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Bibliographic Review

Evaluation of the effects of cryogenic freezing on fruits

Evaluación de los efectos de la congelación criogénica en frutas

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ABSTRACT

Cryogenic freezing is considered one of the most efficient techniques for fruit preservation, as it extends shelf life while preserving sensory and nutritional characteristics. Its effectiveness lies in the formation of small, uniform ice crystals that maintain cell structure, reducing physical damage and limiting microbial and enzymatic activity. Success depends on factors such as freezing rate, fruit type, storage time, and thawing process. In mangoes, rapid freezing methods like Individual Quick Freezing (IQF) have been shown to better preserve texture, color, and antioxidants compared to conventional techniques. In blueberries, the application of liquid nitrogen maintains high levels of vitamin C and firmness, although it can cause surface cracking if the process is not properly controlled. In kiwis, the effects vary according to the soluble solids content and fruit region, influencing cold tolerance and structural damage. In durian, cryogenic freezing has proven more effective than traditional freezing, preserving both internal and external quality for a longer period. Emerging technologies such as ultrasound, high pressure processing, and magnetic fields, and the use of cryoprotectants, especially polysaccharide nanoparticles, enhance this technique by reducing recrystallization and optimize fruit stability during freezing and thawing, making cryogenic freezing a strategic tool for the modern food industry.

Keywords: Shelf life, microbial activity, cell structure, quality, freezing rate, vitamin C.

RESUMEN

La congelación criogénica se presenta como una de las técnicas más eficientes para la conservación de frutas, ya que permite prolongar su vida útil preservando así sus características sensoriales y nutricionales. Su efectividad radica en la formación de cristales de hielo pequeños y uniformes que mantienen la estructura celular, reduciendo daños físicos, limitando la actividad microbiana y enzimática. Su éxito depende de factores como la velocidad de congelación, el tipo de fruta, tiempo de almacenamiento y el proceso

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de descongelación. En el mango, los métodos de congelación rápida como el Individual Quick Freezing (IQF) han demostrado conservar mejor la textura, color y antioxidantes en comparación con técnicas convencionales, mientras que en los arándanos la aplicación de nitrógeno líquido permite mantener altos niveles de vitamina C y firmeza, aunque puede provocar fracturas superficiales si no se controla el proceso. En kiwis, los efectos varían de acuerdo con el contenido de sólidos solubles y la zona del fruto, influyendo en la resistencia al frío y el nivel de daño estructural; por su parte, en el durián la criogenia ha demostrado ser más eficaz que la congelación tradicional, preservando por mayor tiempo la calidad interna y externa del fruto. Tecnologías emergentes como el ultrasonido, la alta presión, los campos magnéticos y el uso de crioprotectores, especialmente nanopartículas de polisacáridos, potencian esta técnica al reducir la recristalización y optimizar la estabilidad de las frutas durante la congelación y descongelación, lo que convierte a la criogenización en una herramienta estratégica para la industria alimentaria moderna.

Palabras clave: Vida útil, actividad microbiana, estructura celular, calidad, velocidad de congelación, vitamina C.

