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Rapid assessment of melting resistance in fruit-fortified frozen soy yogurt

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Abstract

Background: Melting resistance is a critical quality attribute of frozen soy yogurt, directly influencing consumer perception, sensory acceptance, and market competitiveness. Fruit fortification, while enhancing flavour and nutritional value, introduces additional complexity to melting behavior due to changes in water content, acidity, fiber, and sugar composition.

Scope and approach: This review critically examines recent advances (2020-2025) in rapid and predictive assessment techniques for melting resistance in fruit-fortified frozen soy yogurt. Emphasis is placed on physicochemical mechanisms, matrix structuring, analytical tools, and correlations between formulation variables and melting performance.

Key findings and conclusions: Fruit-derived sugars, organic acids, and fibers significantly influence ice recrystallization, air cell stability, and protein-polysaccharide networks. Rapid instrumental methods, image-based analysis, rheological proxies, and data-driven models offer reliable alternatives to time-consuming conventional melting tests. Integration of rapid assessment tools with formulation optimization is essential for industrial-scale quality control and product innovation.

Keywords: Frozen soy yogurt, Melting resistance, Fruit fortification, Rapid assessment, Ice recrystallization, Texture stability

1. Introduction

Frozen soy yogurt has emerged as a promising plant-based alternative to dairy frozen yogurt, combining the nutritional benefits of soy proteins with the sensory appeal of frozen desserts. Among quality attributes, melting resistance is particularly important, as it reflects the structural integrity of the frozen matrix under ambient conditions and strongly affects consumer satisfaction.

Fruit fortification further enhances product appeal by improving flavour, colour, and functional value. However, fruits introduce sugars, acids, fibers, and bioactives that modify freezing point, ice crystal dynamics, and protein gel networks, thereby altering melting behaviour. Traditional melting tests are labor-intensive and poorly suited for rapid formulation screening. Consequently, there is increasing interest in rapid, predictive methods for assessing melting resistance in fruit-fortified frozen soy yogurt systems.

2. Structural Basis of Melting Resistance in Frozen Soy Yogurt

2.1 Ice Crystal Size and Distribution

Melting resistance is inversely related to ice crystal size and recrystallization rate. Smaller, uniformly distributed ice crystals reduce serum drainage and delay structural collapse. Fruit sugars depress freezing point, influencing ice fraction and crystal morphology.

2.2 Air Phase and Overrun Stability

Air cells contribute to insulation and slow heat transfer during melting. In soy-based systems, weaker protein interfacial films limit air cell stability. Fruit fibers and pectins can partially compensate by increasing viscosity and stabilizing air-water interfaces.

2.3 Protein-Polysaccharide Network Formation

Soy protein gelation, reinforced by fruit-derived pectins and soluble fibers, improves water-holding capacity and structural rigidity. However, excessive fruit juice addition may dilute proteins and weaken the network, accelerating melt-down.

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3. Influence of Fruit Fortification on Melting Behavior

3.1 Fruit Sugars and Freezing Point Depression

Glucose, fructose, and sucrose from fruit juices lower the freezing point, increasing unfrozen water fraction and accelerating melt if not balanced by stabilizers.

3.2 Organic Acids and pH Effects

Fruit acids reduce pH, promoting soy protein aggregation and potentially enhancing gel firmness. Over-acidification, however, may cause protein destabilization and syneresis.

3.3 Dietary Fibers and Pectins

Fruit fibers increase mix viscosity, limit ice crystal growth, and improve melting resistance. Pectin-protein interactions are particularly effective in fruit-fortified frozen soy yogurt systems.

4. Conventional Methods for Assessing Melting Resistance

Traditional techniques include:

- Static melt-down tests (drip loss measurement)
- First drip time determination
- Melting rate under controlled temperature

While informative, these methods are time-consuming, operator-dependent, and unsuitable for high-throughput formulation screening.

5. Rapid and Predictive Assessment Techniques

5.1 Image-Based and Optical Methods

Digital image analysis and video tracking allow real-time monitoring of shape retention, drip formation, and collapse kinetics. These methods provide rapid, reproducible melting profiles with minimal sample preparation.

5.2 Rheological and Thermal Proxies

Dynamic rheology (storage modulus, yield stress) and differential scanning calorimetry (DSC) parameters (freezable water fraction, enthalpy) serve as indirect predictors of melting resistance.

5.3 Low-Field Nuclear Magnetic Resonance (LF-NMR)

LF-NMR enables rapid assessment of water mobility and distribution, offering insights into structural stability and melt behavior without destructive testing.

5.4 Spectroscopic and Sensor-Based Approaches

Near-infrared (NIR) spectroscopy and hyperspectral imaging are emerging as rapid, non-invasive tools for predicting melting resistance based on compositional fingerprints.

5.5 Data-Driven and Modeling Approaches

Machine learning models integrating formulation parameters, rheological data, and thermal properties have demonstrated high predictive accuracy for melting resistance, enabling rapid formulation optimization.

6. Application in Quality Control and Product Development

Rapid assessment tools enable:

- High-throughput screening of fruit types and concentrations
- Real-time quality monitoring during scale-up

- Reduction in product development time and cost

Such approaches are particularly valuable for clean-label formulations where stabilizer options are limited.

7. Challenges and Limitations

Key limitations include:

- Variability in fruit composition and seasonality
- Calibration requirements for rapid analytical tools
- Translation of laboratory correlations to industrial conditions

Standardization of rapid methods remains a critical research need.

8. Future Perspectives

Future research should focus on:

- Integration of rapid analytical tools with inline processing sensors
- Development of universal predictive models for plant-based frozen systems
- Optimization of fruit-protein-polysaccharide interactions for melt control

Advances in digitalization and food process analytics will further enhance rapid quality assessment.

9. Conclusions

Fruit fortification significantly influences the melting resistance of frozen soy yogurt through complex interactions involving sugars, acids, fibers, and protein networks. Rapid assessment techniques provide efficient, reliable alternatives to conventional melting tests, enabling accelerated product development and quality control. Their integration into industrial workflows will be critical for the successful commercialization of fruit-fortified frozen soy yogurt products.

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