Received: 10 November 2024 | Revised: 13 January 2025 | Accepted: 20 January 2025

DOI: 10.1111/1541-4337.70136

COMPREHENSIVE REVIEW

Comprehensive REVIEWS in Food Science and Food Safety WILEY

Thawing frozen foods: A comparative review of traditional and innovative methods

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Abstract

Due to the changing consumer lifestyles, the tendency to adopt foods that require less preparation time and offer both variety and convenience has played a significant role in the development of the frozen food industry. Freezing is one of the fundamental food preservation techniques, as it maintains high product quality. Freezing reduces chemical and enzymatic reactions, lowers water activity, and prevents microbial growth, thereby extending the shelf life of foods. The freezing and thawing procedures directly impact the quality of frozen foods. The degree of tissue damage is determined by the freezing rate and the structure of the ice crystals that form during the freezing process. Generally, thawing occurs more slowly than freezing. During thawing, microorganisms, as well as chemical and physical changes, can cause nutrient damage. Thus, the goal of this review is to identify innovative and optimal thawing strategies. In order to save energy and/or improve quality, new chemical and physical thawing aids are being developed alongside emerging techniques such as microwave-assisted, ohmic-assisted, high pressure, acoustic thawing, and so on. In addition to discussing the possible uses of these technologies for the thawing process and their effects on food quality, the purpose of this study is to present a thorough comparative overview of recent advancements in thawing techniques.

KEYWORDS

freezing, thawing, thawing aids, tissue damage, water activity

Abbreviations: EF, electrostatic field; HPT, high-pressure thawing; HVEF, high-voltage electric field; HVEFT, high-voltage electrostatic field thawing; IRT, infrared thawing; MT, microwave thawing; OT, ohmic thawing; PAW, plasma-activated water; PEF, pulsed electric field; RFT, radio frequency thawing; SAEW, slightly acidic electrolyzed water thawing; TBARS, Thiobarbituric acid reactive substances; TVB-N, Total volatile basic nitrogen; UAET, ultrasound-assisted slightly acidic electrolyzed; UAT, ultrasound-assisted thawing; VSTT, vacuum steam thawing technology.

1 | INTRODUCTION

Microbial growth and enzymatic activity reduce the shelf life of refrigerated food products, particularly in items such as meat, fish, and shellfish. Consequently, freezing is a widely used preservation technique to ensure the quality and safety of these products, until they undergo further industrial processes or are used immediately after thawing. Every stage of the cold chain, from initial chilling or freezing to storage, transportation, retail display, and home storage, requires meticulous management to maintain safe, high-quality chilled food items. The cold chain involves two main components: chilled or frozen storage, transportation, and retail display, which aim to maintain food temperature; and primary and secondary chilling, which focuses on adjusting food temperature. As food progresses along the cold chain, temperature control becomes more challenging, especially as bulk packages are less sensitive to minor temperature changes. Before additional processing or portioning, frozen products must be thawed or tempered to an appropriate temperature (James & James, 2023; Llave & Erdogdu, 2022).

The three primary processes in freezing are prefreezing, freezing, and frozen storage. The freezing process alters the vitamin and mineral contents; however, if the product is stored for a short period of time at a low nonfreezing temperature, minimal losses may occur. Depending on a number of variables, including the product, prefreezing procedures, pack and package type, and storage circumstances, significant losses may occur during frozen storage (Fennema, 2019). Ice crystallization is a critical phase that impacts both the efficiency of freezing processes and the overall quality of frozen food products. Rapid freezing facilitates the formation of small, uniformly distributed ice crystals, both externally and internally, within the cellular structure, thereby minimizing damage to the food matrix. The cellular structure and changes that occur during rapid and slow freezing are illustrated in Figure 1. This process is beneficial for maintaining the intrinsic qualities of food that has been frozen. Thawing, on the other hand, is an exact opposite of freezing and may drastically change the physicochemical properties and quality of the frozen parts (Qiu et al., 2020). The emergence of synergistic technologies for freezing is being recognized as the most effective approach for frozen food processing, attributed to their ability to improve quality preservation and streamline thawing procedures (Hu et al., 2022).

Traditional thawing techniques apply heat to the surfaces of food products using air or water, which causes the food to transmit heat within. The water thawing method is characterized by its rapidity; however, it presents two significant drawbacks. First, thawing in water results in a greater loss of soluble substances, which adversely affects the processing quality, particularly the water-holding capacity of foods and cohesion. Second, prolonged immersion in water increases the risk of microbial contamination, as it may become exposed to microorganisms present in the water. Additionally, thermal conductivity is decreased by the thawed insulating properties of the surface. The insulating layer thickens as the product thaws, slowing down and lengthening the process (Jiao et al., 2018; Llave & Erdogdu, 2022; Qian et al., 2022). Besides that, losses in commercial value and changes in some properties (apart from thermal conductivity) of food products may occur during thawing. Although more recent thermal and nonthermal techniques are quick and easy to use, they have drawbacks such as favored surface heating, runaway heating, and relatively elevated energy usage. Nonthermal methods, such as vacuum thawing, ultra-high pressure, and ultrasound, are difficult to execute; because they cause localized warmth and low penetration and can lead to food quality denaturation. The quality of frozen food can be decreased by physicochemical changes and microbiological development that are accelerated by suboptimal thawing (Cai et al., 2019a; Hanenian & Mittal, 2004).

