

Multiscale Analysis of Water Mobility and Gluten Network Evolution in Polysaccharide-Based Frozen Dough Systems

Pien Honing

Department of Computer Science, Colorado State University, Fort Collins, CO, USA.
pien1987@colostate.edu

Eimer Slyne

Department of Computer Science, George Mason University, Fairfax, VA, USA.
eimerslyne97@gmu.edu

Abstract

Frozen dough systems are increasingly important to centralized food production, retail baking, and distributed cold-chain infrastructures, yet their quality depends on coupled physical, chemical, and operational processes that span molecular to logistical scales. This paper develops a multiscale systems analysis of water mobility and gluten network evolution in polysaccharide-based frozen dough. It treats dough as a socio-technical architecture in which water distribution, ice recrystallization, gluten polymerization, starch transitions, polysaccharide cryoprotection, and cold-chain governance interact across scales. The analysis emphasizes that water is not a passive solvent but a plasticizing, transport, and structural agent whose mobility shapes gluten continuity, gas retention, and final bread quality. Gluten network evolution is discussed as a dynamic balance among hydration, disulfide bonding, hydrophobic association, and freeze-induced mechanical stress. Polysaccharide interventions are examined as cryoprotective sol-gel architectures that modify ice formation, water immobilization, and network repair, with structural trade-offs between extensibility, strength, and processability. The paper then connects these material phenomena to sensing infrastructures, digital twins, deployment constraints, sustainability, robustness, fairness, and policy implications. It argues that frozen dough quality should be governed as a multiscale infrastructure problem rather than as an isolated ingredient or unit-operation issue. By integrating food material science with systems thinking, the paper identifies pathways for more resilient, transparent, and equitable frozen dough supply systems.

Keywords

frozen dough; water mobility; gluten network; polysaccharides; cryoprotection; multiscale systems; cold chain; digital twin; food policy.

1. Introduction

Frozen dough is a deceptively simple material that embeds a complex multiscale system. At the molecular scale, water molecules organize around flour proteins, starch granules, polysaccharides, and solutes, influencing hydrogen bonding, hydrophobic interactions, and chain mobility. At the mesoscopic scale, ice crystals, gluten strands, starch ghosts, and hydrocolloid networks form heterogeneous domains whose interfaces determine mechanical behavior. At the macroscopic scale, dough rheology, proofing capacity, oven spring, crumb structure, and consumer acceptance emerge from these coupled processes. At the

infrastructural scale, freezing rates, storage temperature stability, transportation logistics, retail handling, and policy frameworks determine whether the material potential of dough is preserved or degraded. A multiscale analysis therefore requires more than a conventional review of freezing damage; it requires an architectural account of how water mobility and gluten network evolution are embedded in technological, economic, and governance systems.

Water mobility is central because freezing is fundamentally a phase transition and redistribution process. Classical water activity concepts provide useful but incomplete explanations of frozen food stability, particularly when glass transition behavior, solute concentration, and ice crystal growth are considered [1]. Phase transitions in foods shape mechanical properties, reaction rates, and microbial stability, and frozen dough is no exception [2]. In frozen systems, the glass transition of the unfrozen concentrated phase influences diffusion, recrystallization, and structural relaxation [3]. During freezing and frozen storage, water migrates from gluten-rich regions toward growing ice crystals, altering protein hydration and concentrating solutes in unfrozen domains. These changes can impair gluten development, reduce gas retention, and produce bread with lower volume and coarser crumb [4]. The result is not a single defect but a cascade of coupled material and operational failures.

Polysaccharides have emerged as promising cryoprotective agents because they can modify water mobility, ice crystal habit, and network continuity. A recent study has proposed a structural basis for a cryoprotective sol-gel transition in a polysaccharide fraction for frozen dough applications [5]. This finding is important because it reframes polysaccharides as active architectural components rather than inert fillers or simple water binders. Polysaccharide-based frozen dough systems can be understood as engineered soft matter infrastructures in which biopolymer networks, ice phases, gluten networks, and process conditions co-evolve. Reviews of frozen bread dough have documented the effects of freezing storage and dough improvers [6], while broader reviews have synthesized frozen dough quality mechanisms [7]. However, the field often remains fragmented between ingredient-level studies and process-level optimization. A systems-oriented multiscale account can connect these layers and clarify trade-offs among robustness, sustainability, fairness, and deployability.

