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Advancements and Future Avenues in Cryo-Processing Technologies in Food

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14.1 Introduction

Cryogenics is a field of engineering that focuses on the generation and utilization of low temperatures, ranging from absolute zero (-273.15°C) to -150°C (Goswami 2017). Cryo-processing and preservation are the most advanced technologies used in the food sector to extend shelf life, preserve nutrients, retain flavour and aroma, and provide a customer-friendly product (Jha et al. 2024). The Greek words ‘Kryos’ (frost) and ‘Genic’ (create) are the basis of the word ‘cryogenics’. The field of cryogenic research most likely began with gas liquefaction (Balasubramanian et al. 2012).

The product’s surface may be subjected to a liquid N_2 spray, a solid (‘snow’) and gaseous CO_2 mixture, or a direct immersion in the liquid cryogen during the cryogenic processing procedure. The cryogenic material is typically delivered to the food manufacturing facility as a high-pressure liquid, making handling the refrigerant far easier than with mechanical refrigeration systems. After that, it is stored in a tank that requires chilling or insulation. A pipe assembly is used for spraying with a nozzle and valve. For both cryogens, the equipment is the same, but the design parameters are different (Estrada-Flores 2012). Cryogenic applications have revolutionized the food sector by enabling low-temperature uses in food processing, rapid freezing, and preservation. Cryogenic grinding is a practical technique used in the processing of spices.

14.1.1 Significance of Cryogenic Technology

When compared to traditional methods, cryogenic freezing significantly reduces the time required to freeze food. This quick process ensures that the food’s texture, flavour, colour, and nutritional content are better retained after thawing by preventing the formation of

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large frozen crystals, which can damage the cellular structure (Brown 1967; Pravarthika and Karthickumar 2025). Delivering foods that taste and appear more like their fresh counterparts is made feasible by the process, which preserves the food's organoleptic (sensory) attributes and freshness.

Cryogenic freezing significantly extends the shelf life of sensitive goods and enhances food safety by rapidly reducing temperatures and creating an environment inhospitable to microbial growth. By simply adjusting the freezing conditions, the technique can be applied to a wide range of food products, including prepared meals, meats, shellfish, and baked goods. Larger yields, reduced product loss, lower maintenance, and a smaller system size result in operating savings, even though the original investment in cryogenic technology may be higher. Compared to mechanical refrigeration devices that employ hydrofluorocarbons, the technique is more sustainable due to its efficiency and use of naturally occurring gases (Mudgulkar 2024; Volokitina et al. 2024).

14.1.2 Overview of Recent Trends and Global Outlook

Cryogenic freezing is being revolutionized by the incorporation of innovative technologies, including dynamic airflow management, predictive analytics, and real-time monitoring (Radu et al. 2025). By identifying inefficiencies and anticipating maintenance requirements, these systems minimize downtime, improve product consistency, and optimize energy use. Automation, such as sophisticated Clean-in-Place (CIP) systems, is accelerating cleaning cycles, reducing water usage, and improving hygiene (Brown 1967). Hybrid systems that combine ammonia for high-capacity cooling and CO₂ for low-temperature freezing are gaining popularity, supporting both sustainability and performance objectives. The method prolongs shelf life without the use of chemical preservatives, supporting the clean-label movement. North America and Europe are at the forefront of premium frozen food products, automation adoption, and environmental measures (Banerjee 2021).

Urbanization, growing middle-class consumption, and the demand for prepared foods, seafood, and baked goods are driving the rapid market expansion in the Asia-Pacific and Latin America regions. In India, due to consumer and corporate demand for cutting-edge freezing solutions, the cryogenic freezers market is anticipated to expand at a compound annual growth rate (CAGR) of more than 4%, reaching around \$30 million by 2033 (Kypraiou and Varzakas 2025).

14.2 Cryogenics

The liquids used in the cryogenic process are referred to as 'cryogenics'. Cryogenics are liquids of nitrogen (N₂), oxygen (O₂), helium (He), and carbon dioxide (CO₂). Depending on their characteristics, needs, and system viability, these fluids are employed in various fields. Along with the liquefaction and separation of air gases, liquid nitrogen (LN₂) is one of the largest and fastest-growing industries in the field of cryogenic applications. The primary motivation behind cryogenics is the densification (condensation) and separation (distillation) of gases. Cryogenics utilizes a substance's latent heat of vaporization to achieve low temperatures by submerging it in a cryogenic bath (Balasubramanian et al. 2012).

14.2.1 Liquid Nitrogen

Nitrogen in its liquid state, following exposure to low temperatures (below its boiling point, which is -196°C or -321°F), is known as cryogenic liquid nitrogen (LN_2). Since 78% of air is nitrogen, it is a colourless liquid that is created by fractional distillation of liquid air. Due to its unique properties, including its ability to maintain freezing temperatures, cryogenic liquid nitrogen offers a wide range of applications once it is generated. Specialized Dewar containers, which are insulated vessels designed to reduce heat transfer and sustain extremely low temperatures, are required to store LN_2 (Kim et al. 2011).