This review provides a comprehensive analysis of both traditional and advanced thawing methods for frozen foods, focusing on their principles, techniques, and applications. It evaluates conventional approaches alongside innovative techniques such as high-pressure, microwave, ohmic, acoustic, and high-voltage electrostatic field methods, highlighting their respective advantages and limitations. Beyond individual methods, the paper explores the synergistic effects of combining novel techniques, such as microwave thawing with magnetic nanoparticles or ultrasound-assisted thawing using slightly acidic electrolyzed water, offering fresh perspectives on enhancing thawing efficiency and food quality. Unlike prior studies that often center on a single food type, this work adopts a broader scope by examining multiple food categories. Additionally, it delves into emerging technologies like high-voltage electric field thawing, vacuum sublimation-rehydration thawing, and multi-frequency ultrasonic thawing, which remain relatively underexplored. By incorporating insights from food science, engineering, and consumer research, the review provides a multidimensional resource. It also suggests leveraging artificial intelligence and machine learning to optimize thawing processes, paving the way for future advancements in the field.

2 | FREEZING OF THE FOODS

Freezing is a widely used method to extend the shelf life of various foods, because freezing technology effectively

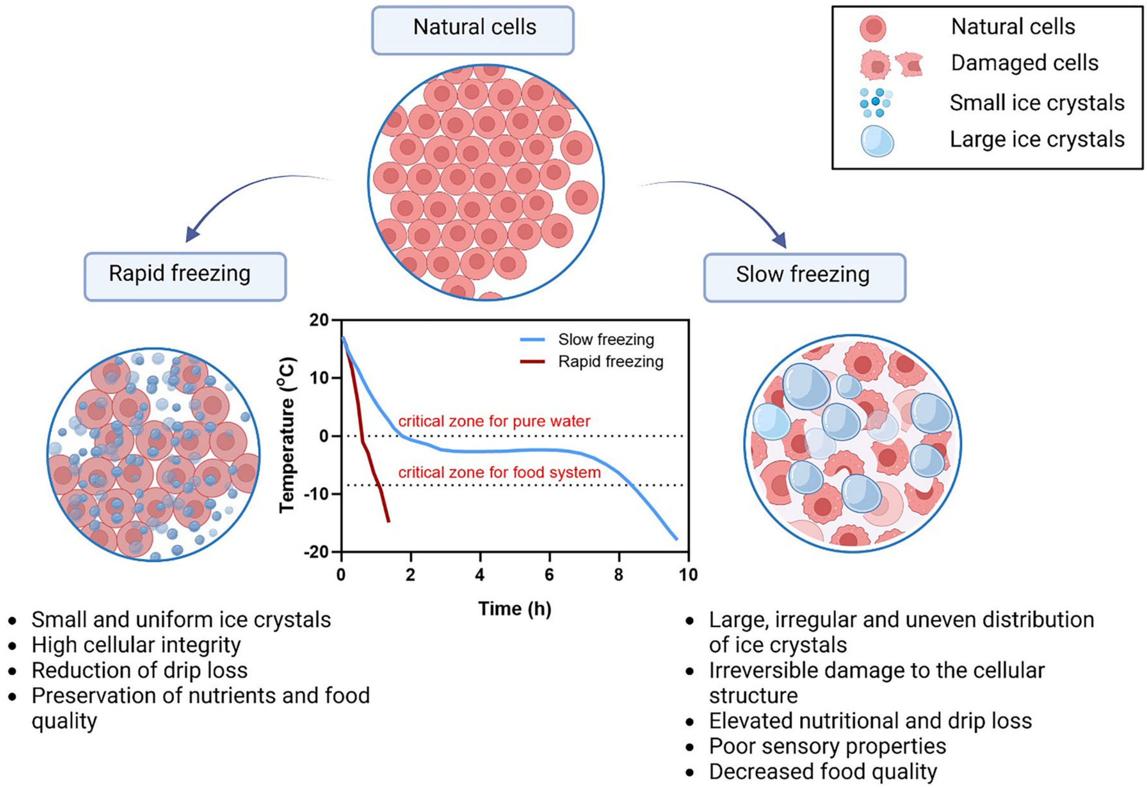

FIGURE 1 The cellular structure and changes that occur during rapid and slow freezing (adapted from Jiang et al., 2023; Köprüalan Aydın et al., 2023) (created by Biorender.com).

preserves product quality (James et al., 2015; Zhao & Takhar, 2017). Freezing process works by reducing chemical and enzymatic reactions, lowering water activity, and inhibiting microbial growth (Sun, 2005), and typically involves nucleation, growth, and maturation (recrystallization) of ice crystals. The frozen product eventually undergoes a transition from the liquid/rubbery phase to the solid/glassy phase, if the temperature decreases enough. The overall quality, texture, and appearance of frozen meals are significantly influenced by the crystalline microstructure (Zhaon & Takhar, 2017; Zhu et al., 2019). The process through which a minimal crystal of critical radius forms, and has the potential to develop and expand is known as nucleation. The freezing point of water represents an equilibrium point. Before ice starts to form, the temperature must drop significantly below the freezing point, as nucleation cannot occur unless pure water is supercooled. Once a stable ice core forms, molecules at the solid–liquid interface can facilitate further ice development. In solutions, crystal growth is influenced by the rate of mass transfer and the release of latent heat during the phase change (Fennema et al., 1973; Sun, 2005). Recrystallization is the process through which an ice crystal's shape, size, number, orientation, and perfection change over time. After initial crystallization, recrystallization takes place in frozen storage to generate more stable crystals on the surface of larger crystals (Fennema et al., 1973).

The size of the ice crystal is determined by the rate of freezing; the faster the rate, the more nucleation occurs, and the smaller the crystals that will form (Figure 1). During freezing, two distinct mechanisms of cell damage are visible:

(i) Solution damage: This occurs at moderate cooling rates, when the cell remains near osmotic equilibrium, and cells cool down too slowly. The slower the cells are cooled, the longer dehydration takes to trigger irreparable damage.
(ii) Intracellular ice damage: This occurs, when supercooled water inside the cell freezes rapidly. By the time cells are cooled too quickly, they retain water which expands during freezing, causing intracellular ice crystals to break apart and damage the cell. This phenomenon is known as intracellular ice damage (James et al., 2015; Mazur, 1984; Sun, 2005; Zhu et al., 2019).

