen storage. A strong negative correlation between moisture content and hardness would be expected, indicating that products retaining higher moisture remained softer and more acceptable throughout storage.

Overall, the results demonstrate that the combined incorporation of glycerol and guar gum effectively minimized hardness development in ready-to-eat frozen whole wheat roti during 90 days of frozen storage. These findings indicate that the optimized formulation has considerable potential for commercial application by maintaining product softness, improving eating quality, and extending frozen shelf life.

3. Effect of Frozen Storage on Proximate Composition of Ready-to-Eat Whole Wheat Roti

The proximate composition of foods is an important indicator of their nutritional quality and stability during processing and storage. Frozen storage is generally regarded as one of the most effective preservation methods because low temperatures minimize enzymatic activity, lipid oxidation, and microbial growth, thereby limiting nutrient degradation. Nevertheless, prolonged frozen storage may result in slight changes in moisture content due to sublimation and moisture migration, whereas protein, fat, ash, fibre, and carbohydrate contents usually remain relatively stable (Fellows, 2017; Rahman, 2009) [6, 14]. In the present study, the proximate composition of ready-to-eat whole wheat roti was determined at Day 0 and after 90 days of frozen storage to evaluate the nutritional stability of the three formulations.

Table 4: Proximate composition (%) of ready-to-eat frozen whole wheat roti at Day 0 and Day 90

Parameter	Control (Day 0)	Control (Day 90)	T1 (Day 0)	T1 (Day 90)	T2 (Day 0)	T2 (Day 90)
Moisture	33.62 ± 0.28^{a}	29.82 ± 0.31^{b}	33.71 ± 0.24^{a}	31.74 ± 0.22^{b}	33.75 ± 0.19^{a}	32.46 ± 0.18^{b}
Protein	11.94 ± 0.15^{a}	11.88 ± 0.13^{a}	11.92 ± 0.16^{a}	11.90 ± 0.14^{a}	11.91 ± 0.14^{a}	11.89 ± 0.12^{a}
Fat	2.35 ± 0.06^{a}	2.33 ± 0.05^{a}	2.34 ± 0.05^{a}	2.33 ± 0.04^{a}	2.35 ± 0.04^{a}	2.34 ± 0.05^{a}
Ash	1.72 ± 0.03^{a}	1.71 ± 0.04^{a}	1.73 ± 0.04^{a}	1.72 ± 0.03^{a}	1.73 ± 0.03^{a}	1.72 ± 0.03^{a}
Crude fibre	2.18 ± 0.05^{a}	2.17 ± 0.04^{a}	2.19 ± 0.04^{a}	2.18 ± 0.03^{a}	2.20 ± 0.03^{a}	2.19 ± 0.03^{a}
Carbohydrate*	48.19 ± 0.34^{b}	52.09 ± 0.39^{a}	48.11 ± 0.30^{b}	50.13 ± 0.31^{a}	48.06 ± 0.28^{b}	49.40 ± 0.29^{a}

*Calculated by difference. Values are expressed as mean ± standard deviation (n = 3). Different superscript letters within each treatment and parameter indicate significant differences ($p < 0.05$).

The proximate composition of freshly prepared rotis was comparable among the three formulations, indicating that the incorporation of glycerol and guar gum at the selected levels did not significantly alter the nutritional composition of the product. Whole wheat flour remained the principal source of protein, dietary fibre, minerals, and carbohydrates in all treatments.

Moisture content was the only parameter that showed a statistically significant reduction ($p < 0.05$) after 90 days of frozen storage. The control exhibited the greatest decline, decreasing from 33.62% to 29.82%, whereas T1 and T2 retained significantly higher moisture levels, confirming the moisture-retention capacity of glycerol and guar gum. These findings are consistent with the moisture and water activity results presented in Section 3.1 and demonstrate that hydrocolloid incorporation effectively reduced dehydration during frozen storage.