Chemical inertness, a high volumetric expansion ratio linked to the liquid-to-vapour phase change, and a high enthalpy of vaporization are the primary characteristics of LN_2 that make it a desirable choice in the food and beverage industry (Bonga 2024). Because nitrogen is non-corrosive and chemically inert, it can be used in food without negatively impacting its organoleptic qualities. Notably, LN_2 's superior thermophysical qualities allow it to be used as a refrigerant. Due to its high-volume expansion ratio, LN_2 can also be utilized for specific inert packaging applications, such as LN_2 dosing. When LN_2 is exposed to higher temperatures, it becomes volatile. The energy density of LN_2 is high, allowing it to absorb a large amount of heat during evaporation (Kim et al. 2011).

When a liquid cryogen is introduced into a target medium, it changes phases and becomes saturated vapour. The vapour phase then warms up to room temperature. The sensible heat difference, linked to the temperature rise of the vapours and the latent heat of vaporization for the liquid-to-saturated vapour phase transition, determines a liquid cryogen's capacity to extract heat from the target medium (Bonga 2024).

14.2.2 Carbon Dioxide (CO_2)

Compared to LN_2 , liquid CO_2 sublimates at -78.5°C (-109.3°F) and has a milder cryogenic impact. Although it is not as quick as LN_2 , CO_2 freezing is still significantly faster than traditional mechanical techniques. Snow horns or tunnels, which create and apply CO_2 snow to food products, are frequently used in CO_2 systems. In general, CO_2 is considered less expensive than LN_2 and poses fewer safety risks. It works effectively with a variety of food items, especially those that are less susceptible to changes in freezing rates. Additionally, because it can be captured from industrial operations, CO_2 is frequently regarded as a more sustainable choice; nonetheless, life-cycle assessments are essential for a comprehensive sustainability practice (Bagwan et al. 2023).

14.3 Advanced Cryogenic Processing in the Food Sector

14.3.1 Freezing and Cooling

Preservation is one of the important phenomena when it comes to storage and shelf life. The shelf life of many animal and plant-based food products is extended by low-temperature (cooling and freezing) techniques. Because low temperatures do not cause thermal damage to products, those treated using low-temperature techniques are of

higher quality than those produced using traditional thermal techniques. By decreasing the product's water activity, it delays cellular metabolic responses, lowers microbiological activity, and decreases enzymatic reactions, all of which contribute to a longer shelf life (Goswami 2017; Alhamdan et al. 2018). Furthermore, since the development of low-temperature processing techniques, the need for chemical preservatives in foods has significantly decreased. Air-blast, plate, contact, fluidized, immersion, and cryogenic cooling are some of the cooling techniques (Bashir et al. 2025).

Frozen foods and chilled products are getting popular nowadays. Due to the changing lifestyle, diet plans, and easy-to-use products, they are attracting consumers rapidly (Çalışkan Koç et al. 2025). In the food sector, the frozen food category, which encompasses quick-frozen meat, fruits, vegetables, flour, and rice products, is experiencing rapid expansion. However, there are serious safety hazards associated with their manufacture and storage. The freezing rate significantly affects the quality of food, with the majority of published data indicating that rapid cooling is the most effective method for improving quality preservation in cellular food systems (Truonghuynh et al. 2020).

Traditionally, freezing injuries are reduced by promoting a higher freezing rate or by using pretreatment methods prior to the initiation of freezing. Modern freezing techniques, which include the use of physical fields and high-pressure processing, have proven effective in producing high-quality frozen foods. Cryogenic fluids enable ultra-rapid freezing, which results in high-speed freezing rates. By producing a large number of tiny ice crystals in the intracellular and intercellular spaces, this process reduces the negative consequences of dehydration and shrinkage-induced damage. As a result, the overall quality of frozen foods is successfully maintained (Jha et al. 2024).

14.3.1.1 Cryogenic Freezing

Cryogenic freezing beats conventional techniques in maintaining the quality of food items both during and after freezing (Table 14.1). Numerous factors, including the preservation of the original microstructure, reduced exudate loss, enhanced texture retention, decreased dehydration losses, reduced lipid oxidation, and minimal colour change,

Table 14.1 Comparison of cryogenic vs. conventional freezing techniques.