2. Frozen Dough as a Multiscale Socio-Technical Architecture

Frozen dough can be modeled as a layered architecture. The molecular layer includes water, gluten proteins, starch polymers, polysaccharides, salts, sugars, lipids, and enzymes. The mesoscopic layer includes ice crystals, air cells, protein fibrils, starch granule remnants, and hydrocolloid gel domains. The macroscopic layer includes dough pieces, trays, packaging, and proofing units. The infrastructural layer includes freezers, blast tunnels, refrigerated warehouses, trucks, retail freezers, and household or bakery thawing practices. The governance layer includes food safety standards, labeling rules, quality grading, waste reduction targets, and labor practices. These layers are not independent. A change in freezer airflow can alter ice crystal size distribution, which then changes gluten network continuity, which then alters gas cell stabilization and final crumb texture. A policy decision about storage temperature tolerance can reshape the economic viability of distributed baking and the environmental burden of cold-chain energy use.

From a systems perspective, frozen dough exhibits structural trade-offs. Strong gluten networks may resist freeze-induced weakening but can reduce extensibility and impair proofing. High polysaccharide concentrations may immobilize water and limit ice

recrystallization but can also increase viscosity, delay hydration, or create gel domains that interfere with gluten continuity. Rapid freezing can produce small ice crystals and better structural preservation, yet it requires greater energy input and more sophisticated equipment. Slow freezing may be more accessible to small producers but can cause large ice crystals, protein dehydration, and yeast damage. These trade-offs are not merely technical; they determine who can participate in frozen dough markets, how much energy is consumed, and how resilient supply chains are to temperature excursions. The architecture of frozen dough is therefore simultaneously material, industrial, and social.

The socio-technical character of frozen dough is visible in the cold chain. A frozen dough product may be manufactured in a central facility, stored for weeks or months, transported across regions, thawed in a retail bakery, and proofed under conditions that differ from those assumed during product development. Each transition creates a potential mismatch between material state and process control. Water mobility is especially sensitive to temperature fluctuations because ice recrystallization and moisture migration continue even below zero degrees Celsius. Gluten network evolution also continues through thiol-disulfide exchange, hydrophobic aggregation, and mechanical stress relaxation. Thus, the effective quality of frozen dough is not fixed at the point of freezing; it is continuously negotiated across the infrastructure. Governance mechanisms such as temperature logging, shelf-life dating, and quality assurance protocols are attempts to stabilize this negotiation, but they often operate at coarse scales that miss local material heterogeneity.

3. Water Mobility Across Molecular, Mesoscopic, and Macro Scales

At the molecular scale, water mobility describes the translational and rotational motion of water molecules, the exchange between bound and bulk-like water, and the plasticization of amorphous biopolymers. In dough, water is distributed among gluten, starch, arabinoxylans, soluble polysaccharides, yeast, and salt. Some water is tightly associated with protein surfaces, some is confined in starch granules, and some forms continuous channels that support diffusion. When freezing begins, pure water tends to crystallize first, leaving behind a concentrated unfrozen phase containing solutes and biopolymers. This cryoconcentration changes pH, ionic strength, and molecular crowding, which in turn affects gluten solubility, enzyme activity, and polysaccharide gelation. Glass transition concepts help explain why some frozen doughs remain structurally stable while others undergo collapse, stickiness, or ice recrystallization during storage [1][2][3].

At the mesoscopic scale, water mobility is expressed through ice crystal size, distribution, and morphology. Small ice crystals are generally less damaging because they create fewer mechanical discontinuities and less dehydration of gluten networks. Large crystals, by contrast, can rupture protein films, disrupt gas cells, and create channels for moisture migration after thawing. Polysaccharides can influence ice crystal growth through kinetic inhibition, gel network formation, and water immobilization. A cryoprotective sol-gel transition may create a hydrated network that moderates ice formation and preserves local water distribution [5]. The mesoscopic architecture is also shaped by air cells introduced during mixing. These air cells are stabilized by gluten films and surface-active components; if ice crystals puncture these films, gas retention declines and final loaf volume decreases [8]. Water mobility and gas cell stability are therefore coupled through interface properties.