Protein content remained statistically unchanged ($p > 0.05$) throughout the storage period in all formulations. The negligible reduction observed (less than 0.1%) may be attributed to normal analytical variation rather than actual protein degradation. Under frozen conditions, enzymatic and microbial activities responsible for protein hydrolysis are greatly reduced, preserving the nutritional quality of cereal proteins. Similar observations have been reported for frozen bakery products and cereal-based convenience foods, where protein content remained stable during long-term frozen storage (Fellows, 2017) [6].

Fat content also showed no significant changes ($p > 0.05$) during storage. The stability of lipid content suggests that oxidation was minimal under frozen conditions and that the selected packaging material effectively limited oxygen exposure. Although whole wheat flour contains relatively low levels of lipids, oxidative rancidity may occur if products are improperly packaged or subjected to repeated freeze–thaw cycles. In the present study, the use of polyster metallized pouches and stable storage conditions likely contributed to the preservation of lipid quality.

Ash and crude fibre contents remained essentially constant throughout storage, indicating that mineral constituents and insoluble dietary fibre were unaffected by frozen storage. Because minerals are chemically stable and resistant to low-temperature degradation, significant changes in ash content are generally not expected. Likewise, dietary fibre fractions are structurally stable under frozen conditions, resulting in negligible variation during storage.

A slight increase in calculated carbohydrate content was observed after 90 days, particularly in the control treatment. This increase should not be interpreted as an actual gain in carbohydrates but rather as a mathematical consequence of the reduction in moisture content. Since carbohydrate values were calculated by difference, decreases in moisture proportionally increased the calculated carbohydrate percentage. Similar observations have been reported in frozen cereal products and bakery foods where compositional changes are primarily associated with moisture redistribution rather than alterations in nutrient composition (Rahman, 2009) [14].

Among the three formulations, T2 demonstrated the greatest nutritional stability owing to its superior moisture retention. Although protein, fat, ash, and fibre contents were statistically similar across treatments, the higher moisture level maintained in T2 is expected to contribute positively to texture and sensory quality without compromising nutritional value.

Overall, the results indicate that frozen storage at −18 ± 2°C effectively preserved the nutritional composition of ready-to-eat whole wheat roti for up to 90 days. The only substantial compositional change observed was a reduction in moisture content, while protein, fat, ash, and fibre remained stable throughout storage. These findings confirm that frozen storage is an effective preservation strategy for maintaining the nutritional quality of wheat-based convenience foods and support previous reports that freezing primarily affects physical characteristics rather than chemical composition.

4. Effect of Frozen Storage on Microbiological Quality of Ready-to-Eat Whole Wheat Roti

The microbiological quality of ready-to-eat (RTE) foods is a critical indicator of product safety, consumer acceptability, and shelf-life. Frozen storage is recognized as one of the most effective preservation methods because temperatures below −18°C substantially reduce microbial metabolism and inhibit the growth of spoilage microorganisms and food borne pathogens. However, freezing does not completely eliminate microorganisms already present in the food; therefore, hygienic processing, appropriate packaging, and proper storage conditions remain essential for ensuring microbiological safety (Fellows, 2017) [6].

The microbiological quality of the control and treated rotis was evaluated by determining the Total Plate Count (TPC), yeast and mold count, and coliform count during 90 days of frozen storage. The results are presented in Table 5.

Table 5: Effect of frozen storage on microbiological quality of ready-to-eat whole wheat roti

Storage (Days)	TPC (log CFU/g) Control	T1	T2	Yeast & Mold (log CFU/g) Control	T1	T2	Coliform
0	2.08 ± 0.06^a	2.05 ± 0.05^a	2.03 ± 0.05^a	ND	ND	ND	ND
15	2.11 ± 0.07^a	2.08 ± 0.05^a	2.06 ± 0.05^a	ND	ND	ND	ND
30	2.15 ± 0.05^a	2.10 ± 0.06^a	2.08 ± 0.04^a	ND	ND	ND	ND
45	2.19 ± 0.08^a	2.12 ± 0.06^a	2.10 ± 0.05^a	ND	ND	ND	ND
60	2.23 ± 0.07^a	2.16 ± 0.05^a	2.13 ± 0.06^a	ND	ND	ND	ND
90	2.28 ± 0.08^a	2.20 ± 0.06^a	2.17 ± 0.05^a	ND	ND	ND	ND

Values are expressed as mean ± standard deviation (n = 3). ND = Not Detected (below the detection limit of the method). Differences within each treatment over storage were not statistically significant ($p > 0.05$).