There are several traditional (air blast, plate contact, cryogenic, fluidized-bed, immersion, etc.) and novel food freezing techniques, such as high-pressure freezing, microwave-assisted freezing, ultrasound-assisted freezing, electrically and magnetically disturbed freezing, osmodehydro-freezing, and so on (Cheng et al., 2017). By utilizing various technologies, innovative freezing procedures can enhance or inhibit the nucleation and growth of ice crystals and improve the crystallization process (Dai et al., 2016; James et al., 2015; Zhu et al., 2019). In addition to new technologies developed to prevent intracellular damage during ice formation, antifreeze proteins (which irreversibly bind to the surface of ice crystals to prevent further growth) and ice-nucleating proteins/agents (which can trigger ice crystal formation) are also being used (Li et al., 2002; Zhu et al., 2019).

In conclusion, ice crystals created by freezing have a major impact on food quality and cellular integrity. Conditions during the freezing process (freezing rate, temperature, etc.) substantially affect the size, shape, and distribution of ice crystals. Large and unevenly distributed ice crystals in the food matrix, resulting from slow freezing rates, can irreversibly damage the cellular structure. But smaller, more uniformly distributed crystals produced at high freezing rates cause less damage to the food (Cheng et al., 2017; James et al., 2015; Zhu et al., 2019).

3 | THAWING OF FROZEN FOODS

Food thawing refers to the process of converting food from a frozen state back to a simply unfrozen condition, preparing it for further preparation or consumption. When food is frozen, molecular activity is significantly reduced, and thawing restores the activity of water molecules within the food. However, this process is not merely a matter of allowing the food to sit at room temperature (Ice Cool Trailers, 2023). As a frozen product warms, it absorbs heat from its surroundings, causing it to melt gradually from the outer layers inward. The temperature changes occurring during the thawing of the frozen product are shown in Figure 2. Notably, the thawing process generally takes longer than freezing, even when exposed to the same temperature gradient. This is because, during thawing, water melted from the outer layers acts as the medium for heat transfer, and its thermal conductivity is lower than that of ice in the outer layers of the frozen product during freezing (Jiang et al., 2023; Zaritzky, 2012). The melting of ice crystals can significantly impact the quality of frozen foods, leading to chemical and physical changes, like gaps in the product, a softer texture, and altered flavor. Various factors—including the freezing rate, storage temperature, and both the temperature and duration of thawing—affect the quality of frozen foods. While some changes (moisture migration, textural softening, etc.) are immediate, others (such as oxidation, spoilage, contamination, etc.) become more evident during storage after thawing (Hassoun et al., 2020; Leygonie et al., 2012; Nakazawa and Okazaki, 2020; Shumilina et al., 2020; Wu et al., 2017). The ideal thawing temperature is one that prevents the rapid growth of harmful microorganisms. According to USDA (2024), keeping the temperature below 5°C (41°F) ensures food remains outside the "danger zone," where bacteria multiply quickly. Rapid thawing is preferred over slow defrosting at room temperature, as it minimizes the risk of bacterial contamination (Xiao et al., 2024).

Thawing loss is a key indicator used to assess the quality of foods, as it reflects the extent of damage to cells and tissues caused by freezing and thawing. This metric primarily measures the loss of juice and water during the thawing process. Significant thawing loss, which includes the loss of substantial fluid and nutrients, can negatively impact the nutritional value and sensory qualities of the food. Therefore, minimizing thawing losses is essential to maintaining food quality (Cai et al., 2020; Wang et al., 2021; Zhang et al., 2023a). In the case of a particular food group, for instance, thaw loss in meat is an inevitable outcome of freezing and subsequent thawing, largely attributed to the damage caused to muscle fibers by ice crystal formation and the denaturation of myofibrillar proteins during freezing. The denaturation of myofibrillar proteins during freezing is a complex process that significantly impacts meat quality. Recent studies have elucidated key mechanisms. Ice crystal formation during freezing increases solute concentration in unfrozen water, disrupting protein structure and leading to partial unfolding or denaturation of myofibrillar proteins (Zhang et al., 2023b). Cold denaturation occurs at typical meat freezing temperatures (below −18°C), altering secondary and tertiary protein structures and affecting functional properties (Lee et al., 2024). Freezing damages muscle cell membranes, releasing enzymes that accelerate protein degradation and oxidation. Freeze-thaw cycles cause irreversible changes in myofibrillar protein structure, including decreased solubility, increased hydrophobic interactions, and disulfide bond formation (Yu et al., 2024). These structural modifications negatively impact the gel-forming properties of proteins during subsequent heating, crucial for processed meat quality (Zhang et al., 2023b). To mitigate these effects, proper freezing techniques are essential, such as maintaining temperatures below the glass transition temperature and avoiding temperature fluctuations during storage (Lee et al., 2024). The impact of protein denaturation on thawing losses has not been thoroughly explored in existing literature (Zhang et al., 2022). To assess the effects of thawing on muscle foods, indicators of eating quality, along with microbiological and chemical stability, are evaluated. These indicators—including color, texture, cooking and water-holding capacity, and thaw loss—reveal both the intrinsic quality and sensory attributes of the food. In muscle foods, pH is linked to spoilage microorganism growth

