

Molecular Mechanisms of Plant-Derived Polysaccharides in Regulating Ice Crystal Formation During Dough Freezing

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Abstract

Frozen dough systems occupy a critical position in contemporary bakery supply chains because they enable centralized production, long-distance distribution, and consumer-side baking. However, freezing and frozen storage impose severe physicochemical stresses on dough, most notably through ice nucleation, ice crystal growth, recrystallization, and the redistribution of water among gluten, starch, and soluble biopolymer phases. Plant-derived polysaccharides have emerged as promising cryoprotective agents because they can alter water dynamics, modify ice crystal habit, stabilize colloidal networks, and modulate the mechanical response of the frozen matrix. This paper examines the molecular mechanisms by which plant-derived polysaccharides regulate ice crystal formation during dough freezing, with attention to hydration, hydrogen bonding, steric hindrance, viscosity enhancement, gelation, phase separation, and ice recrystallization inhibition. It further situates these mechanisms within a system-level framework that considers structural trade-offs, processing architecture, cold-chain infrastructure, industrial deployment, sustainability, robustness, and policy implications. The analysis suggests that polysaccharide cryoprotection is not a single molecular event but a distributed property emerging from interactions among polymer chemistry, water state, dough microstructure, freezing kinetics, and storage conditions. A recent study of a *Phyllanthus emblica* L. polysaccharide fraction illustrates how sol-gel transition behavior can be coupled to cryoprotective function in frozen dough applications. The paper concludes that effective deployment requires integrated design across molecular, colloidal, engineering, and governance scales, because isolated molecular optimization without cold-chain reliability, energy justice, and regulatory coherence is unlikely to deliver durable benefits.

Keywords

frozen dough, plant polysaccharides, ice recrystallization, cryoprotection, dough microstructure, cold-chain governance, food system resilience.

1. Introduction

Frozen dough technology has become a foundational element of modern bakery manufacturing because it decouples dough mixing, fermentation, shaping, and baking across time and space. This decoupling supports economies of scale, reduces waste at retail sites, and

allows consumers to access fresh-baked products with minimal labor. Yet the same freezing process that enables this architectural flexibility also introduces a cascade of physicochemical disruptions. Ice crystals formed during freezing can mechanically damage gluten networks, disrupt starch granules, puncture gas cells, and concentrate solutes in unfrozen domains, leading to reduced dough strength, impaired gas retention, and inferior final bread quality [1]. The severity of these effects depends on freezing rate, final temperature, storage duration, temperature fluctuations, and the composition of the dough matrix [2]. Consequently, frozen dough quality is not merely a formulation problem but a systems problem involving thermodynamics, polymer physics, process control, logistics, and consumer expectations [3].

Plant-derived polysaccharides have attracted attention as cryoprotective ingredients because they are abundant, biodegradable, generally compatible with food systems, and capable of interacting with water and biopolymers in multiple ways. Unlike simple sugars or polyols, polysaccharides can simultaneously raise viscosity, form gels, adsorb to interfaces, modify ice crystal habit, and alter the glass transition behavior of the freeze-concentrated phase [4]. These properties suggest that polysaccharides may act as multifunctional cryoprotectants rather than passive bulking agents. However, the mechanisms are not fully resolved, and outcomes depend strongly on molecular weight, degree of branching, charge density, substituent chemistry, and concentration relative to gluten and starch [5]. A central challenge is therefore to connect molecular structure to ice crystal regulation without reducing the problem to a single variable such as water activity or viscosity.