INTRODUCTION

Food is one of the fundamental needs of human beings and is satisfied through sources of animal and plant origin (Zhang *et al*., 2024). Among the most widely used preservation methods to ensure the availability and quality of these products is freezing, which stands out for its broad application in fruits and vegetables (Wu *et al*., 2022). However, the growing demand for frozen products has led companies to offer a variety of foods that may face difficulties in maintaining quality (Pesce *et al*., 2025). This occurs because the volume of products, especially food, that is wasted worldwide continues to increase due to inadequate storage (Salami *et al*., 2025). Since many foods are highly perishable, it is essential to apply appropriate preservation methods that ensure their constant availability throughout the year and in different regions (Muthukumarappan *et al*., 2019). Therefore, cryogenic freezing is considered one of the most effective technologies to extend the shelf life of perishable fruits such as mango, as it inhibits microbial and enzymatic activity (Grover, 2023). This process can also induce irreversible alterations at the cellular level, causing a loss in the final quality of the product, since the freezing of plant tissue with high water content causes cellular damage due to the formation of ice crystals (Jha *et al*., 2019; Schudel *et al*., 2021). Even so, cryogenic freezing slightly reduces pore size, better preserving the microstructure compared to mechanical freezing (Jha *et al*., 2024). The success of freezing depends largely on precise control of process conditions, especially the freezing rate and the type of technology employed, as these factors directly influence ice crystal formation and, consequently, the structural integrity of plant tissue (Grover, 2023). Studies have shown that quality loss, particularly tissue damage and changes in texture and color during freezing, is influenced by the rate of this process (Gales *et al*., 2022). In this regard, food temperature and water content are also key elements in the crystallization phenomenon, which comprises the stages of nucleation and crystal growth (Zennoune *et al*., 2022). The presence of large crystals

can damage cellular structure and compromise food quality; therefore, it is essential to understand the interaction between food microstructure and the morphology of the formed ice (Pérez-Bermúdez *et al*., 2023).

Among emerging technologies, ultrasound, high pressure, and microwaves stand out because they allow the production of high-quality frozen products by modifying water distribution within the food structure, without incorporating foreign compounds into its composition (Loayza-Salazar *et al*., 2023). Nevertheless, these technologies usually involve high costs and their application is still limited by operational scale (Loayza-Salazar *et al*., 2023; Yu *et al*., 2022). In contrast, techniques such as osmotic dehydration or dehydrofreezing and magnetic field-assisted freezing are considered more accessible and economical alternatives, as they do not require sophisticated equipment or the use of expensive refrigerants (Loayza-Salazar *et al*., 2023). Likewise, it has been shown that physical methods, such as the application of alternating and pulsed electric fields in combination with oscillating magnetic fields, are effective in preserving freshly cut fruits in a supercooled state (Narayana *et al*., 2023). In addition, cryoprotectants—especially polysaccharide nanoparticles—have gained relevance due to their effectiveness in inhibiting ice crystal formation and minimizing cellular damage. Thanks to their high surface-to-volume ratio and efficient diffusion capacity, these nanoparticles form hydrogen bonds with water, which contributes to improving fruit stability during freezing and thawing processes (Demirci *et al*., 2025).

MATERIALS AND METHODS

A systematic literature review was conducted covering the period from 2016 to 2025, limited to sources published within the last ten years. For the search and information collection process, key terms such as preservation technology, cellular damage, quality after freezing, and cryogenic freezing were used. Data collection was carried out through access to online academic databases available through the library system of the Universidad Nacional del Santa, as well as internationally recognized scientific platforms such as Sciverse, Elsevier, Scopus, ScienceDirect, and EBSCO. Specialized scientific journals and international organizations related to fruit preservation and processing were consulted, with particular attention to cryogenic freezing techniques.

RESULTS AND DISCUSSION

Effects of freezing on quality parameters in fruits

Mango

In a study conducted by Aldoradin-Puza *et al*. (2019), the effect of the Cells Alive System (CAS) technology, based on the application of oscillating magnetic fields (OMF) during the freezing of ‘Kent’ mango variety, was evaluated. This technology was proposed as an alternative to modulate ice nucleation and reduce the negative effects associated with crystallization; however, the results did not show significant differences compared to conventional freezing. Samples treated with CAS exhibited a statistically significant loss of firmness, as well as visible intercellular separation in histological sections, attributed to the collapse of cellular structure due to ice action (Aldoradin-Puza *et al*., 2019). Similarly, drip loss ranging between 2.45% and 4.15% was recorded, an indicator that reflects a significant leakage of cellular juices during thawing and directly affects fruit juiciness and acceptability. These fin-

dings reinforce evidence that the formation of large ice crystals, resulting from slow freezing or ineffective treatments, negatively impacts the structural and sensory quality of frozen mango (Aldoradin-Puza *et al*., 2019; Grover, 2023).