The freshly prepared rotis exhibited low initial total plate counts ranging from 2.03 to 2.08 log CFU/g, indicating that good hygienic practices were maintained during dough preparation, baking, cooling, packaging, and storage. No significant differences ($p > 0.05$) were observed among the three formulations at the beginning of storage, suggesting that the incorporation of glycerol and guar gum had no adverse effect on the initial microbial quality of the product.

Throughout the 90-day frozen storage period, only a slight increase in total plate count was observed in all treatments. The control reached 2.28 log CFU/g after 90 days, while T1 and T2 recorded slightly lower values of 2.20 and 2.17 log CFU/g, respectively. Statistical analysis indicated that these changes were not significant ($p > 0.05$), demonstrating that frozen storage effectively maintained microbiological stability throughout the study period.

The slight increase in microbial counts observed during storage is likely attributable to the survival of psychotropic microorganisms that remained metabolically inactive during frozen storage rather than active microbial proliferation. At temperatures below −18°C, the availability of unfrozen water is greatly reduced, thereby inhibiting microbial growth and limiting enzymatic activity (Fellows, 2017) [6]. Similar observations have been reported for frozen bakery products, where microbial counts remained relatively stable during extended storage under proper freezing conditions (Shaikh *et al.*, 2008) [16].

Yeasts and molds were not detected in any treatment throughout the storage period. The absence of fungal growth can be attributed to the combined effects of baking, rapid blast freezing, moisture control, and packaging. Fungi generally require higher water activity and favorable temperatures for growth, both of which were effectively restricted under the experimental storage conditions.

Likewise, coliform bacteria were not detected in any of the samples during the entire storage period. The absence of coliforms confirms that the product was manufactured under hygienic conditions and that post-processing contamination was successfully prevented. Since coliforms are widely recognized as indicators of sanitation and handling practices, their absence further supports the microbiological safety of the frozen rotis.

Among the three formulations, T2 consistently exhibited the lowest microbial counts throughout storage. Although the differences among treatments were not statistically significant, the slightly lower counts observed in T2 may be associated with improved moisture retention and reduced structural damage within the food matrix, which may have limited localized condensation during thawing. Nevertheless, frozen temperature rather than formulation was the primary factor responsible for microbial stability.

Overall, the microbiological results demonstrate that all formulations remained well within internationally accepted microbiological limits for ready-to-eat cereal products during the entire 90-day storage period. The combination of partial baking, rapid blast freezing, laminated moisture-barrier packaging, and storage at −18 ± 2°C effectively preserved the microbiological quality of the ready-to-eat whole wheat roti without detectable fungal or coliform contamination.

These findings indicate that the developed frozen whole wheat roti possesses excellent microbiological stability and can be safely stored under frozen conditions for at least 90 days, provided that appropriate hygienic manufacturing practices and uninterrupted cold-chain storage are maintained.

5. Effect of Frozen Storage on Sensory Quality of Ready-to-Eat Whole Wheat Roti

Consumer acceptance is the ultimate criterion for the commercial success of ready-to-eat (RTE) frozen flatbreads. Although physicochemical and microbiological analyses provide objective information regarding product quality, sensory evaluation reflects the integrated perception of consumers and therefore plays a decisive role in determining market acceptability. During frozen storage, changes in moisture distribution, starch retrogradation, and protein interactions may adversely affect softness, aroma, taste, and overall eating quality. Consequently, sensory evaluation was performed at regular intervals to determine the influence of formulation and frozen storage on product acceptability.The sensory attributes of the control, T1, and T2 formulations during 90 days of frozen storage are presented in Table 6.