This paper argues that plant-derived polysaccharides regulate ice crystal formation through a distributed set of molecular and colloidal mechanisms that intersect with dough architecture. It first reviews the thermodynamic and colloidal framework of ice formation in dough. It then analyzes the molecular mechanisms of polysaccharide cryoprotection, including hydration, hydrogen bonding, steric effects, gelation, phase separation, and ice recrystallization inhibition. It subsequently considers structural trade-offs and system-level architecture in frozen dough applications, followed by governance, infrastructure, sustainability, robustness, fairness, and policy implications. The discussion is intentionally interdisciplinary because frozen dough is a socio-technical system in which molecular design, manufacturing reliability, cold-chain energy use, and regulatory frameworks co-produce outcomes. A recent investigation of a *Phyllanthus emblica* L. polysaccharide fraction is used as a specific illustration of sol-gel transition behavior in cryoprotection [14], but the broader argument is that no single molecular mechanism can be optimized in isolation from the infrastructure and governance that determine whether technical gains persist in real supply chains.

2. Thermodynamic and Colloidal Framework of Ice Formation in Dough

Ice formation in dough begins with nucleation, proceeds through crystal growth, and continues during storage through recrystallization, a process in which larger crystals grow at the expense of smaller ones. Because dough is a complex colloidal system containing gluten proteins, starch granules, yeast cells, lipids, salts, and soluble carbohydrates, freezing is not spatially uniform. Water exists in multiple states, including bulk-like water, interfacial water, and water associated with hydrophilic surfaces. As temperature decreases, ice formation excludes solutes from the growing crystal lattice, creating freeze-concentrated regions with altered ionic strength, pH, and viscosity [6]. These regions can destabilize gluten disulfide bonding, promote starch retrogradation, and concentrate enzymes or metabolites that affect yeast viability. The glass transition of the freeze-concentrated matrix is especially important

because molecular mobility below the glass transition is severely restricted, whereas above it, diffusion-limited reactions and recrystallization can proceed [7].

From a state-diagram perspective, frozen dough stability depends on the relationship between temperature, ice content, and the glass transition of the maximally freeze-concentrated phase. When storage temperature fluctuates above the glass transition, the unfrozen phase becomes more mobile, allowing water molecules to migrate to existing ice crystals and increasing the mean crystal size [8]. Larger crystals are more damaging to gluten strands and gas cells than smaller, more numerous crystals because mechanical stress is concentrated at crystal interfaces. In cellular systems, similar principles explain why slow freezing and repeated freeze-thaw cycles reduce viability through extracellular ice growth and osmotic dehydration [9]. In dough, the absence of a truly cellular compartment does not eliminate these effects; rather, it redistributes them across a porous gluten-starch network in which gas cells act as compressible inclusions and starch granules act as rigid fillers.

Plant polysaccharides can intervene at several points in this thermodynamic and colloidal framework. They can reduce the amount of freezable water by binding water through hydroxyl groups and hydration shells. They can increase the viscosity of the unfrozen phase, slowing diffusion and hindering water transport to ice nuclei. They can form gel networks that compartmentalize water and restrict crystal growth. They can also modify the glass transition behavior of the freeze-concentrated phase by introducing high-molecular-weight species that alter the free volume and molecular mobility of the matrix. These effects are not mutually exclusive, and their relative importance shifts with freezing rate, storage temperature, and polysaccharide concentration. A slow freezing process may favor thermodynamic control and recrystallization, whereas fast freezing may favor nucleation-dominated kinetics and smaller initial crystals. Thus, the same polysaccharide may be cryoprotective under one freezing regime and ineffective or even detrimental under another if it disrupts gluten network formation or excessively increases dough stiffness.

3. Molecular Mechanisms of Plant-Derived Polysaccharides in Ice Regulation

The molecular mechanisms of polysaccharide cryoprotection can be understood through several interacting pathways. The first is hydration and hydrogen bonding. Plant polysaccharides such as pectin, arabinoxylan, beta-glucan, inulin, and various seed or fruit mucilages possess abundant hydroxyl groups that can form hydrogen bonds with water. This hydration reduces the pool of water available for ice nucleation and growth, but it also changes the solvent quality for gluten proteins and starch. If water is tightly bound, the freeze-concentrated phase may become more viscous and less able to support recrystallization. However, excessive water binding can reduce the plasticity of the dough, hinder gluten development, and create a dry, tight matrix that fails to expand during proofing and baking.