At the macroscopic scale, water mobility determines dough rheology, proofing behavior, baking expansion, and staling. Frozen storage often increases dough stiffness and decreases extensibility because water becomes less available to gluten and because protein aggregation

progresses. Thawing can release water irregularly, leading to wet surfaces, uneven hydration, and variable proofing times. In bread, these effects appear as reduced specific volume, denser crumb, thicker cell walls, and faster staling. Starch transitions also matter because freezing and thawing can alter starch retrogradation and gelatinization behavior during baking [17]. The macroscopic outcome is thus a manifestation of molecular and mesoscopic histories. A systems approach must therefore treat water mobility as a cross-scale control variable, not as a single measurable property.

4. Gluten Network Evolution Under Freeze-Thaw and Storage Stress

The gluten network is a viscoelastic protein architecture formed primarily by glutenin and gliadin fractions. Glutenin contributes elasticity through high-molecular-weight polymers and disulfide-linked subunits, while gliadin contributes extensibility and plasticity. The network is stabilized by covalent disulfide bonds, hydrogen bonds, hydrophobic interactions, and entanglements. Its microstructure is heterogeneous, with fibrillar and lamellar domains that reorganize under hydration and mechanical work [9]. The elasticity of wheat gluten depends on the balance between chain entanglements, cross-links, and mobile segments [10]. Cereal seed storage proteins have evolved structural features that support both compact storage and functional networking upon hydration [11]. The chemistry of gluten proteins further explains how sulfhydryl and disulfide exchange, hydrophobic surfaces, and charged residues govern aggregation [12].

During freezing, ice formation removes water from gluten domains and concentrates solutes. This dehydration promotes protein chain proximity and can increase hydrophobic association and disulfide bonding. Some aggregation may strengthen the network, but excessive aggregation reduces extensibility and gas retention. Mechanical damage from ice crystals can also fragment gluten films and create weak points. During frozen storage, these processes continue slowly, especially when temperature fluctuates. Thawing introduces additional stress because ice melts unevenly and water redistributes. The network may partially recover, but irreversible cross-links and structural discontinuities accumulate. The result is often a dough that appears acceptable at the surface but fails during proofing or baking. Reviews of frozen dough have consistently identified gluten weakening and yeast damage as central mechanisms of quality loss [6][7].

Polysaccharides can modulate gluten network evolution in several ways. First, they can compete for water and alter hydration kinetics, which may protect gluten from excessive dehydration or delay network development. Second, they can form gel networks that provide mechanical support and reduce ice crystal damage. Third, they can interact with gluten proteins through electrostatic, hydrophobic, or hydrogen-bonding mechanisms, potentially stabilizing interfaces. Fourth, they can modify the viscosity of the unfrozen phase and slow diffusion-limited aggregation. However, these benefits depend on concentration, molecular weight, charge density, branching, and processing sequence. Some polysaccharides may dilute gluten continuity, interfere with disulfide bonding, or create phase-separated domains that weaken gas cell stability. The gluten network is therefore not simply protected or damaged; it is reconfigured through a balance of cryoprotective and disruptive effects.

5. Polysaccharide Interventions and Cryoprotective Sol-Gel Transitions

Polysaccharides used in frozen dough include hydrocolloids, arabinoxylans, beta-glucans, pectins, gums, and modified starches. Their functionality arises from water-binding capacity, gelation, film formation, viscosity enhancement, and interfacial activity. Wheat flour

constituents such as arabinoxylans influence water distribution and starch behavior, and their molecular characteristics affect dough and bread quality [13]. In frozen dough, polysaccharides are often added to reduce ice crystal growth, improve water retention, and stabilize gluten networks. A cryoprotective sol-gel transition is particularly interesting because it implies a temperature-responsive change from a flowing sol to a structured gel that can immobilize water and reinforce the network during freezing [5]. This mechanism can create a temporary scaffold that protects gluten and gas cells while allowing sufficient flow during mixing and proofing.