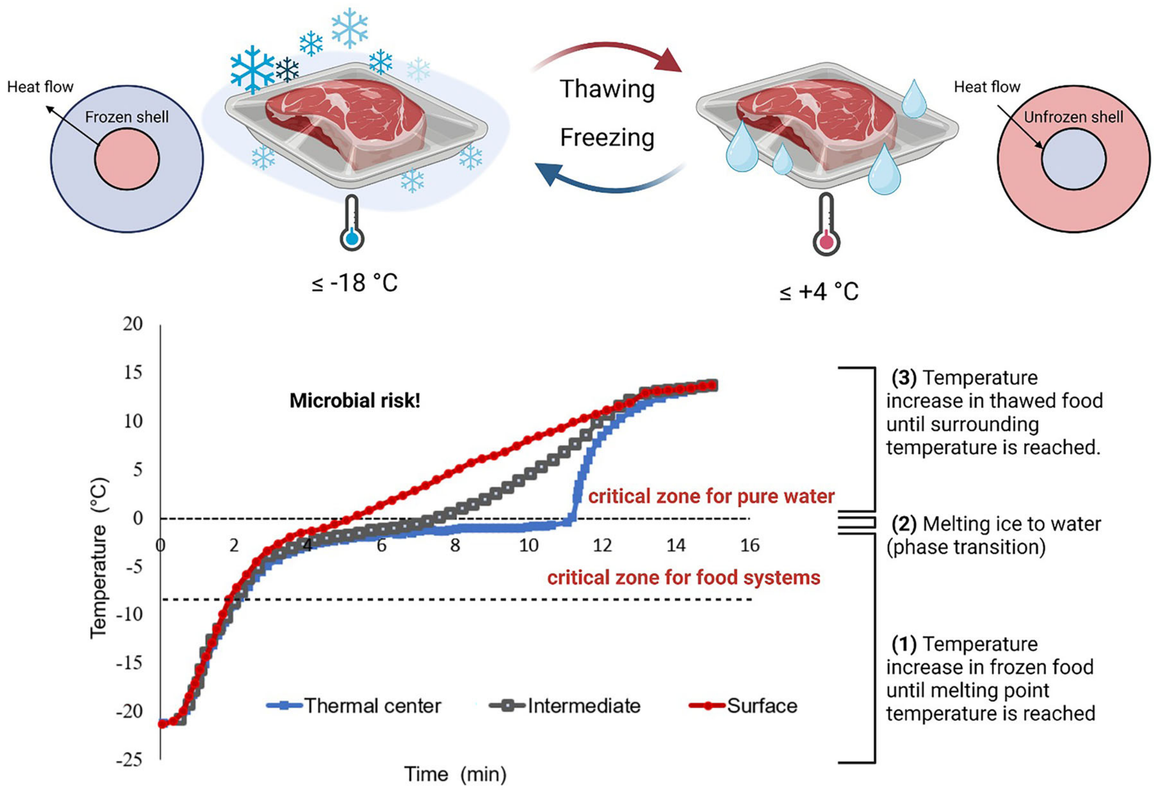

FIGURE 2 The temperature changes occurring during the thawing of the frozen product (adapted from EFSA et al., 2021; Pham 2016) (created by Biorender.com).

and protein degradation, while Total volatile basic nitrogen (TVB-N) and Thiobarbituric acid reactive substances (TBARS) values indicate lipid oxidation and the formation of nitrogenous compounds. Accurately assessing these quality indicators aids in enhancing and optimizing freezing technology by determining the quality state of muscle foods (Bekhit et al., 2021; Fernández-Segovia et al., 2012; Ju et al., 2018; Toldrá, 2022; Zhang et al., 2023a).

While thawing has been underexplored in the scientific literature (FRPERC, 2024) and often studied in the context of domestic practices, commercial thawing systems like those provided by Klinge Corporation (2022) represent efforts to bring more controlled and efficient thawing processes into industrial settings. These systems, such as portable thawing containers and built-in units, offer potential solutions to address the challenges of implementing rigorously controlled thawing systems in the food industry. For instance, the integration of built-in units helps minimize delays and ensures smoother workflows within processing facilities.

3.1 | Traditional thawing methods

Traditional thawing methods for frozen foods involve using air at ambient temperature, immersion in cold water, and refrigeration. Due to low heat conductivity, these techniques have relatively slow thawing rates, which may negatively impact food quality. The longer it takes for food to reach 1°C, the greater the risk of microbial contamination. Frequently, people circulate air in a refrigerator at 4°C, until the food's internal temperature matches the refrigerator's. However, there are certain drawbacks to this method, namely, extended thawing durations and considerable drip loss. While thawing food in cold water expedites the process, it necessitates storing it in a hermetically sealed container or other packaging to avoid contamination. There are several air thawing methods, such as air blast thawing and still air thawing, both of which are thought to be economical. Continuous air thawing, which uses saturated air to prevent dehydration, has serious disadvantages, including uneven thawing, potential microbial growth, and food quality deterioration (Anderson et al., 2004; Aydin et al., 2023; Backi, 2018; Brown et al., 2006; Cai et al., 2019a and 2020; Liao et al., 2020; Zhang et al., 2021a).