The second pathway is steric and kinetic inhibition. High-molecular-weight polysaccharides can adsorb to ice crystal surfaces or accumulate in the interfacial region, creating a diffusion barrier that slows the addition of water molecules to the crystal lattice. This mechanism resembles, but is not identical to, the action of antifreeze proteins and glycoproteins, which often exhibit specific ice-binding faces and hysteresis effects [10]. Polysaccharides generally lack the precise structural complementarity of antifreeze proteins, but they can still reduce ice recrystallization by increasing local viscosity and by forming a three-dimensional network that confines crystal growth [11]. Synthetic macromolecules have demonstrated that ice recrystallization inhibition can be achieved through relatively nonspecific interactions when polymer architecture, hydrophilicity, and molecular weight are controlled [12]. This insight

supports the view that plant polysaccharides may act as broad-spectrum cryoprotectants rather than highly specific ice-binding agents.

The third pathway is gelation and sol-gel transition. Some plant polysaccharides form reversible physical gels upon cooling or in the presence of ions, and this gelation can coincide with the freezing process. A sol-gel transition during cooling can immobilize water, restrict ice crystal growth, and reinforce the dough matrix against mechanical damage. The cryoprotective effect may depend on the temperature at which gelation occurs relative to ice nucleation and on the rheological properties of the gel. If gelation occurs too early, it may trap air poorly and inhibit gluten network development. If it occurs too late, it may not provide sufficient structural resistance during the critical period of ice growth. A recent study of a *Phyllanthus emblica* L. polysaccharide fraction reported structural features underlying a cryoprotective sol-gel transition in frozen dough applications [14]. This example is instructive because it links molecular conformation, gelation behavior, and ice crystal regulation within a single plant-derived system. It also suggests that the functional window of a polysaccharide is defined by the coupling between its sol-gel transition and the freezing trajectory of the dough.

The fourth pathway is phase separation and interfacial activity. In dough, polysaccharides may partition into distinct phases, form coacervates with proteins, or associate with starch granule surfaces. Such phase behavior can concentrate cryoprotective polymers in the unfrozen phase, alter the mechanical contrast between ice and matrix, and modify the propagation of ice-front stresses. Phase separation can also create heterogeneous nucleation sites, which may either promote smaller crystals or, if uncontrolled, lead to large localized crystals. Therefore, the net effect depends on the length scale and morphology of the separated phases. A fine, uniform dispersion of polysaccharide-rich domains may improve cryoprotection by distributing stress and limiting crystal growth, whereas coarse domains may create weak planes and ice pockets that fracture the dough.

The fifth pathway is interaction with gluten and starch. Polysaccharides can compete with gluten for water, adsorb to gluten surfaces, or form thermodynamically incompatible blends that alter protein aggregation. Some hydrocolloids improve dough stability by reinforcing the gluten network and reducing starch retrogradation, while others interfere with gluten hydration and reduce loaf volume [16]. The balance depends on polysaccharide charge, molecular weight, and concentration. Anionic polysaccharides such as pectin and xanthan can interact electrostatically with gluten proteins, whereas neutral polysaccharides such as guar gum and konjac glucomannan primarily act through viscosity and water binding. Starch can also be affected: polysaccharides may coat starch granules, restrict swelling, and reduce amylopectin retrogradation during frozen storage [17]. These interactions determine whether a polysaccharide functions as a cryoprotectant, a texture modifier, or an anti-staling agent, and they highlight the need to treat ice regulation as part of a broader colloidal design problem.