Parameter	Cryogenic freezing	Conventional freezing
Cooling rate	Very high	Moderate to low
Ice crystal formation	Small, uniform, intracellular	Large, extracellular
Product quality (texture, flavour)	Superior	Often compromised
Nutrient retention	High	Moderate
Processing time	Short (seconds to minutes)	Long (hours)
Equipment cost	High	Moderate
Operating cost	High (due to cryogen consumption)	Lower
Common applications	Premium meat, berries, seafood	General frozen goods

demonstrate that this is one of the highest-quality preservation methods (Truonghuynh et al. 2020). The outer layer of ice crust grows on the product's surface when it is exposed to cryogens. In addition to increasing the product's mechanical strength, this crust serves as a moisture-retaining barrier. This crust's development could help to preserve and encapsulate the food's flavour, providing an extra benefit in terms of flavour retention (Jha et al. 2024). For freezing products, different types of freezers are available, based on the properties of the food being subjected to freezing.

14.3.1.2 Cryogenic Immersion Freezers

It utilizes a liquid refrigerant as a heat transfer medium. Because liquids have a high thermal coefficient, food comes into direct or indirect contact with the refrigerant during a quick cooling or freezing process. It has frequently been demonstrated in these tests that the substantial freezing rate of immersion freeze treatment maintains the original food quality. Protein structural stability is maintained, and cell damage is reduced in immersion freeze-treated samples due to the small size of the ice crystals, which significantly improves product quality. Food preservation is favoured by the increased quantity of tiny ice crystals produced by immersion freezing. Additionally, the preservation of protein properties was enhanced by the immersion freeze technique (Ikram et al. 2025).

14.3.2 Fruits and Vegetables

Fruits offer higher nutritional benefits, but at the same time, they are highly perishable, resulting in shorter shelf life. Additionally, fruits are seasonal; to maintain year-round availability, proper preservation techniques are necessary. The final quality of frozen meals depends on the size and structure of the ice crystals, with the rate of heat removal being a primary parameter that influences the rate of crystal development. Rapid freezing encourages intense nucleation and the development of intracellular small ice crystals, whereas slow freezing facilitates the formation of large extracellular ice crystals that harm vegetative tissues. The rapid freezing of berries and other food items using liquid nitrogen spray has gained interest recently (Dalmau et al. 2024).

During the frozen storage period, measurements were made of the colour values, textural characteristics (hardness, elasticity, chewiness, and resilience), and nutritional characteristics (enzymes and sugars) of the fresh and frozen dates. The freezing process and the frozen storage time had an impact on the colour value of the frozen dates. The quality of frozen fruits produced by cryogenic freezing differs significantly from that of those produced using conventional slow freezing. The findings revealed a significant difference in the freezing times between the two approaches. In the cryogenic freezing approach, the freezing period was 10 minutes, whereas in the standard slow-freezing system, it was 30 hours (Alhamdan et al. 2018). By presenting a novel approach to reducing fruit cracking during freezing without the need for packaging, this technology offers fresh perspectives on the field of food freezing technology. The results also suggest potential benefits for the food processing sector, including reduced nitrogen consumption, shorter freezing times, and lower operating expenses (Dalmau et al. 2024).

14.3.3 Meat and Seafood

Due to microbial deterioration during storage, high-nutrient meat products degrade rapidly. Low temperatures are necessary to preserve the meat's quality. Freezing is a common technique for preserving meat and meat products (Ikram et al. 2025). Meat that is frozen and then thawed can undergo significant changes, affecting the nutritional profile, texture, colour, flavour, and microbiological stability of the end product (Pesce et al. 2025).

Seafood quality can be well preserved during frozen storage by pretreatment with liquid nitrogen freezing (LNF). A study investigated the effect of LNF temperatures on the meat quality of gazami crabs (*Portunus trituberculatus*) to improve their flesh quality during frozen storage. The findings demonstrated that the LNF temperature of -100°C , which is lower than the ideal LNF temperature for shell-free aquatic items like fish, more successfully prevented the oxidative deterioration of crab meat during storage, increasing the shelf life of frozen gazami crab to four months. By offering recommendations for determining the optimal LNF temperature for aquatic products, this study enhances the application parameters of LNF in the freezing sector of crustacean aquatic products (Ren et al. 2025). When compared to conventional procedures, Atlantic salmon treated with LN_2 supercooling showed better gaping scores, a lower incidence of blood spots, and increased firmness after smoking (Chan et al. 2020). LNF decreased thawing loss and water migration in crucian carp and catfish, assisting in maintaining the fillet's succulence by retaining its water-holding capacity (Jin et al. 2025).

14.3.3.1 Changes to the Physical Characteristics of Frozen Meat Products

- **Microstructure:** Monitoring the development of ice crystals throughout the freezing process is essential. The time allotted for crystal formation determines how ice crystals develop.
- **Colour:** It is the primary consideration in consumer preference. During freezing and after thawing, the colour of the meat will change.
- **Tenderness:** Shear force, a sensory characteristic used to evaluate the quality of raw meat, is frequently used to objectively measure tenderness. Meat becomes less tender as the shear force rises. The enzymatic breakdown of muscle fibres and the tenderization of beef tissue were caused by protein hydrolysis and the aging process.
- **Drip Loss and Water Holding Capacity:** Drip loss, snow recrystallization, sublimation, and the fixing and reorganization of dampness can all result in moisture damage. Food's weight, surface, juiciness, and appearance are all impacted by moisture migration.