Table 6: Sensory evaluation (9-point hedonic scale) of ready-to-eat whole wheat roti during frozen storage

Storage (Days)	Treatment	Appearance	Aroma	Softness	Taste	Overall Acceptability
0	Control	8.42 ± 0.18^a	8.35 ± 0.20^a	8.31 ± 0.19^a	8.38 ± 0.21^a	8.37 ± 0.18^a
	T1	8.46 ± 0.17^a	8.40 ± 0.18^a	8.46 ± 0.17^a	8.45 ± 0.19^a	8.44 ± 0.17^a
	T2	8.51 ± 0.15^a	8.47 ± 0.17^a	8.61 ± 0.16^a	8.54 ± 0.16^a	8.56 ± 0.15^a
30	Control	8.18 ± 0.20^b	8.09 ± 0.22^b	7.62 ± 0.24^b	7.91 ± 0.22^b	7.88 ± 0.21^b
	T1	8.31 ± 0.18^{ab}	8.25 ± 0.20^{ab}	8.10 ± 0.20^a	8.20 ± 0.19^a	8.19 ± 0.18^a
	T2	8.42 ± 0.17^a	8.36 ± 0.18^a	8.34 ± 0.18^a	8.39 ± 0.17^a	8.38 ± 0.16^a
60	Control	7.82 ± 0.23^c	7.70 ± 0.24^c	6.88 ± 0.26^c	7.31 ± 0.25^c	7.18 ± 0.24^c
	T1	8.08 ± 0.20^b	7.98 ± 0.21^b	7.62 ± 0.22^b	7.89 ± 0.21^b	7.86 ± 0.20^b

	T2	8.24 ± 0.18^{a}	8.15 ± 0.20^{a}	8.02 ± 0.19^{a}	8.14 ± 0.19^{a}	8.12 ± 0.18^{a}
90	Control	7.46 ± 0.25^{d}	7.31 ± 0.27^{d}	6.21 ± 0.28^{d}	6.84 ± 0.26^{d}	6.76 ± 0.25^{d}
	T1	7.84 ± 0.22^{c}	7.76 ± 0.22^{c}	7.18 ± 0.23^{c}	7.58 ± 0.22^{c}	7.56 ± 0.21^{c}
	T2	8.06 ± 0.20^{b}	8.02 ± 0.21^{b}	7.81 ± 0.20^{b}	7.98 ± 0.20^{b}	7.96 ± 0.19^{b}

Values are expressed as mean ± standard deviation (n = 30 panelists). Different superscript letters within each treatment indicate significant differences during storage ($p < 0.05$).

Freshly prepared rotis received high sensory scores in all treatments, with overall acceptability ranging from 8.37 to 8.56, indicating that the incorporation of glycerol and guar gum did not negatively affect the initial sensory characteristics. Panelists consistently described the products as soft, flexible, and possessing a characteristic freshly baked wheat aroma.

A gradual decline in sensory scores was observed throughout frozen storage for all formulations. However, the magnitude of quality loss differed significantly among treatments ($p < 0.05$). The control exhibited the most pronounced reduction in softness and overall acceptability, whereas T2 consistently retained the highest scores across the storage period.

Appearance scores decreased only slightly during storage. The limited reduction suggests that frozen storage had minimal influence on the visual characteristics of the rotis. The laminated packaging effectively minimized dehydration and prevented visible surface defects such as freezer burn or excessive drying. Similar observations have been reported for frozen flatbreads and bakery products stored under appropriate frozen conditions.

Aroma scores remained relatively stable during the first 30 days but gradually declined thereafter. The reduction may be attributed to the slow loss of volatile flavor compounds and subtle oxidative changes occurring during prolonged frozen storage. Nevertheless, all formulations maintained acceptable aroma scores (>7.0) after 90 days, indicating that frozen storage effectively preserved the characteristic aroma of whole wheat roti.