3.2 | Novel thawing methods

Traditional thawing methods are characterized by their operational simplicity and cost-effectiveness (Arshad et al., 2023; Lan et al., 2021). Nevertheless, these methods necessitate extended thawing durations, and there is a

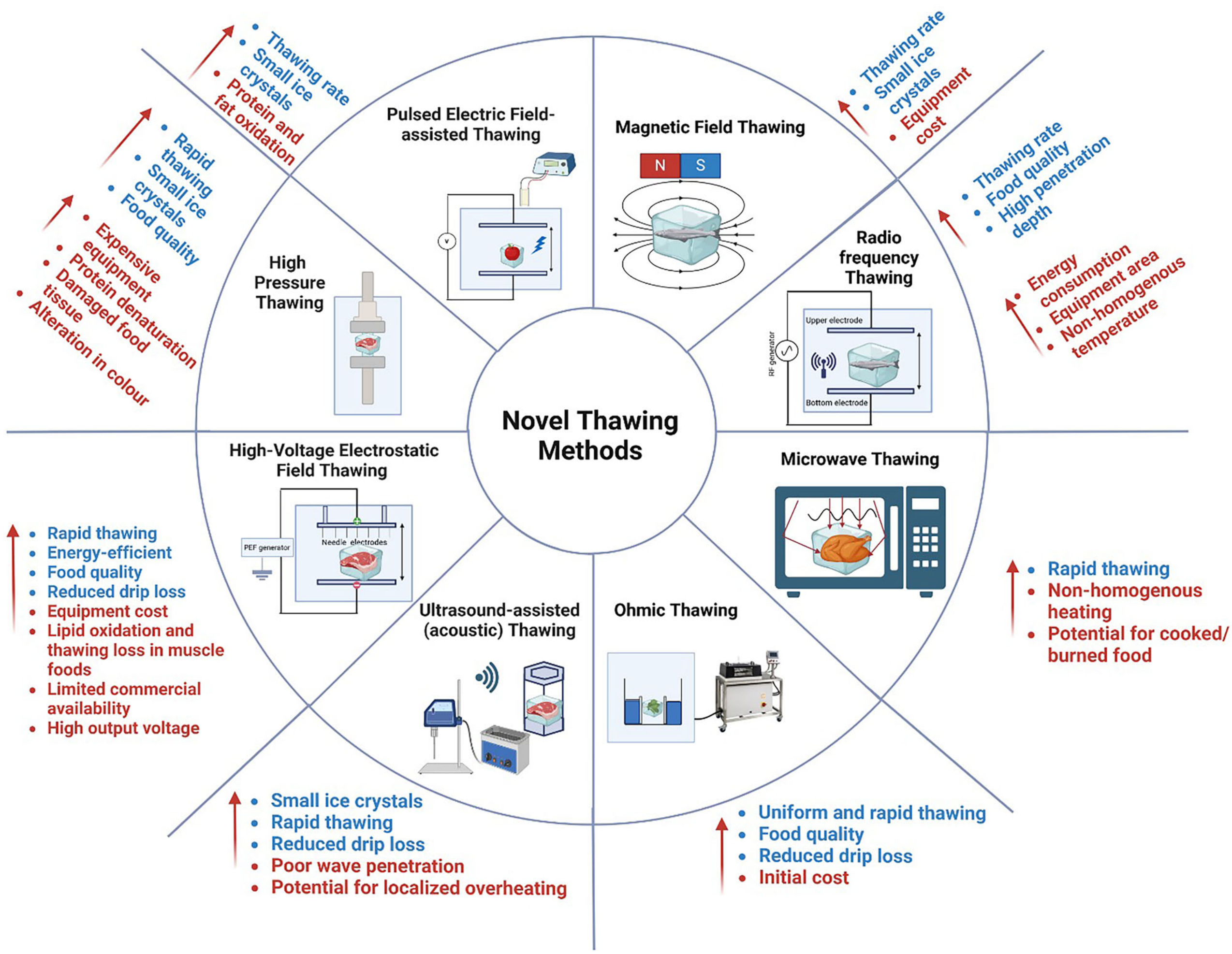

FIGURE 3 The advantages and disadvantages of the novel thawing methods (adapted from Amiri et al., 2019; Çabas et al., 2022; Jia et al., 2020; Köprüalan Aydın et al., 2023; Liu et al., 2024; Mohsenpour et al., 2023; Sun et al., 2023; Wang et al., 2024; Wiktor et al., 2015; Zhang et al., 2022) (created by Biorender.com).

significant proliferation of microorganisms on the surface of the food (Guo et al., 2021). For instance, significant quantities of wastewater are generated during the process of still water thawing, which also accelerates the deterioration of food products, particularly meat (Gan et al., 2022). Consequently, to mitigate the quality degradation associated with thawing, it is essential to implement alternative thawing methods, including high-pressure, microwave, ohmic, ultrasonic, and pulsed electric field thawing (Zhang et al., 2021b). The advantages and disadvantages of novel thawing methods are shown in Figure 3. The application of thawing methods to different types of foods is provided in Tables 1 and 2.

3.2.1 | High-pressure thawing

High hydrostatic pressure is a method that applies pressures between 100 and 800 MPa, sometimes combined with heat, to inactivate harmful microorganisms and ensure food safety (Park & Kim, 2024). High-pressure thawing had been first applied to food preservation by Takai et al. (1991), whose work discovered that the process would thaw food at temperatures below 5°C more quickly, although it affected the color and texture of the products. Initially used in biological research, HPT has been slow to gain widespread use in the food industry, due to its complexity and need for specialized equipment. Despite these challenges, HPT improves heat transfer, speeding up the thawing process (Cai et al., 2019a). At high pressures, ice's melting point drops, and its thermal properties change, creating a larger temperature difference between the heat medium and the thawing surface, which increases efficiency. At pressures up to 210 MPa, the boiling point of water decreases, according to HPT, but at pressures higher than this, it starts to increase again. The food is vacuum-sealed and then put in a chamber that is filled with a liquid that transmits pressure,

TABLE 1 Application of the thawing methods to meat and seafood.