14.4 Cryogenic Grinding

India is the world's top producer and exporter of spices. Ground powders of various spices, either alone or in the form of spice mixes, have demonstrated enormous potential for commercial exploitation as value-added products (Saxena et al. 2018a). Although there are other ways to add value to spices, ground powders are the most widely used and significant. In addition to adding taste and flavour, powdered spices of different types provide a preservative benefit to prepared meals.

Grinding is a unit operation used in the food industry to reduce the size of materials and produce powders. For the grinding process, different types of grinding mills are available. Each mill has a specific application. Since ancient times, spices have been valued for their distinct aroma and unique flavour. Spice grinding has long been accomplished with various grinding tools tailored to the specific situation. The demand for high-quality processed spices has increased in recent years. Thermal damage is one of the primary drawbacks of the traditional grinding method. Grinding under regulated temperature conditions is one effective way to minimize thermal damage. Therefore, it is particularly crucial to grind at lower temperatures. The basic idea of grinding remains the same in both ordinary and cryogenic settings.

The intrinsic quality of the spices is determined by their moisture, volatile oil, and fixed oil content. A premium spice powder with a distinctive flavour and high essential oil content is always preferred by consumers in the culinary sector. Consequently, it is preferable to grind in a way that preserves the most essential volatile oils while minimizing quality loss. A well-known method for producing high-quality spice grinding is cryogenic grinding, which involves low temperatures (below -153°C). By absorbing the heat produced during the grinding process, the LN_2 in this method provides the refrigeration required to pre-cool the spices and maintain the appropriate low temperature (Saxena et al. 2018b).

For materials that contain large amounts of volatile oils and fats that are readily oxidized, changes in the material's quality during grinding are incredibly complicated. There are two reasons to use cryogen, such as liquid nitrogen (LN_2). It lowers the grinding temperature and creates an atmosphere that prevents the material from undergoing oxidative changes. In the food industry, cryogenics plays a crucial role. Among all the cryogens available, liquid nitrogen is the most recommended for achieving the required low temperature in food grinding. Superior grade ground powder with improved hygiene was generated by grinding spices at a very low temperature (Saxena et al. 2018a).

14.4.1 Effects of Cryogenic Grinding on Spices

The impact of cryogenic grinding on cumin was assessed at different temperatures (230 to -108°C and ambient), feed rates (5–7 kg/h), and sieve sizes (0.8–1.5 mm) on mean particle size, grinding duration, and volatile oil content. Cryogenic grinding preserved 62.56% more volatile oil compared to grinding at ambient temperature. Based on the retention of volatile oil, the highest-quality cumin powder was achieved at a grinding temperature of 230°C , with a feed rate of 7 kg/h and a sieve size of 0.8 mm. Storage tests on cryogenically ground cumin powder indicated that refrigeration provided benefits over ambient storage regarding freshness and volatile oil retention over extended periods (Saxena et al. 2018b).

Cryogenic grinding can increase the velocity and yield of essential oils (Yan et al. 2025). In comparison to a simple grinding pretreatment technique, cryogenic grinding successfully increased the variety of compounds in nutmeg essential oils (NEO), thereby improving the quality of the essential oil, as determined by gas chromatography-mass spectrometry (GC-MS) analysis conducted to assess the composition of the extracted essential oils. Cryogenic grinding in conjunction with ultrasonic-assisted pretreatment and hydrodistillation (CG-UAP-HD) is a successful extraction technique that improves the quantity and

Table 14.2 Summary of cryogenic grinding benefits on spices.

Spice	Key benefits of cryogenic grinding	References
Cumin	+62.56% volatile oil retention, better shelf life	Saxena et al. (2018b)
Nutmeg	Enhanced essential oil diversity (via GC-MS)	Yan et al. (2025)
Coriander	Higher antioxidant content and oleoresin yield	Saxena et al. (2015)
Pepper	Superior aroma retention vs. hammer milling	Liu et al. (2013)

quality of essential oils, supporting research in the field of nutmeg essential oil extraction with theoretical data.

The colour, taste, and sensory qualities of the spices were barely impacted by cryogenic grinding (Table 14.2) (Liu et al. 2013). Although the concentrations of the primary scent ingredients were significantly decreased after holding the samples at 4 °C for six months, cryogenic grinding was still superior to hammer milling in terms of maintaining the major potent aroma compounds. Cryogenic grinding outperformed hammer milling in maintaining the pepper's taste and sensory qualities without appreciably lowering its quality.