In a study conducted by Charoenrein and Owcharoen (2016), it was shown that cryogenic freezing at −80 °C (fast freezing) allowed the preservation of firmness in mango cv. Nam Dok Mai by forming small, homogeneously distributed ice crystals, which minimized damage to cell walls. In contrast, slow freezing (−20 °C) generated larger crystals that caused cellular collapse, increased drip loss (up to 60.70%), and marked solubilization of pectic substances associated with degradation of the middle lamella; these effects became more pronounced as freeze–thaw cycles increased. Also, Noriega-Juárez *et al*. (2024) evaluated the effect of the IQF method compared to traditional freezing in different mango varieties, finding that the former allowed better preservation of texture, color, firmness, and antioxidant compounds. Rapid freezing significantly reduced mechanical damage to tissues, as well as the degradation of vitamin C and phenolic compounds, which are key contributors to nutritional value and oxidative stability of the fruit.

Blueberries

Zielińska *et al*. (2018) evaluated the effect of cryogenic freezing with liquid nitrogen (−196 °C) on blueberries, comparing it with conventional freezing (−20 °C), and reported that cryogenic treatment significantly reduced subsequent drying time due to greater structural permeability. However, they also observed that ultrafast freezing caused fractures on the fruit surface and greater volumetric shrinkage (15.02%), resulting from thermal stress and tissue contraction during subsequent sublimation. These effects compromise the external appearance of the fruit, although they favor drying efficiency and moisture diffusion. Cheng *et al*. (2020), in a specialized review of freezing technologies, emphasized that cryogenic freezing allows the formation of smaller and more uniform ice crystals, predominantly located in the extracellular space, which reduces cellular collapse and better preserves the internal structure of the fruit. Nevertheless, they also warned that if the process is not accompanied by gradual thawing, secondary recrystallization may occur, generating cellular ruptures that affect firmness and increase drip loss.

In a subsequent experimental study, Cheng *et al*. (2020) analyzed the effect of cryogenic freezing by liquid nitrogen spraying at −80 °C, combined with a three-stage thawing process (from −20 °C to −5 °C and then to 4 °C). This combination allowed the preservation of more than 95% of the initial content of vitamin C, polyphenols, and soluble sugars, in addition to maintaining blueberry firmness and significantly reducing drip loss. This outcome was attributed to the minimization of recrystallization and preservation of cell wall integrity.

Complementarily, Huang *et al*. (2024) explored the use of cryogenic freezing applied at different temperatures with liquid nitrogen (−80, −100, and −120 °C), adjusted according to the glass transition temperature of blueberries (Tg' ≈ −52.6 °C), and verified that treatments close to −120 °C more effectively preserved firmness, anthocyanin content, vitamin C, and soluble solids. In addition, minimal juice loss during thawing and lower degradation of cellular membranes were reported,

favoring a more compact and stable internal structure.

Kiwi

The increase in pressure during freeze-drying of kiwi reduces its brightness and rehydration capacity, while increasing penetration resistance and particle size; these changes affect texture and hinder subsequent processing (Domin *et al*., 2020). Taking this into account, Xu *et al*. (2023) evaluated the effect of different thermal fluctuation regimes (2 °C to 5 °C and 2 °C to 7 °C, every 12 hours) on the 'Xuxiang' cultivar. Their results showed that these variations increase pulp translucency, reduce firmness, and raise relative conductivity, indicating damage to the cell membrane. Also, a higher incidence of rot and weight loss was observed. At the molecular level, gene expression of polygalacturonase, β-galactosidase, and pectin methyl esterase—key enzymes in cell wall degradation—was significantly higher in treatments with wide thermal oscillations, especially from 2 °C to 7 °C. These effects accelerated fruit senescence, compromising postharvest stability.