The structural trade-offs of polysaccharide interventions are significant. A gel that is too strong may increase dough stiffness, reduce extensibility, and impair oven spring. A gel that is too weak may not protect against ice recrystallization. High water-binding capacity may reduce freezable water but can also starve gluten of hydration, leading to incomplete network development. Anionic polysaccharides may interact with charged gluten residues and alter aggregation, while neutral polysaccharides may mainly affect viscosity and steric hindrance. Molecular weight matters because high-molecular-weight polymers can form entanglements and gels at low concentrations but may also increase viscosity excessively. The sequence of addition is equally important because polysaccharides added before gluten hydration may compete for water, whereas those added after network formation may reinforce existing structures.

The sol-gel transition can be understood as an architectural control point. If gelation occurs during freezing, it may align with ice crystal formation and provide localized protection. If gelation occurs too early, it may interfere with mixing and gas cell development. If it occurs too late, it may fail to influence ice crystal growth. The required precision suggests that polysaccharide-based frozen dough systems need process-aware design rather than static formulation. Sensors, models, and control systems could monitor temperature, water activity, rheology, and gas cell structure in real time. Such infrastructure would allow formulations to be tuned to specific freezer profiles, storage durations, and thawing conditions. The material science of polysaccharides thus becomes inseparable from the engineering of cold-chain control.

6. Sensing, Data Infrastructures, and Digital Twins for Process Governance

The multiscale nature of frozen dough creates a data problem. Relevant variables exist at different time and length scales: molecular mobility, ice crystal size distribution, gluten cross-link density, dough rheology, gas cell structure, freezer air velocity, package position, storage temperature, and retail thawing practice. No single sensor captures this range. A practical infrastructure might combine dielectric spectroscopy, near-infrared spectroscopy, nuclear magnetic resonance relaxometry, ultrasound, rheometry, imaging, and environmental logging. These measurements can be integrated into digital twins that simulate water mobility and gluten network evolution under different scenarios. A digital twin could support formulation design, process optimization, shelf-life prediction, and quality assurance. It could also inform policy by quantifying the effects of temperature tolerance, energy use, and waste reduction.

However, digital twins introduce governance challenges. Data ownership, model transparency, and algorithmic accountability matter when quality decisions affect suppliers, workers, and consumers. A model trained on large industrial freezers may not generalize to small bakeries or regional supply chains. If predictive systems favor certain flour qualities, polysaccharide additives, or equipment profiles, they may disadvantage smaller producers or regions with different wheat varieties. Fairness therefore becomes a technical and policy concern. The

deployment of sensing infrastructures requires standards for calibration, data sharing, privacy, and interoperability. It also requires fallback procedures when sensors fail or models drift. Robustness is not only about preventing material failure; it is about ensuring that the socio-technical system remains functional under uncertainty, disruption, and resource constraints.

The cold chain itself is an infrastructure with uneven capacity. In high-income settings, frozen dough may move through automated warehouses and monitored retail freezers. In other contexts, intermittent electricity, long transport distances, and limited refrigeration capacity create temperature abuse. A multiscale analysis must therefore avoid assuming ideal freezing and storage. It should consider how water mobility and gluten network evolution behave under realistic temperature profiles. Polysaccharide cryoprotection may be especially valuable in such contexts because it can buffer against fluctuations. Yet the affordability, local availability, and cultural acceptability of polysaccharide ingredients must be evaluated. Sustainability also matters because some hydrocolloids require energy-intensive extraction or long-distance transport. The environmental footprint of cryoprotection must be weighed against reductions in dough waste and improvements in distribution efficiency.

7. Robustness, Sustainability, Fairness, and Policy Implications

Robustness in frozen dough systems can be defined as the capacity to maintain acceptable water distribution, gluten functionality, and baking performance across variable freezing, storage, transport, and thawing conditions. This capacity depends on material design, process control, and infrastructure resilience. Polysaccharide-based systems can enhance robustness by reducing sensitivity to temperature fluctuations and ice recrystallization. However, robustness may be achieved at the cost of flexibility, cost, or nutritional profile. For example, a formulation that performs well under long frozen storage may require higher additive levels, which can affect labeling, consumer acceptance, and clean-label positioning. A systems approach should therefore evaluate robustness as a multi-objective property rather than a single optimum.