Cryogenic grinding has outperformed ambient grinding in post-harvest processing, producing higher-quality coriander powder (Hiremath et al. 2025). An analysis has been conducted to investigate the impact of cryogenic grinding on the volatile oil, oleoresin content, total phenolics, flavonoid content, and antioxidant properties of seed extracts from nine genotypes of coriander (*Coriandrum sativum* L.). The amount of volatile oil and oleoresin in cryogenically ground samples was considerably higher. All genotypes' cryoground samples consistently produced large yields of methanol crude seed extract, and all genotypes also had high levels of total phenolic content and total flavonoid content. The total antioxidant and 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging percentages are also higher in cryoground samples of all genotypes (Sharma et al. 2016).

The impact of cryogenic grinding on the recovery of fatty oil and volatile oil, as well as their contents in two cumin genotypes (*Cuminum cyminum* L.), has been examined. In addition to preserving the volatiles, cryogenic grinding increased recovery by 33.9% in GC 4% and 43.5% in RZ 209. Additionally, genotype RZ 209 showed a notable increase (29.9%) in oil percentage above typical grinding. The essential oil of both genotypes contained 19 main components. The primary component in both genotypes was cumin aldehyde, whose quantity rose from 48.2% to 56.1% in GC 4 upon cryogrinding (Sharma et al. 2016).

14.5 Advantages of Cryogenic Technology

There are potential commercial applications for cryogenic grinding of spices and herbs, as it preserves volatiles without compromising flavour quality or uniqueness. Another significant application of this technique for grinding herbs in Ayurveda and other traditional medical systems is made possible by the improvement of its pharmacological

properties. Cryogenic grinding can produce particles up to 50 μm in size, thereby increasing their efficacy in therapeutic or medical applications. It is possible to conclude that, regardless of genotype, cryogenic grinding technology preserves the flavour and antioxidant qualities of spices. It can also increase the yield and recovery (Saxena et al. 2015).

It can increase the shelf life of the products by reducing the use of chemical preservatives. When compared to samples frozen using an air-blast freezer, the overall quality of cryogenic immersion-frozen products was superior (Qian et al. 2018). Cryogenics helps create a more sustainable food supply chain by lowering food waste through improved preservation and shelf life. Significantly lowering the risk of foodborne illness, cryogenics quickly stops microbial activity (Pravarthika and Karthickumar 2025).

14.6 Challenges of Cryogenic Processing

Despite being a proven technology, its high initial cost has made it unpopular in developing nations (Pravarthika and Karthickumar 2025). Cryogenic freezers and other equipment needed for cryogenic processing are not always accessible. Cryogenic system operation requires highly qualified staff and strict adherence to safety regulations. The creation of cryogenic gases may have an impact on the environment, even though cryogenics reduces waste.

14.7 Integration of Artificial Intelligence in Cryogenic Processing

The development of the frost layer on cryogenic surfaces is a significant subject, and studies on heat and mass transport may benefit from a precise forecast of this growth. It is beneficial and worthwhile to employ artificial intelligence (AI) approaches for estimation since they are affordable, dependable, and easy to apply. The frost layer thickness, δ , on vertical cryogenic surfaces was estimated using four models: multiple linear regression (MLR), least squares support vector machine (LSSVM), artificial neural network (ANN), and adaptive neuro fuzzy inference system (ANFIS) (Zendejboudi et al. 2017).

The freezing procedure has a significant impact on the quality of both frozen and thawed meat. Meat that is frozen at will may lose some of its nutritional value and suffer from a significant decline in sensory qualities (Qiao et al. 2024). AI is anticipated to support the advancement of freezing technology and oversee the freezing procedure to preserve the nutritional value and quality of meat products as much as possible. The method was developed to track the oxidative damage to pork's lipids and proteins during the freeze–thaw cycle. This approach features end-to-end multitask analysis, combining convolutional neural network (CNN) and hyperspectral imaging, which provides the advantage of quick freezing. The automation also facilitates a simple optimization process.

14.8 Hybrid Cryogenic Systems

To improve the quality of meat, radiofrequency-assisted nitrogen cryogenic freezing (RF-CCF) has been suggested. Both pulsed cryogenic freezing (PCF, 3 seconds pulse with a 10 seconds interval for 10 minutes) and continuous cryogenic freezing (CCF, for 2.5 minutes) freezing methods were employed. RF-CCF (10 seconds 2 kV RF pulse with 20 seconds interval and 2.5 minutes of continuous N₂ flow) and RF-PCF (30 seconds 2 kV RF pulse with 60 seconds intervals, with 3 seconds nitrogen pulse with 10 seconds interval for 10 minutes) were subsequently created by combining CCF and PCF with radiofrequency (RF) pulses. These procedures have been compared with blast freezing (BF) and slow freezing (SF) (Manzocco et al. 2022).