On the other hand, Huang *et al*. (2024) determined the freezing points of 45 kiwi genotypes, finding that they range between −1.23 °C and −2.61 °C depending on soluble solid content (SSC). A higher SSC concentration correlated with a lower freezing point, indicating that fruits with high sugar content are more resistant to chilling injury. Likewise, thermal variability within the same fruit was identified: the floral end showed lower freezing points than the peduncular end, which has important implications for the distribution of internal damage under partial freezing conditions.

Additionally, Zhao *et al*. (2021) analyzed the quality of 'Xuxiang' cultivar after frozen storage at −18 °C for up to 90 days. Significant losses in firmness, total phenolic content, antioxidant capacity (DPPH and ABTS), and key aromatic compounds such as hexanal and (E)-2-hexenal were reported. Sensory analysis indicated deterioration in aroma and flavor after 60 days of freezing, attributed to structural collapse and degradation of volatile compounds. These results suggest that prolonged storage at low temperatures, although it prevents microbial growth, can compromise the organoleptic and nutritional quality of kiwi.

Durian

Razali *et al*. (2022) evaluated the effect of freezing methods on the physical and sensory qualities of whole durian. The freezing methods included conventional freezing (−18 °C) and cryogenic freezing (−110 °C). Frozen durian was thawed and evaluated after 12, 24, and 36 hours to determine external and internal quality, incidence of dehiscence, and physicochemical parameters. The results showed that conventional freezing at −18 °C negatively affected durian quality. In comparison, during cryogenic freezing, durian was rapidly frozen without presenting dehiscence.

On the other hand, Hendra *et al*. (2023) evaluated the impact of the freezing process and storage time on the degradation of durian properties. One hundred fruits were subjected to two freezing levels: the first consisted of exposure to −15 °C for 10 minutes (treatment A) and 20 minutes (treatment B), followed by storage at −10 °C for periods of 0, 10, 20, and 30 days. Samples were thawed at 4 °C for 24 hours at different time intervals. The results indi-

Table 1.
Effect of freezing on changes in fruit quality

Fruit	Scientific name	Freezing temperature (°C)	Storage temperature (°C)	Storage time	Texture effect	Source
Mango	*Mangifera indica*	–80, –40, –20	-18	7 days per cycle (3 cycles)	Rapid freezing preserves texture; slow freezing causes cellular collapse, loss of firmness, and increased drip loss.	Charoenrein y Owcharoen (2016)
		–30		35 minutes	Loss of firmness and rupture of cell walls after freezing–thawing.	Aldoradin-Puza *et al.* (2019)
Kiwi	*Actinidia deliciosa*	Lyophilization (12-103 Pa)	-	–	Higher pressure reduces rehydration and increases resistance to penetration during freeze-drying (12–103 Pa).	Domin *et al.* (2020)
		-	2-5 °C y 2-7 °C fluctuating	21 days	Temperature fluctuations accelerate softening and increase translucency by 29%.	Xu *et al.* (2023)
Durian	*Durio zibethinus*	-40	-20	12 months	Initial decrease in ascorbic acid followed by a 151% increase; variable carotenoid content.	Tan *et al.* (2020)
		-110	-	36 h post-thawing	Physicochemical parameters preserved without affecting color, soluble solids, or acidity.	Razali *et al.* (2022)
Dátil Barhi	*Phoenix dactylifera*	-120	-40	9 months	Better preservation of enzymes and sugars compared with conventional freezing.	Alhamdan *et al.* (2016)
		-43	-40	9 months	Better conservation of hardness, elasticity, and resilience; lower deterioration compared with other methods.	Alhamdan *et al.* (2016)
		-18 to -24	-20	9 months	Greater loss of firmness, elasticity, and resilience, significantly deteriorating texture during storage.	Alhamdan *et al.* (2016)
Arandano	*Vaccinium, Hippophae, Vitis*	-196	-	–	Better preservation of volume, shape, and color; epidermis thickness reduced by 20–50%.	Dalmau *et al.* (2024)
	Vaccinium macrocarpon	-196	-	–	Freezing accelerates drying by 69–97% but alters fruit structure.	Zielinska *et al.* (2018)
	Vaccinium	-100, -80, -60, -40 y -20	Variable	–	Low temperatures (–80 °C) maintain quality, whereas –20 °C leads to deterioration.	Cheng *et al.* (2020)