Sustainability intersects with frozen dough at multiple points. Cold-chain energy consumption is significant, and improvements in freezing efficiency or storage stability can reduce emissions. Reduced dough waste from better freeze-thaw tolerance also lowers the environmental burden of producing, transporting, and disposing of failed products. Polysaccharides derived from agricultural byproducts or locally available biomass could support circular economy goals, but their extraction and purification must be assessed. Water use is another consideration because polysaccharide production and dough formulation both require water. The multiscale analysis suggests that sustainability cannot be reduced to ingredient sourcing alone; it must include process energy, packaging, logistics, retail handling, and consumer behavior. Policy instruments such as carbon labeling, cold-chain efficiency standards, and food waste reduction targets can shape these trade-offs.

Fairness is a less conventional but necessary dimension. Frozen dough technologies can concentrate market power in large firms that can afford advanced freezers, digital twins, and proprietary formulations. Smaller bakeries and regional producers may struggle to adopt complex cryoprotective systems or comply with data-intensive quality assurance. If policy and investment favor only large-scale infrastructure, the benefits of improved frozen dough may be unevenly distributed. Fairness also concerns labor: automated cold-chain systems can change skill requirements and working conditions. Consumer fairness involves transparency about additives, allergens, and processing aids. A just transition toward more resilient frozen dough systems would require accessible technologies, open standards, training, and support

for diverse producers. It would also require inclusive innovation that considers local preferences, nutritional needs, and affordability.

Policy implications emerge at several levels. Food safety regulations must ensure that frozen dough products remain safe under realistic storage and thawing conditions. Quality standards could incorporate multiscale indicators such as water mobility, ice crystal size, and gluten network integrity, although such metrics must be practical and verifiable. Research funding could support open datasets and shared models for water mobility and gluten evolution. Infrastructure policy could improve cold-chain reliability, especially in underserved regions. Trade policy could affect access to polysaccharide ingredients and equipment. Sustainability policy could incentivize energy-efficient freezing and waste reduction. Together, these instruments shape the design space for polysaccharide-based frozen dough. The technical and the political are not separate; they co-produce the material possibilities of frozen dough.

8. Conclusion

This paper has developed a multiscale analysis of water mobility and gluten network evolution in polysaccharide-based frozen dough systems. It has argued that frozen dough is best understood as a layered socio-technical architecture in which molecular water dynamics, mesoscopic ice and biopolymer structures, macroscopic dough rheology, and infrastructural cold-chain governance are mutually constitutive. Water mobility acts as a cross-scale control variable that influences gluten hydration, ice crystal formation, gas cell stability, starch transitions, and final bread quality. Gluten network evolution is a dynamic process of hydration, aggregation, cross-linking, mechanical damage, and partial recovery. Polysaccharide interventions, especially cryoprotective sol-gel transitions, offer promising routes to stabilize these processes, but they also introduce trade-offs in rheology, processing, cost, and consumer acceptance. The required cryoprotective mechanism reported for a polysaccharide fraction illustrates how material design can be linked to frozen dough performance without reducing the problem to a single ingredient effect [5].

The systems perspective also reveals that technical optimization alone is insufficient. Sensing infrastructures, digital twins, data governance, cold-chain resilience, sustainability, fairness, and policy all shape whether improved frozen dough technologies can be deployed equitably and robustly. Future research should integrate multiscale material characterization with process monitoring, lifecycle assessment, and participatory technology assessment. It should also develop accessible models that can be adapted to different wheat varieties, polysaccharide sources, freezer profiles, and regional constraints. By treating frozen dough as an infrastructure problem, researchers and policymakers can move beyond isolated formulation studies toward designs that are structurally sound, environmentally sustainable, socially fair, and operationally resilient. The multiscale analysis presented here provides a conceptual foundation for that agenda.

References

1. Slade, L., & Levine, H. (1991). Beyond water activity: Recent advances based on an alternative approach to the assessment of food quality and safety. *Critical Reviews in Food Science and Nutrition*, 30(2-3), 115-360.
<https://doi.org/10.1080/10408399109527543>
2. Roos, Y. H. (1995). *Phase transitions in foods*. Academic Press.

