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Eco-Friendly Cryoprotection of Seafood: Mitigating Freezing-Induced Damage with Green Cryoprotective Agents

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INTRODUCTION

Seafood is highly perishable due to its rich moisture and protein content, making preservation vital for maintaining its quality, safety, and shelf life (Solinho et al., 2025; Yadav et al., 2025). Freezing is a common method used to slow microbial and enzymatic activity by reducing molecular motion at sub-zero temperatures. However, it presents challenges that affect seafood's structural and nutritional integrity (Salami et al., 2025; Mehta et al., 2025). A major concern is the formation of ice crystals. As the water within seafood tissues freezes, the resulting ice crystals can disrupt cellular structures, affecting texture, nutrition, and appearance. More critically, ice recrystallization (IR), where small crystals melt and reform into larger ones damages the microstructure further, especially during repeated freeze-thaw cycles. This is a serious issue for seafood sold thawed but uncooked, such as fillets and shellfish. Repeated freezing also causes volumetric expansion and contraction, leading to protein denaturation, moisture loss, and degraded texture, all of which reduce product quality and consumer appeal. To address these issues, cryoprotective agents (CPAs), particularly green cryoprotective agents (GCAs), are gaining attention. While traditional CPAs like glycerol and DMSO are effective, their toxicity limits food applications. Therefore, research into safe, eco-friendly GCAs is crucial for improving frozen seafood preservation while aligning with sustainability and food safety goals (Mahato et al., 2019).

What Are Green Cryoprotective Agents (GCAs)

Green Cryoprotective Agents (GCAs) are natural, environmentally friendly substances used to protect biological materials particularly perishable foods like seafood during freezing and thawing. They minimize ice crystal formation, which can damage texture, flavour, and nutritional quality (Salami et al., 2025).

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Unlike traditional synthetic cryoprotectants such as dimethyl sulfoxide (DMSO), ethylene glycol, or glycerol often toxic and unsuitable for food use GCAs are derived from non-toxic, sustainable sources, making them ideal for clean-label, health-conscious, and eco-friendly food systems. Table 1 highlighting the benefits and applications of green cryoprotective agents (GCAs) in seafood preservation. These include plant-based compounds like natural sugars (trehalose, sucrose), polyphenols, and polysaccharides, as well as marine-derived substances such as antifreeze proteins, fish peptides, and seaweed extracts like alginate and carrageenan. Many GCAs, particularly those using natural deep eutectic solvents (NADESs), form strong hydrogen bonds with water, preventing ice formation and protecting cells during freezing. They are biodegradable, highly biocompatible, and offer preservation efficiency comparable to or better than synthetic agents, making them a promising alternative for both food and biomedical applications.

Table 1. Benefits and Applications of Green Cryoprotective Agents (GCAs) in Seafood Preservation

Benefit	Description	Application with Examples
Improved Texture	Prevents structural damage by reducing ice crystal formation and cell rupture.	Use of trehalose or antifreeze proteins in frozen shrimp to maintain firmness.
Flavour Retention	Minimizes oxidation and enzymatic changes, preserving natural seafood flavours.	Application of seaweed extracts in fish fillets to prevent off-flavours and rancidity.
Extended Shelf Life	Inhibits microbial growth and maintains product quality over longer storage.	Fish peptides added to frozen salmon to prolong freshness and reduce spoilage.
Health Safety	Uses non-toxic, natural ingredients safe for human consumption.	Replacement of synthetic CPAs (like DMSO) with plant-based NADESs in seafood glazing.
Clean Label Appeal	Supports demand for sustainable, additive-free, and eco-friendly food options.	Use of natural sugars and marine polysaccharides in organic or premium seafood packs.

How Freezing Damages Seafood

Freezing damages seafood through mechanical damage by ice crystal growth, protein denaturation (especially with repeated freeze–thaw cycles), and texture degradation due to water and nutrient loss upon thawing. Rapid freezing and limiting freeze–thaw cycles are important strategies to maintain seafood quality (Bao et al., 2023; Jin et al., 2025).