It is challenging to effectively break down the plant cell wall using simple grinding as a pre-treatment, which slows the release of essential oils. Additionally, the machine's localized high temperature will cause the loss of heat-sensitive chemicals. The nutmeg was pretreated using cryogenic grinding and ultrasonication, and the addition of sodium chloride (NaCl) was intended to minimize the loss of essential oil during the extraction and separation procedures. The essential oil from nutmeg was then extracted using hydrodistillation. Following a methodical optimization of the extraction conditions, the yields for cryogenic grinding and simple grinding of nutmeg were 7.0409% and 5.7084%, respectively (Yan et al. 2025).

Membrane technology and membrane-based hybrid technology are strongly driven by the high CO₂ concentration and high pressure of the feed used in pre-combustion carbon capture (Ni et al. 2025). The membrane–cryogenic hybrid method offers a novel approach, complementing conventional separation techniques, as it can economically achieve high CO₂ purity and recovery.

14.9 Quantum Cryogenics in Food: A Theoretical Approach

At the most advanced field of study, known as quantum cryogenics, ultra-low temperatures made possible by cryogenic methods are integrated with the concepts of quantum mechanics. It focuses on utilizing the unique behaviours of quantum systems at extremely low temperatures to investigate fundamental scientific processes and develop new technologies (Braga et al. 2021).

14.9.1 Benefits of Quantum Cryogenics

The delicate quantum states required for quantum computing, which hold the potential to transform computation, cryptography, and optimization issues, must be created and maintained at extremely low temperatures. Cryogenic temperatures enable quantum sensors and detectors to achieve lower noise levels and higher sensitivity. Applications such as magnetic resonance imaging (MRI), gravitational wave detection, and precise measurements depend on this. The precise control of quantum systems for simulating intricate physical processes is made possible by quantum cryogenics, which has applications in areas such as drug development and materials science.

Cryogenics is essential to the development of quantum computing because it maintains the stability of qubits, which is necessary for preserving their quantum states at extremely low temperatures. A key component of many quantum systems, superconducting qubits require sophisticated cooling techniques, as they function optimally at temperatures of a few millikelvins. Cryogenics helps to optimize other aspects of quantum systems in addition to cooling. Readout instruments and control circuits can function more efficiently in cryogenic environments, guaranteeing that all system components work together harmoniously in low-temperature settings (Braga et al. 2021).

Advanced refrigeration methods, such as dilution refrigerators, which use a sequence of cooling stages employing various helium isotopes, are necessary to maintain ultra-low temperatures. Improvements in refrigeration and materials science will have a significant impact on the advancement of cryogenics in quantum technologies. By providing more effective cooling solutions and lowering operating costs, innovations like magnetic refrigeration and new superconducting materials have the potential to transform the industry completely.

14.10 Precision Cryogenic Processing

In the food industry, precision cryogenic processing primarily refers to the rapid freezing or chilling of food products using extremely low temperatures, which are achieved with the use of liquid nitrogen or carbon dioxide. Compared to traditional mechanical freezing, this technique is advanced and superior due to its speed, effectiveness, and ability to maintain food quality. To ensure uniform and consistent freezing across batches, modern cryogenic systems allow for precise temperature and exposure duration adjustments. When food is exposed to extremely low temperatures, as low as -196°C , with LN_2 , the water in the food nearly immediately freezes. Very tiny ice crystals are formed as a result of the rapid freezing, protecting cells and preserving the food's texture, flavour, and nutritional content (Pravarthika and Karthickumar 2025).

14.11 Advances in Cryogenic Equipment and Material Science

14.11.1 Machining Technology

Cryogenics has become a cutting-edge technique in machining technology, enabling the lubrication and cooling of cutting tools during the machining process. Cryogenic machining can enhance cutting performance, decrease tool wear, lengthen tool life, and improve surface smoothness, accuracy, and precision by cooling the cutting tool using LN_2 or other cryogenic gases. Furthermore, cryogenic machining can reduce the likelihood of thermal distortion and damage, particularly when machining challenging materials. This increases the tool's wear resistance and hardness, increasing its longevity and effectiveness. It has been discovered that cryogenically treated tools can last up to four times longer than untreated ones, which lowers the frequency of tool replacement and boosts productivity (Christensen et al. 2025).

To achieve a lower total cutting time than traditional cutting procedures, the Cryogenic Cooling and Cutting System (CCCS) utilizes cryogenic cooling to decrease its impact energy absorption capabilities substantially. The effectiveness of CCCS is evaluated and compared with that of the abrasive water jet (AWJ) technology using numerical analysis. The results show that CCCS can cut at speeds up to 46.8 times faster and reduce cutting times by 87.1–97.9% across a range of monopile diameters and wall thicknesses. The purpose of this study is to demonstrate the distinct advantages of the CCCS technology over traditional approaches, such as AWJ, by significantly reducing cutting times and adverse environmental impacts, and enhancing the sustainability and economic viability of offshore wind farm decommissioning (Anand Shukla et al. 2023).