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Meat					
Meat	➢ Ultrasound thawing	Submerged defrosting Environmental conditions: 25°C Sonic energy input: varied at 200, 400, and 600 W Vibrational rate: 20 kHz	Product size/shape: Not specified Driving force: Acoustic cavitation and mechanical agitation	-» Sonic waves enhanced both the freezing and defrosting speeds -» Applying 400 W sonic energy during freezing maintained key quality aspects (cellular structure, moisture retention, visual appeal, nutritional content) -» Aromatic components were more abundant compared to the standard method -» Excessive sonic power at 600 W had detrimental effects on the overall process	Guo et al. (2021)
Porcine longissimus dorsi	➢ High-pressure thawing	Aqueous submersion Atmospheric exposure Pressurized thawing Thermal conditions: 20°C and 4°C Applied force: 70, 140, and 210 MPa	Product size/shape: Not specified Driving force: Pressure-induced phase transition	-» Optimal moisture retention achieved at 140 MPa pressure -» Most significant muscle fiber contraction observed at 210 MPa pressure	Jia et al. (2020)
Porcine longissimus dorsi	➢ Microwave thawing	Sonic wave-assisted (20°C) Electromagnetic radiation exposure (20°C, 800 W) Reduced pressure environment (25°C, 9 kPa) Aqueous submersion (14°C)	Product size/shape: Not specified Driving force: Dielectric heating	-» Electromagnetic radiation thawing diminished the meat's gel-forming capacity, impacting overall product quality -» Samples defrosted via electromagnetic radiation exhibited decreased surface smoothness and altered structural integrity compared to fresh meat	Wang et al. (2020)
Pork loin	➢ Radiofrequency thawing	Atmospheric exposure Aqueous submersion Electromagnetic wave-assisted Environmental conditions: 15°C Energy specifications: • Output: 5 kW • Frequency: 27.12 MHz • Input power variants: 200, 300, and 400 W • Distance between electrodes: 30 mm	Product size/shape: Not specified Driving force: Electromagnetic field-induced heating	Compared to conventional methods: -» Electromagnetic wave-assisted defrosting at 400 W outperformed: • Air exposure method by five times • Aqueous submersion technique by 94 times -» Quality indicators favored electromagnetic wave-assisted thawing over microwave systems: • Superior moisture retention • Enhanced water-binding capacity • Improved protein solubility	Choi et al. (2017)

(Continues)

TABLE 1 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Pork steaks	➢ Low-voltage electric field (LVEF)-assisted thawing	Controlled low-temperature storage LVEF-facilitated method Environmental conditions: 4°C LVEF specifications: • Electrode dimensions: 14 cm × 12 cm • Applied voltage: 2500 V	Product size/shape: Not specified Driving force: Electric field-induced heating	-» Accelerated defrosting process -»Reduced moisture loss -» LVEF-assisted thawing yielded: • Texture characteristics comparable to fresh meat • Enhanced moisture retention capacity	Hu et al. (2021)
Beef	➢ High-voltage electric field (HVEF)-assisted thawing	Environmental conditions: • Temperature: 25°C • RH: 30% Electrical parameters: • Frequency: 50 Hz • Electrode spacing: 8, 9, 10, 11, and 12 cm • Alternating current voltages: 0, 12, 16, 20, 14, and 28 kV	Product size/shape: Not specified Driving force: High-voltage electric field-induced heating	-» HVEF-thawed beef outperformed control samples in: Thawing characteristics Water retention ability Color attributes -» Voltage increase correlated with: Reduced thawing duration Decreased water-holding capacity -» Wider electrode spacing resulted in: Diminished water retention in beef Shorter thawing times	Zhang and Ding (2020)
Chicken breast	➢ HVEF thawing	Atmospheric exposure HVEF assisted Electrical parameters: • Field intensities: 1.5, 2.25, and 3 kV/cm • Electrode spacing: 3, 4.5, and 6 cm	Product size/shape: Chicken breast (relatively flat, uniform thickness) Driving force: High-voltage electric field-induced heating	-» Compared to conventional air-based defrosting: HVEF application significantly accelerated the thawing process -» Optimal results were observed with HVEF at 2.25 kilovolts per centimeter: Minimal alteration of protein structure Maximal moisture retention capacity	Rahbari et al. (2018)

(Continues)

TABLE 1 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Pekin duck meat	➢ Pulsed electric field (PEF)-assisted thawing	Controlled low-temperature storage PEF-facilitated method Environmental conditions: 12°C PEF specifications: • Field intensity range: 1–3 kV/cm • Applied voltages: 5.5, 11, 16.5, and 22 kV • Frequency: 50 H • Pulse duration: 2000 µs • Distance between electrodes: 55 mm	Product size/shape: Not specified Driving force: Pulsed electric field-induced heating	-» PEF at 3 kV/cm halved the defrosting duration -» PEF-assisted thawing significantly reduced: Overall thawing loss Moisture drip -» Protein content in the exuded liquid -» PEF-treated samples exhibited textural properties more akin to fresh meat compared to conventional methods	Lung et al. (2022)
Ground beef	➢ Ohmic thawing	Environmental conditions: 4°C Electrical parameters: Voltage gradients: 10, 13, and 16 V/cm	Product size/shape: Not specified Driving force: Joule heating	-» Higher fat content in frozen ground beef correlated with lower effective electrical conductivity -» Effective electrical conductivity of frozen ground beef rose with increasing sample temperature -» More rapid increase observed above −4°C	Cevik and Icier (2018)
Lean beef	➢ Ohmic thawing	Environmental conditions: 4°C Electrical parameters: Voltage gradients: 10, 13, and 16 V/cm	Product size/shape: Not specified Driving force: Joule heating	-» Maximum voltage gradient (16 V/cm) yielded the most rapid defrosting -» Optimal energetic and exergetic efficiency were observed at the highest voltage gradient (16 V/cm)	Cokgezme et al. (2021)
Seafood					
Fish meat	➢ Microwave thawing ➢ Refrigerator thawing ➢ Water thawing ➢ Immersion thawing	**-Microwave thawing-** Power and time: 120 W for 10 min **-Refrigerator thawing-** Temperature and time: 4°C for 24 h **-Water thawing-** Temperature and time: 20°C for 1 h **-Immersion thawing-** Temperature and time: 20°C for 1 h (water was replaced after 30 min).	Product size/shape: Not specified Driving forces: Varied (dielectric heating, convection, conduction)	-» The effect of using various thawing methods on the formation of Acrylamide was investigated, and it was determined that using different thawing methods did not significantly affect the formation of Acrylamide.	Keskin-Alkaç et al. (2024)