Ice Crystal Formation: During freezing, water inside and between cells turns into ice crystals. Slow freezing leads to the development of larger, jagged ice crystals that can rupture cell membranes and muscle fibres, causing physical damage to the tissue structure. Rapid freezing generates much smaller crystals that are less likely to harm cellular structure (Dalvi-Isfahan et al., 2029).

Protein Denaturation: The disruption and concentration of cellular solutes as more water freezes can cause changes in proteins called denaturation, especially after repeated freeze–thaw cycles. This denaturation is often accelerated by oxidative modifications involving amino acids, (Bao et al., 2023) which reduces the nutritional and functional qualities of seafood (e.g., less water-holding, lower solubility, and weaker gels).

Texture Loss (Quality Deterioration): When seafood thaws, previously damaged cells cannot reabsorb all the lost water, leading to drip loss (leakage of fluid), softer texture, and poorer mouthfeel. Protein denaturation and tissue breakdown further contribute to a loss of firmness and juiciness (Qiao et al., 2022). Additional contributing factors include lipid oxidation, where ice damage exposes fats to air, causing rancid flavours and discoloration. Cry-concentration increases salt and solute levels in unfrozen liquid, intensifying protein and cell damage. Together, these accelerate seafood quality deterioration during freezing.

Protective Mechanisms of GCAs Against Freezing-Induced Damage

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Hydrogen Bonding and Freezing Point Depression: GCAs such as natural deep eutectic solvents (NADESs), sugars, and amino acids form strong hydrogen bonds with intracellular and extracellular water molecules. This interaction restricts water mobility, lowering the freezing point and reducing the amount of ice formed inside cells. By binding water, GCAs inhibit the conversion of water into damaging ice crystals (Chang and Zhao, 2021).

Ice Crystal Growth Control and Vitrification: GCAs and their components (e.g., sugars, antifreeze proteins) inhibit the nucleation and growth of ice crystals by adsorbing on ice crystal surfaces. They prevent recrystallization, a process where small ice crystals fuse into larger, more damaging ones during freeze–thaw cycles. This leads to the formation of smaller, more rounded ice crystals or even glass-like (vitrified) states that mechanically reduce damage to cells (Jahed et al., 2023).

Cell Membrane Protection and Osmotic Regulation: By modulating intracellular solute concentration and maintaining osmotic balance, GCAs help preserve membrane fluidity and integrity under freezing stress. They decrease cell dehydration by regulating water movement across membranes and stabilize plasma membranes against freeze-induced rupture. Additionally, they can scavenge reactive oxygen species (ROS), reducing oxidative damage linked with freezing (Jahed et al., 2023).

Future of Frozen Seafood: Cleaner, Greener, Better

As consumers become increasingly health-conscious and environmentally aware, the demand for clean-label and sustainably preserved seafood continues to grow. Green Cryoprotective Agents (GCAs) are poised to play a transformative role in shaping the next generation of frozen seafood products. Unlike traditional synthetic additives, GCAs derived from plants, marine organisms, and other natural sources offer non-toxic, biodegradable, and eco-friendly alternatives. Their ability to preserve the structural, nutritional, and sensory qualities of seafood during freezing and thawing makes them ideal for future food systems focused on quality, safety, and sustainability. Advancements in biotechnology and food science are driving the development of next-generation GCAs, such as bioengineered antifreeze proteins, natural deep eutectic solvents (NADESs), and marine-derived peptides. These innovations promise to deliver more effective cryoprotection with minimal processing and no harmful residues. In the coming years, GCAs are expected to be integrated into smart packaging, supply chain optimization, and cold-chain monitoring systems, ensuring better preservation from sea to plate. This forward-looking approach not only reduces food waste and energy use but also supports the global push toward greener, safer, and more resilient food systems.

CONCLUSION

Green cryopreservation is emerging as a vital approach in food preservation, with GCAs offering a safer and more sustainable alternative to synthetic cryoprotectants. For effective development, key factors such as toxicity, biocompatibility, cost, and eco-friendliness must be prioritized. Advances in chemical synthesis, nanotechnology, and computational modelling (e.g., molecular docking and simulation) can accelerate the creation of next-generation GCAs. Multidisciplinary collaboration across material science, polymer chemistry, and biology will be essential to designing highly efficient, biocompatible, and high-penetrating GCAs for precise ice control in frozen food systems.

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