The glass transition behavior of the freeze-concentrated phase provides an additional molecular-level control point. When a polysaccharide is added, it changes the composition and molecular mobility of the unfrozen phase, potentially raising or lowering the glass transition temperature depending on its molecular weight and plasticizing or antiplasticizing effects [15]. A higher glass transition can stabilize the matrix against recrystallization during temperature fluctuations, whereas a lower glass transition may increase mobility and accelerate structural damage. Because frozen dough storage often involves imperfect temperature control, the practical benefit of a polysaccharide may depend less on its equilibrium ice-binding capacity and more on its ability to maintain a glassy or highly viscous

state across realistic temperature excursions. This insight connects molecular design to cold-chain engineering: a cryoprotectant that performs well under ideal laboratory freezing may fail in a distribution system with door openings, defrost cycles, and partial thawing.

4. Structural Trade-offs and System Architecture in Frozen Dough Applications

The design of polysaccharide cryoprotectants involves unavoidable trade-offs. Increasing polysaccharide concentration can enhance water binding and ice recrystallization inhibition, but it can also increase dough viscosity, reduce gas cell expansion, and produce a denser crumb. High molecular weight may improve network formation and steric hindrance, but it can also limit solubility and create uneven hydration. Charged polysaccharides may interact strongly with gluten and improve stability, but they can also promote excessive aggregation or phase separation. Neutral polysaccharides may be more compatible with gluten but less effective at modifying ice crystal habit. These trade-offs mean that cryoprotection cannot be optimized as a single-objective problem. Instead, it requires multi-objective formulation in which ice crystal size, dough extensibility, fermentation tolerance, oven spring, crumb texture, and storage stability are considered simultaneously.

At the system architecture level, frozen dough production can be organized in several ways. Centralized mixing and freezing followed by distribution to retail or consumer sites creates economies of scale but exposes dough to long cold-chain durations and multiple temperature transitions. Par-baked frozen products shift some processing to the retail site and may reduce freezing stress on the final product, but they introduce additional handling and energy costs. Frozen dough pieces for home baking offer convenience but depend on consumer freezer performance and thawing practices. Each architecture imposes different requirements on polysaccharide cryoprotectants. A product intended for long-haul distribution may require robust recrystallization inhibition and glass transition stabilization, while a product intended for rapid local baking may tolerate a narrower safety margin. The choice of polysaccharide therefore cannot be separated from the deployment context.

Robustness is a central concern because frozen dough systems are subject to variability in raw materials, mixing, freezing equipment, storage temperature, and baking conditions. A cryoprotectant that works well with one wheat cultivar may fail with another because gluten composition, starch properties, and endogenous arabinoxylan content differ. Likewise, a polysaccharide extracted from one plant source may vary in molecular weight and substitution pattern across seasons and processing methods. This variability creates a governance challenge: specifications must be broad enough to accommodate natural variation but narrow enough to ensure functional performance. In practice, robust cryoprotection may require blending polysaccharides with complementary mechanisms, such as a high-viscosity polymer for water immobilization and a smaller oligosaccharide for glass transition modification. Such formulations increase complexity but may reduce sensitivity to any single molecular parameter.

Sustainability and infrastructure also shape the viability of plant polysaccharide cryoprotectants. Many plant polysaccharides are derived from agricultural side streams, which can improve resource efficiency and reduce waste [19]. However, extraction, purification, drying, and transport consume energy and water, and the environmental benefits depend on the full life-cycle accounting. If a polysaccharide must be shipped long distances or purified to high specifications, its sustainability advantage may diminish. Cold-chain infrastructure adds another layer: frozen dough requires reliable refrigeration, which is energy-intensive and contributes to greenhouse gas emissions when electricity is carbon-intensive [13]. A

cryoprotectant that extends shelf life or tolerates temperature abuse can reduce waste and improve system resilience, but it may also encourage longer storage and more energy use if not accompanied by appropriate policy and operational incentives [20]. Thus, molecular innovation and infrastructure design must be evaluated together.