(Continues)

TABLE 1 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Litopenaeus vannamei	➢ Air thawing ➢ Immersion thawing ➢ Ultrasonic thawing ➢ Microwave thawing ➢ Refrigerator thawing	**- Air thawing -** Temperature: 21 ± 2°C **-Immersion thawing-** Temperature: 15 ± 1°C. **-Ultrasonic thawing –** Temperature: 15 ± 1°C Power: 300 W Frequency: 40 kHz **-Microwave thawing-** Power: 700 W Frequency: 2450 MHz **-Refrigerator thawing-** Temperature: 4°C	Product size/shape: Not specified Driving force: Acoustic cavitation and mechanical agitation	-» Ultrasonic thawing has been found to reduce fat oxidation and discoloration and is more effective than other thawing processes (air, immersion, microwave, and refrigerator thawing) in retaining water. -» Based on the results of surface hydrophobicity, turbidity, particle size, and Zeta potential, the ultrasonic thawing method reduces the aggregation and oxidation of myofibrillar proteins during the thawing process compared to other thawing methods. -» The ultrasonic thawing method can be considered a new thawing technique for preserving the quality of shrimp meat quickly and effectively compared to other methods (air, immersion, microwave, and refrigerator thawing).	Sun et al. (2024)
Lates niloticus and Mormyrus kannume fish fillets	➢ Flowing water thawing ➢ Air thawing ➢ Refrigerator thawing ➢ Microwave thawing	**-Flowing water thawing-** Temperature: 20 ± 1°C Flow rate: 10 L/h **-Air thawing-** Temperature: −10 ~ 100°C **-Refrigerator thawing-** Temperature: 4°C **-Microwave thawing-** Power: 400 W	Product size/shape: Fish fillets (flat, thin pieces) Driving forces: Flowing water: Convection and conduction Air: Convection Refrigerator: Slow conduction Microwave: Dielectric heating	-» It has been determined that the applied thawing methods have different effects on the microbial quality, antioxidant activity enzymes, and microstructure of Nile perch (*Lates niloticus*) and elephant nose (*Mormyrus kannume*) fish. -» It has been emphasized that the microwave thawing method has a more positive effect than other thawing methods. -» It has been reported that Nile perch (*Lates niloticus*) and elephant nose (*Mormyrus kannume*) fish are preserved almost like fresh fish with the flow water thawing method application.	Elbarbary et al. (2023)
Rainbow trout	➢ Magnetic field thawing	**-Magnetic field thawing-** Temperature: 4°C Power/frequency: 1, 40, and 80 Hz Magnetic field intensity: 10 mT	Product size/shape: Not specified Driving force: Magnetic field-induced molecular motion	-» It has been determined that magnetic field thawing significantly shortens the thawing time, and the water retention capacity is higher. -» It has been stated that the magnetic field does not significantly affect the solubility of proteins, but the proteins are denatured due to the low-frequency magnetic field.	Mohsenpour et al. (2023)

(Continues)

TABLE 1 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Sea cucumber	➢ Refrigerator thawing ➢ Air thawing ➢ Water immersion thawing ➢ Ultrasound-assisted thawing	**-Refrigerator thawing-** Temperature: 4 ± 1°C **-Air thawing-** Temperature: 20 ± 2°C **-Water immersion thawing-** Temperature: 20 ± 1°C **-Ultrasonic-assisted thawing-** Temperature: 20 ± 1°C Frequency: 43 kHz Power: 200 W	Product size/shape: Whole sea cucumber (elongated, cylindrical) Driving forces: Refrigerator: Slow conduction Air: Convection Water immersion: Conduction and convection Ultrasonic: Acoustic cavitation and mechanical agitation	-» It was determined that ultrasonic thawing occurred in the shortest time. -» It was determined that the water retention capacities, hardness values, and rheological properties of the samples in the refrigerator thawing method showed the best results. Ultrasonic thawing samples followed these. -» It was determined that the water immersion and air thawing methods showed more curling and breaking in the microstructures of sea cucumbers, which were more prone to the deterioration of protein thermal stability and the destruction of protein structure. -» It was emphasized that the ultrasonic thawing method could preserve the quality of frozen, ready-made sea cucumbers in the shortest time.	Ge et al. (2022)
Cuttlefish	➢ Hydrostatic thawing ➢ Flowing water thawing ➢ Saline solution thawing ➢ Ultrasonic water thawing ➢ Microwave thawing ➢ 4°C refrigerator thawing	**-Hydrostatic thawing -** Temperature and area: 25 ± 1°C/water bath **-Flowing water thawing-** Temperature and area: 25 ± 1°C water Flow rate: 25 mL/s **-Saline solution thawing-** Temperature: 25 ± 1°C Area: saline solution with a concentration of 3.0% **-Ultrasonic water thawing-** Temperature: 25 ± 1°C Frequency: 53 kHz Power: 200 W **-Microwave thawing-** Area and mode: microwave oven/defrost mode **-Refrigerator thawing-** Temperature and area: plastic tray in a refrigerator at 4°C	Product size/shape: Whole cuttlefish (oval, soft-bodied) Driving forces: Hydrostatic: Pressure and conduction Flowing water: Convection and conduction Saline solution: Osmosis and conduction Ultrasonic: Acoustic cavitation and mechanical agitation Microwave: Dielectric heating Refrigerator: Slow conduction	-» It was found that microwave thawing time was the shortest, but after thawing, the samples' water-holding capacity was the worst, and the total volatile base nitrogen content was the highest. -» The ultrasonic thawing method had the best water-holding capacity, but the ultrasound technique promoted the oxidation of protein and fat. -» Microscopic observation showed that the muscle fiber bundles in the samples thawed in saline solution were compactly arranged and intact with minimal gaps. This shows that the samples thawed in saline solution had the highest hardness and chewiness. -» The comprehensive analysis results show that saline solution thawing and ultrasonic water thawing are more suitable methods for thawing cuttlefish.	Lv and Xie (2022)