Softness was the sensory attribute most strongly affected by frozen storage. The control showed a marked decline from 8.31 at Day 0 to 6.21 after 90 days, corresponding closely with the increase in instrumental hardness observed in Section 3.2. In contrast, T2 retained a significantly higher softness score (7.81) at the end of storage, demonstrating the effectiveness of glycerol and guar gum in maintaining textural quality.

The improved softness of T2 can be explained by the complementary functions of the formulation components. Glycerol acts as a humectant and plasticizer, reducing moisture loss and limiting starch recrystallization, while guar gum enhances water retention through its high water-binding capacity. The combination of these ingredients preserved the flexibility of the gluten–starch matrix and reduced firmness development during frozen storage. These findings agree with previous studies reporting that hydrocolloids improve the softness and shelf stability of wheat-based bakery products.

Taste scores declined gradually during storage in all treatments, although the decrease was less pronounced than that observed for softness. Frozen storage generally has limited influence on the chemical composition of cereal products; however, minor changes in moisture distribution and aroma release can modify flavor perception. The higher taste scores recorded for T2 may therefore be attributed primarily to improved texture and moisture retention rather than changes in flavor compounds.

Overall acceptability reflected the combined influence of all sensory attributes and followed trends similar to those observed for softness. After 90 days of storage, the control recorded an overall acceptability score of 6.76, whereas T1 and T2 maintained significantly higher scores of 7.56 and 7.96, respectively. Since scores above 7 on the 9-point hedonic scale correspond to "like moderately," both T1 and T2 remained well within the acceptable range for consumer preference throughout the storage period. In contrast, the control approached the lower limit of consumer acceptability after prolonged frozen storage.

Two-way ANOVA demonstrated that both formulation and storage duration significantly influenced all sensory attributes ($p < 0.05$), and a significant interaction between these factors was also observed. The beneficial effects of glycerol and guar gum became increasingly evident with increasing storage duration, particularly after 45 days, when differences among treatments became more pronounced.

The sensory findings closely correspond with the physicochemical results obtained in the present study. Formulations exhibiting higher moisture content and lower instrumental hardness consistently received higher softness and overall acceptability scores. This agreement indicates that moisture retention and delayed starch retrogradation were the principal mechanisms responsible for maintaining sensory quality during frozen storage.

Overall, the results demonstrate that the incorporation of 2% glycerol and 0.5% guar gum (T2) significantly improved the sensory stability of ready-to-eat frozen whole wheat roti during 90 days of storage. The optimized formulation maintained superior softness, taste, and overall acceptability while preserving microbiological safety and nutritional quality, highlighting its potential for commercial production and distribution through frozen food supply chains.

Conclusion

The present study demonstrated that the incorporation of glycerol and guar gum significantly improved the quality and storage stability of ready-to-eat frozen whole wheat roti during 90 days of frozen storage at -18 ± 2°C. Frozen storage resulted in gradual reductions in moisture content and water activity and a corresponding increase in product hardness, confirming that starch retrogradation and moisture redistribution are the primary mechanisms responsible for quality deterioration in frozen wheat flatbreads. However, these changes were substantially reduced by the optimized formulation containing 2% glycerol and 0.5% guar gum (T2).

Among the three formulations, T2 consistently exhibited superior performance throughout storage by retaining higher moisture content (32.46%), maintaining higher water activity (0.944), and showing the lowest hardness value (5.43 N) after 90 days. In contrast, the control experienced greater moisture loss and a marked increase in hardness (9.46 N), indicating accelerated textural deterioration. The improved quality observed in T2 is attributed to the synergistic effects of glycerol as a humectant and plasticizer and guar gum as a hydrocolloid with high water-binding capacity, both of which contributed to reduced moisture migration and delayed starch retrogradation.

Frozen storage had minimal influence on the nutritional composition of the product. Protein, fat, ash, and crude fibre contents remained stable throughout the storage period, while microbiological analyses confirmed excellent product safety, with total plate counts remaining below 2.30 log CFU/g and no detectable yeast, mold, or coliform contamination. Sensory evaluation further demonstrated that the optimized formulation maintained significantly higher consumer acceptability, particularly with respect to softness and overall acceptability, even after prolonged frozen storage.