5. Governance, Infrastructure, Sustainability, and Policy Implications

The governance of frozen dough systems involves food safety regulations, labeling requirements, quality standards, and cold-chain monitoring. Plant-derived polysaccharides may be regulated as food additives, processing aids, or novel foods depending on their source, extraction method, and history of use. Regulatory uncertainty can slow adoption, especially when the mechanism of action is not easily captured by conventional purity or identity specifications. From a policy perspective, it is important to develop performance-based standards that recognize cryoprotective function while ensuring safety and transparency. Such standards could include validated methods for measuring ice recrystallization inhibition, glass transition behavior, and dough quality after controlled freeze-thaw cycles. Without shared metrics, manufacturers may optimize for laboratory performance rather than distribution reliability.

Infrastructure is equally important. Cold-chain reliability varies widely across regions, and small producers may lack access to advanced freezing and storage equipment. A high-performance polysaccharide that requires precise freezing rates or stable sub-zero temperatures may therefore exacerbate inequalities between large and small operators. Fairness considerations suggest that cryoprotectant design should include tolerance to temperature abuse, simple dosing, and compatibility with existing equipment. Open-access data on polysaccharide structure-function relationships could help smaller enterprises formulate effective products without proprietary research budgets. At the same time, intellectual property regimes must balance incentives for innovation with the public interest in affordable, sustainable food technologies.

From a sustainability standpoint, plant polysaccharide cryoprotectants can contribute to waste reduction by extending the usable life of frozen dough and reducing retail and consumer discards [19]. However, sustainability claims should be assessed using life-cycle analysis that includes agricultural production, extraction, refrigeration, packaging, and transport. A polysaccharide derived from a low-value side stream may still have a high environmental footprint if purification requires large amounts of solvent or energy. Policy instruments such as carbon pricing, energy-efficiency standards for refrigeration, and food-waste reduction targets can align molecular innovation with broader environmental goals [20]. Without such alignment, cryoprotectant development may improve product quality while inadvertently increasing total energy demand or shifting burdens to vulnerable communities.

Finally, resilience and robustness require diversified strategies. Relying on a single plant source for cryoprotective polysaccharides creates vulnerability to crop failure, seasonal variability, and supply-chain disruption. A portfolio approach that includes multiple polysaccharide sources, complementary mechanisms, and flexible formulation rules can improve resilience. Governance should encourage transparency in sourcing, traceability, and performance validation while allowing for regional adaptation. In this sense, the molecular mechanisms of ice crystal regulation are not merely laboratory phenomena; they are embedded in a socio-technical system where policy, infrastructure, and equity shape whether technical solutions translate into real-world benefits.

6. Conclusion

Plant-derived polysaccharides regulate ice crystal formation during dough freezing through a combination of hydration, hydrogen bonding, steric hindrance, viscosity enhancement, gelation, phase separation, and interaction with gluten and starch. These mechanisms operate within a thermodynamic and colloidal framework in which nucleation, crystal growth, recrystallization, freeze concentration, and glass transition behavior determine dough quality. The most promising polysaccharides are not necessarily those with the strongest single mechanism but those that balance water binding, network formation, compatibility with gluten, and tolerance to realistic freezing and storage conditions. The example of a *Phyllanthus emblica* L. polysaccharide fraction demonstrates how a sol-gel transition can be structurally coupled to cryoprotective function, but it also shows that molecular performance must be evaluated in the context of dough architecture and processing history [14].

At the system level, frozen dough is a socio-technical infrastructure that connects agricultural production, biopolymer extraction, food manufacturing, cold-chain logistics, retail operations, and consumer behavior. Structural trade-offs mean that no single formulation can optimize all objectives, and governance must support performance-based standards, transparent sourcing, and equitable access. Sustainability requires life-cycle thinking that includes refrigeration energy and food-waste reduction, while resilience demands diversified polysaccharide sources and flexible deployment strategies. Future research should integrate molecular characterization with process engineering, cold-chain modeling, and policy analysis so that cryoprotective design is evaluated not only by laboratory metrics but also by its ability to improve robustness, fairness, and sustainability across the entire frozen dough system.

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