3. Goff, H. D., & Sahagian, M. E. (1996). Glass transitions in aqueous carbohydrate solutions and their relevance to frozen food stability. *Thermochimica Acta*, 280-281, 449-464. [https://doi.org/10.1016/0040-6031\(95\)02656-8](https://doi.org/10.1016/0040-6031(95)02656-8)
4. Ribotta, P. D., León, A. E., & Añón, M. C. (2001). Effect of freezing and frozen storage of doughs on bread quality. *Journal of Agricultural and Food Chemistry*, 49(2), 913-918. <https://doi.org/10.1021/jf000752u>
5. Zhang, T., Fang, J. Q., Wang, P. P., & Chen, C. (2026). Structural basis of the cryoprotective sol-gel transition in a *Phyllanthus emblica* L. polysaccharide fraction for frozen dough applications. *Food Hydrocolloids*, 112842.
6. Selomulyo, V. O., & Zhou, W. (2007). Frozen bread dough: Effects of freezing storage and dough improvers. *Journal of Cereal Science*, 45(1), 1-17. <https://doi.org/10.1016/j.jcs.2006.10.003>
7. Rosell, C. M., & Gómez, M. (2007). Frozen dough: A review. *Food Science and Technology International*, 13(3), 179-188. <https://doi.org/10.1177/1082013207079625>
8. Giannou, V., & Tzia, C. (2007). Frozen dough bread: Quality and textural behavior during prolonged storage—Prediction of final product characteristics. *Journal of Food Engineering*, 79(3), 929-934. <https://doi.org/10.1016/j.jfoodeng.2006.03.021>
9. Kontogiorgos, V. (2011). Microstructure of hydrated gluten network. *Food Research International*, 44(9), 2582-2586. <https://doi.org/10.1016/j.foodres.2010.11.020>
10. Belton, P. S. (1999). On the elasticity of wheat gluten. *Journal of Cereal Science*, 29(2), 103-107. <https://doi.org/10.1006/jcsc.1998.0227>
11. Shewry, P. R., & Halford, N. G. (2002). Cereal seed storage proteins: Structures, properties and role in grain utilization. *Journal of Experimental Botany*, 53(370), 947-958. <https://doi.org/10.1093/jexbot/53.370.947>
12. Wieser, H. (2007). Chemistry of gluten proteins. *Food Microbiology*, 24(2), 115-119. <https://doi.org/10.1016/j.fm.2006.07.004>
13. Goesaert, H., Brijs, K., Veraverbeke, W. S., Courtin, C. M., Gebruers, K., & Delcour, J. A. (2005). Wheat flour constituents: How they impact bread quality, and how to impact their functionality. *Trends in Food Science & Technology*, 16(1-3), 12-30. <https://doi.org/10.1016/j.tifs.2004.02.011>
14. Delcour, J. A., & Hoseney, R. C. (2010). *Principles of cereal science and technology* (3rd ed.). AACC International.
15. Ribotta, P. D., Pérez, G. T., León, A. E., & Añón, M. C. (2004). Effect of emulsifier and guar gum on microstructural, rheological and baking performance of frozen bread dough. *Food Hydrocolloids*, 18(2), 305-313. [https://doi.org/10.1016/S0268-005X\(03\)00086-9](https://doi.org/10.1016/S0268-005X(03)00086-9)
16. Wang, P., Tao, H., Jin, Z., & Xu, X. (2016). Impact of water extractable arabinoxylan with different molecular weight on the gelatinization and retrogradation behavior of wheat starch. *Food Chemistry*, 194, 1177-1184. <https://doi.org/10.1016/j.foodchem.2015.08.125>
17. Biliaderis, C. G. (2009). Structural transitions and related physical properties of starch. In J. BeMiller & R. Whistler (Eds.), *Starch: Chemistry and technology* (3rd ed., pp. 293-372). Academic Press.

18. Goff, H. D. (1992). Low-temperature stability and the glassy state in frozen foods. *Food Research International*, 25(4), 317-325. [https://doi.org/10.1016/0963-9969\(92\)90128-R](https://doi.org/10.1016/0963-9969(92)90128-R)
19. Fennema, O. R. (1996). *Food chemistry* (3rd ed.). Marcel Dekker.
20. Meziani, S., Ioannou, I., Jasniewski, J., Belhaj, N., Muller, J. M., Ghoul, M., & Desobry, S. (2011). Effects of freezing treatments on viscoelastic and structural behavior of frozen sweet dough. *Journal of Food Engineering*, 107(3-4), 358-365. <https://doi.org/10.1016/j.jfoodeng.2011.07.001>