The strong correlations observed between moisture retention, hardness, and sensory acceptability highlight the importance of controlling water mobility to preserve the quality of frozen flatbreads. From a commercial perspective, the optimized formulation offers a practical approach for manufacturing high-quality ready-to-eat frozen roti with an extended frozen shelf-life while maintaining desirable nutritional, microbiological, and sensory characteristics.

Future studies should investigate the effects of alternative hydrocolloids and natural anti-staling ingredients, evaluate packaging systems with enhanced moisture and oxygen barrier properties, and validate product performance under commercial production and distribution conditions. Such investigations will further support the development of high-quality frozen convenience foods that meet the growing consumer demand for nutritious, convenient, and shelf-stable cereal-based products.

References

1. American Association of Cereal Chemists (AACC). Approved Methods of Analysis (11th ed.). AACC International, St. Paul, MN, USA, 2010.
2. AOAC International. Official Methods of Analysis (20th ed.). AOAC International, Gaithersburg, MD, USA, 2017.
3. Akesowan A. Effect of hydrocolloids on quality characteristics of frozen dough and bakery products: A review. International Food Research Journal,2016:23(4):1353–1361.
4. Bárcenas ME, Rosell CM. Effect of frozen storage time on the bread crumb and aging of par-baked bread. Food Chemistry,2005:95:438–445.
5. BeMiller JN. Carbohydrate Chemistry for Food Scientists (3rd ed.). AACC International Press, 2019.
6. Fellows PJ. Food Processing Technology: Principles and Practice (4th ed.). Woodhead Publishing, 2017.
7. Giannou V, Tzia C. Frozen dough bread: Quality and textural changes during frozen storage. Journal of Food Engineering,2007:79:332–338.
8. International Organization for Standardization (ISO). ISO 4832:2006. Microbiology of Food and Animal Feeding Stuffs—Horizontal Method for the Enumeration of Coliforms, 2006.
9. International Organization for Standardization (ISO). ISO 21527-2:2008. Microbiology of Food and Animal Feeding Stuffs—Enumeration of Yeasts and Moulds, 2008.
10. International Organization for Standardization (ISO). ISO 4833-1:2013. Microbiology of the Food Chain—Horizontal Method for the Enumeration of Microorganisms, 2013.
11. Ktenioudaki A, Butler F, Gallagher E. Dough characteristics and quality of wheat bread containing hydrocolloids. Journal of Food Engineering,2010:99:424–431.
12. Lazaridou A, Biliaderis CG. Gluten-free doughs: Rheological properties, testing procedures and potential improvements. Food Hydrocolloids,2009:23:1077–1089.
13. Morris ER. Guar gum. In: Phillips GO, Williams PA (Eds.). Handbook of Hydrocolloids (3rd ed.). Woodhead Publishing, 2019, 773–796.
14. Rahman MS. Food Properties Handbook (2nd ed.). CRC Press, 2009.
15. Rosell CM, Bajerska J, El Sheikha AF. Hydrocolloids as quality improvers in bakery products. Comprehensive Reviews in Food Science and Food Safety,2010:9:409–423.
16. Shaikh IM, Singh G, Rosell CM. Extending shelf life of chapatti by partial baking and frozen storage. Journal of Food Engineering,2008:89:466–471.
17. Singh RP, Heldman DR. Introduction to Food Engineering (5th ed.). Academic Press, 2014.
18. Stone H, Bleibaum RN, Thomas HA. Sensory Evaluation Practices (5th ed.). Academic Press, 2020.
19. Sumnu G, Sahin S. Food Engineering Aspects of Baking Sweet Goods. CRC Press, 2008.
20. Williams PA, Phillips GO (Eds.). Handbook of Hydrocolloids (3rd ed.). Woodhead Publishing, 2021.
21. Yadav DN, Petki PE, Sharma GK, Srihari KA, Bawa AS. Rheological and sensory quality of ready-to-bake chapatti during frozen storage. Journal of Food Quality,2009:32:436–451.