14.11.2 Storage and Transportation

There is a growing need for materials that can withstand extremely low temperatures and cryogenic conditions in various industries, such as energy storage, food processing and preservation, gas pipelines, and hydrogen energy storage tanks (Mekonnin and Waclawiak 2025). In cryogenic application domains, materials that can safely operate at extremely low temperatures are essential to providing the intended function. Additional requirements are placed on the design of storage tanks when transporting and storing hydrogen as a liquefied gas. Liquid hydrogen (LH₂) is particularly favoured due to its high storage density and effective delivery. To ensure that these containers are compatible with LH₂ at such low temperatures, resistant to hydrogen embrittlement, and possess the best mechanical and thermophysical properties, the materials used must be thoroughly examined. Although stainless steel is frequently used to make LH₂ storage tanks, hydrogen embrittlement is an issue (Qiu et al. 2023). The ability of different grades of stainless steel to withstand this problem has been evaluated. Selecting materials for these exceptionally low temperatures remains a significant challenge. Materials must retain their intended qualities at low temperatures without degrading.

The mechanical and physical characteristics of materials, including fatigue, yield strength, and tensile strength, are improved by exposure to cryogenic temperatures. In addition to improving durability and stabilizing strength properties, cryogenic temperatures enhance resistance to corrosion, erosion, wear, and abrasion. Stronger and more resilient materials are produced as a result of this process, which also stabilizes and improves the crystal lattice structure and guarantees more even distribution of carbon particles throughout the material (Mekonnin, and Waclawiak 2025).

The cryogenic storage and transportation container for LH₂ is a crucial component of equipment in the space and energy sectors, as it facilitates the large-scale storage and transportation of LH₂ (Qiu et al. 2021). The scientific application of icy materials enables the design and production of vessels for storing and transporting LH₂. A systematic and comprehensive understanding of the fundamental features of cryogenic materials for this type of container is a crucial assurance for the safe, dependable, and long-term operation of cryogenic propellant storage and transportation vessels. Austenite stainless steel, the most popular material for this container, performs well at low temperatures, making it the first material of choice for low-temperature operating circumstances. The face-centred cubic structure of austenitic stainless steel offers excellent stability at low

temperatures. Its toughness and flexibility will not drastically diminish when the temperature drops.

14.11.3 Material Science

The study of metals' characteristics at low temperatures has become a significant area of interest in materials research in recent years. The scientific study of materials at extremely low temperatures, typically below 150 °C, where temperature-dependent processes and material composition lead to notable changes in their mechanical and physical properties, is known as cryogenics (Mekonnin and Waclawiak 2025). The microstructure of a material can alter at cryogenic temperatures, improving qualities such as durability, hardness, and tensile strength. Similarly, some polymers are suitable for cryogenic applications because they retain their toughness and flexibility at low temperatures. Furthermore, materials can be processed at extremely low temperatures via cryogenic treatment, such as deep cryogenic treatment, to improve the performance characteristics of conventional alloys.

In cryogenic settings, conventional metals and alloys – particularly stainless steels – display exceptional tensile properties, including resistance to oxidation, corrosion, and wear (Fujun Cao et al. 2023). They are ideal for cryogenic applications due to their specific qualities. The most crucial metric for evaluating cryogenic materials is cryogenic toughness. The following test methods are closely associated with containers used for the storage and transportation of LH₂: drop weight, full thickness, double tensile, and wide plate tests; fracture mechanics tests; and low-temperature impact toughness tests (V-notch, German Society for Testing and Materials [DVM] sample).

14.12 Start-ups, Collaborations, and Commercial Innovations

Worldwide, different start-ups are working in the area of cryogenic technology. Some of the top cryogenic engineering start-ups are given below in Table 14.3 while commercial innovations and their impacts are enlisted in Table 14.4.

Table 14.3 Top cryogenic engineering start-ups.

Company/collaboration	Innovation/focus area
P3 Technologies	High-speed cryogenic pumps/turbopumps
Intelline	Scalable, maintenance-free cryogenic coolers
Cryogenx	Portable rapid body cooling device (CGX1)
Kryotech GmbH	Ultra-low temp freezers, cryosurgery without LN ₂
Air Liquide & CEA	Joint R&D in cryogenic systems, pulsed gas tubes
MSU Cryogenic Initiative	Education & research in cryogenic engineering

Table 14.4 Commercial innovation area and its impact.