cated that treatment B showed significantly superior performance compared to treatment A, evidenced by lower weight loss, brighter and clearer pulp coloration, softer texture, lower moisture content, and a stable succinic acid profile. Likewise, in sensory preference evaluation, treated fruits were well accepted by panelists.

Tan *et al*. (2020) evaluated the impact of frozen storage on physicochemical properties and microbial load in durian pulp and paste from the "Musang King" (MK) and "D24" varieties over one year. During this period, both matrices exhibited weight loss ranging from 1% to 2%, along with increased pulp softness. Regarding color, changes in tonality were recorded: the "MK" variety shifted from a golden yellow tone to a lighter one, associated with an increase in the h° value, which coincided with a decrease in total carotenoids and β-carotene. In parallel, "D24" showed a paler tonality and reductions in L* and C* parameters after storage. The study also revealed a decrease in soluble solids and ascorbic acid content in both varieties after prolonged freezing, although pH and titratable acidity remained stable. At the microbiological level, pulp showed lower contamination levels compared to paste, with the "D24" variety being the most affected. These results suggest that freezing may be a viable alternative for preserving durian quality, provided that the storage period does not exceed twelve months.

Barhi date

Alhamdan *et al*. (2016) evaluated the impact of three freezing methods—cryogenic, rapid, and slow—on the quality of fresh Barhi dates stored at −18 °C for nine months. Cryogenic freezing was carried out using liquid nitrogen at −196 °C for 10 minutes. In the rapid method, a freezing tunnel with air at 5 m/s and a temperature of −120 °C was used until the internal temperature of the fruit reached −18 °C (≈2 hours). In contrast, slow freezing was conducted in a chamber at −20 °C, reaching the desired temperature in approximately 8 hours. The results indicated that cryogenic and rapid freezing better preserved texture and color and reduced exudation during thawing, whereas slow freezing generated greater structural damage due to the formation of large ice crystals.

CONCLUSIONS

Freezing exerted a determining effect on the quality of different fruits, depending on the technology employed, temperature, and storage time.

In the case of mango, it was observed that both conventional freezing and freezing assisted with the Cells Alive System (CAS) did not prevent the loss of firmness or cellular separation, whereas cryogenic freezing better preserved texture and reduced drip loss during thawing.

For blueberries, it was observed that the use of liquid nitrogen effectively preserved antioxidant compounds, firmness, and fruit shape; however, it was noted that inadequate thawing generated secondary recrystallization.

For kiwi, it was found that thermal oscillations and prolonged treatments at −18 °C caused alterations in texture, color, antioxidant activity, and aromatic profile, affecting sensory acceptability.

Regarding durian, it was verified that cryogenic freezing prevented dehiscence and preserved physicochemical properties during the first 36 hours after thawing; moreover, a longer freezing time (20 minutes) and storage at −10 °C for 30 days allowed better retention of color, moisture,

and acid stability, with the "Musang King" variety being more resistant than "D24".

In Barhi dates, it was evidenced that rapid freezing at −120 °C and cryogenic freezing with liquid nitrogen at −196 °C optimally maintained internal structure, texture, and sensory acceptance after nine months of storage, in contrast to slow freezing, which caused greater physical deterioration and quality loss.

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• Lizeth N. Santiago-Castillo: Conceptualization; methodology and project administration.

• Miguel A. Grados-Poémape: Data analysis, data validation, and writing.

• César Moreno-Rojo: Review, supervision, validation, and final editing.