Innovation area	Example/impact
Solar-powered cryogenics	Off-grid, sustainable cooling to -196°C
Solid-state cooling	No moving parts, photonic metamaterials
AI-driven optimization	27% energy savings, predictive maintenance
Miniaturized cryocoolers	Smartphone-sized, -196°C for portable applications
Cryogenic isotope separation	40% efficiency gains, modular reactors, medical isotopes
LNG/hydrogen equipment	Specialized joints, arms for energy transition
Hybrid membrane-cryogenic plants	Lower energy, smaller footprint

To spur scientific advancement in cryogenics, these long-time collaborators have established a collaborative laboratory. Their main goals are to improve simulation models for massive cooling systems in fusion reactors, optimize the efficiency of pulsed gas tubes for telescopic sensors, and better integrate cryogenic systems into large-scale projects. This partnership promotes developments in nuclear fusion, particle accelerator architecture, and space exploration. The Michigan State University Cryogenic Initiative, a partnership between the Facility for Rare Isotope Beams (FRIB) and MSU's College of Engineering, prepares students for careers in cutting-edge industries, such as gas liquefaction, aerospace, and quantum computing, by combining classroom instruction with practical cryogenic engineering research. The Cryogenic Engineering Conference and International Cryogenic Materials Conference (CEC/ICMC) serves as a global platform for sharing the latest research and commercial developments, fostering industry-academic partnerships, and showcasing state-of-the-art applications in hydrogen, superconductivity, medical, and space technologies.

14.13 Future Goals of Cryogenics

Advanced cryogenic technology is becoming increasingly necessary due to the growing demand for liquefied natural gas (LNG), which is driving the development of new infrastructure. Cryogenic technology is viewed as an effective method for capturing and storing carbon emissions as companies strive for decarbonization. Automation and AI, combined with cryogenic systems, will enhance operational effectiveness, reduce costs, and increase dependability. The demand for cryogenic systems is expected to increase in various industrial processes as sectors such as electronics, chemicals, and pharmaceuticals continue to expand. Creating our goal of a carbon-neutral society requires the use of CO_2 collection devices. The most developed post-combustion CO_2 capture methods to date, amine-based technologies, have primarily been used in large-scale CO_2 collection applications. Nevertheless, it has also been demonstrated that the cryogenic technique is a promising CO_2 collection technology appropriate for large-scale uses. From a system viewpoint, it has been found that using cryogenic technologies to collect 90% of CO_2 emissions by 2045 can

lower the need for wind power by approximately 47%, resulting in a nearly 45% reduction in annual system costs (Asgharian et al. 2024).

14.14 Technological Gap

To make the technology more efficient, some implementation and research are needed. In cryogenic processing technology, the implementation of advanced sensors and IoT-based systems is necessary to enhance the technology's precision and efficiency (Qiao et al. 2024). For the production of cryogen, solar-based, eco-friendly production systems are important. Regulatory systems are important for managing the system and coordinating with global standards. For the efficient use of cryogenic technology, research into green cryogen, nano-based cryogenic applications, hybrid applications of cryogenic technology, and automated and robotic-controlled processing lines is considered.

14.15 Vision 2030: Strategic Roadmap for Cryogenic Food Processing

Revenue from the cryogenic technology market was assessed at USD 12.5 billion in 2024 and is projected to expand at a CAGR of 6.5% from 2026 to 2033, reaching USD 20.3 billion (Ghorbani et al. 2025). By 2030, cryogenic food processing is expected to undergo a revolutionary expansion due to advancements in technology, the growing need for sustainability, and shifting customer preferences (Chand 2022).

A strategy roadmap with important priorities and concrete actions for stakeholders is provided below:

- 1) Utilize AI algorithms to optimize freezing settings (temperature, LN₂ flow) in real time, enhancing product uniformity and reducing energy consumption by 20–30%. For high-end snacks, medications, and probiotics, combine cryogenic pelletizing and freeze-drying, using sublimation to preserve flavour and nutritional characteristics.
- 2) To cut energy use over traditional procedures, combine LN₂ freezing with microwave drying or pulsed electric fields.
- 3) In large plants, use closed-loop recovery equipment (like Demaco Phase Separators) to cut LN₂ waste by 90%.
- 4) In order to meet worldwide phasedown requirements, replace 30% of HFC-dependent equipment with transcritical CO₂ or ammonia refrigerators by 2028.
- 5) Aim for 15% yearly growth in the high-protein alternative meat and freeze-dried probiotics markets by optimizing cryogenic grinding.
- 6) Collaborate with International Organization for Standardization (ISO)/WHO to standardize cryogenic handling procedures, which will result in a 25% reduction in compliance expenses for multinational operators.
- 7) Connect blockchain traceability to Internet of Things (IoT)-enabled cryogenic tanks for real-time supply chain quality monitoring.

14.16 Conclusion

Cryogenic food freezing is a technique that preserves food at its best, increasing its availability and reducing waste. This technique, grounded in sound science, offers tangible benefits for both food manufacturers and consumers. In food processing, cryogenic technology is a revolutionary development. Its capacity to quickly and consistently freeze or cool food maintains its nutritional content, safety, and quality, satisfying the exacting requirements of both customers and the modern food business. Cryogenic systems will become increasingly important as the industry innovates to ensure effective, sustainable, and superior food production globally.

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