(Continues)

TABLE 1 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Tuna fish	➢ Ohmic thawing ➢ Conventional thawing	**- Ohmic thawing-** Temperature: −18 to −7°C Voltages: 40, 50, and 60 V Electrical conductivities: three brine concentrations (3, 4, and 5 g/L), their electrical conductivities were 6.083, 8.17, and 9.32 (σ, mS/cm), respectively. **-Conventional thawing-** Temperature and area: 25°C/the air; 40 and 27°C/the water	Product size/shape: Not specified (likely large fish pieces) Driving forces: Ohmic: Joule heating Conventional: Convection (air) and conduction (water)	-» Thawing rate plays a vital role in food quality. The ohmic method (0.2 g/s, average of the ohmic group) had significantly higher quality values than the traditional thawing methods (0.15 g/s, average of the traditional group). -» It was stated that the immersion ohmic dissolution method increased the dissolution rate by approximately five times. -» The physicochemical analyses applied in the study emphasized a significant difference between the ohmic and traditional processes in terms of protein solubility, dissolution evaporation, and dissolution loss.	Keshani et al. (2022)
Mackerel (Pneumatophorus japonicus)	➢ Flowing water thawing ➢ Ultrasonic flowing water thawing ➢ Air thawing ➢ Microwave thawing ➢ Low temperature thawing	**-Flowing water thawing-** Temperature: 20 ± 1°C. **-Ultrasonic flowing water thawing-** Temperature: 20 ± 1°C. Power: 200 W **-Air thawing-** Temperature: 20 ± 1°C. **-Microwave thawing-** Power: 400 W. **-Low temperature thawing-** Temperature: 4°C	Product size/shape: Whole fish (elongated, cylindrical) Driving forces: Water thawing: Conduction and convection Ultrasonic: Acoustic cavitation and mechanical agitation Air thawing: Convection Microwave: Dielectric heating Low temperature: Slow conduction	-» Low-temperature thawing was found to have the best water retention and lower protein and fat oxidation. -» It was emphasized that microwave thawing had the shortest thawing time, but uneven heating could lead to partial maturation. -» It is thought that air thawing and prolonged exposure to air could lead to high protein and fat oxidation levels. -» It was found that flowing water thawing had better water retention than ultrasonic flow water thawing, but the thawing time was slightly longer than ultrasonic flowing water thawing. -» Flowing water thawing showed good performance in a short time and was a suitable method for thawing frozen mackerel.	Zhou and Xie (2021)

(Continues)

TABLE 1 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Tuna fish	➢ Ohmic thawing	**- Ohmic thawing-** Temperature: -18 to $-7°C$ Voltages: 40–60 V Frequency: 50 Hz; NaCl solutions 0.3–0.5% (at 25°C)	Product size/shape: Not specified Driving force: Joule heating	-» It was found that the ohmic dissolution method significantly reduced the thawing time of frozen tuna cubes. -» The thawing time was 5.95 times shorter in the ohmic method (50 V—0.3% salt water) than in conventional conditions. -» When the ohmic processes (group 1) were compared with the conventional methods (group 2), the dissolution and total loss rates in group 1 were significantly lower than in group 2.	Fattahi and Zamindar (2020)
Nile tilapia fillets	➢ Cold air thawing ➢ Ambient air thawing ➢ Cold water thawing ➢ Water at normal temperature	**-Cold air thawing-** Temperature: $7 \pm 1°C$ **-Ambient air thawing-** Temperature: $30 \pm 1°C$ **-Cold water thawing-** Temperature: $8 \pm 1°C$ **-Water at normal temperature thawing-** Temperature: $30 \pm 1°C$	Product size/shape: Fillets (thin, flat pieces) Driving forces: Air thawing: Convection Water thawing: Conduction and convection	-» It has been stated that thawing in cold air is the most suitable method compared to thawing in ambient air or water at normal temperatures. -» It has been determined that thawing at normal temperature (in air or water) leads to significantly higher total viable counts and *Pseudomonas* spp. counts. -» It has been emphasized that slow thawing in cold air ($7 \pm 1°C$) is the most suitable method for *Nile tilapia* fillet product or similar ones processed and frozen in pre-rigor mortis.	Mai et al. (2020)
Minced fish	➢ Radiofrequency thawing	**- Radiofrequency thawing-** Temperature: 20°C Power/frequency: 6 kW/27.12 MHz Electrode gap: 14, 16, 18, 20, and 24 cm	Product size/shape: Minced (likely uniform consistency) Driving force: Electromagnetic field-induced heating	-» In order to provide the size of frozen minced fish blocks commonly used in the industry ($25 \times 15 \times 5$ cm), the most suitable electrode spacing in the thawing method was determined to be 16 cm. -» It was emphasized that radiofrequency thawing did not affect the cooked gel properties after thawing, which proves that the system is optimum for use in industrial production.	Yang et al. (2019)

TABLE 2 Application of the thawing methods to fruits, vegetables, bakery products, and other foods.

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Fruits and vegetables					
Mango	➢ High-pressure thawing	**Microwave thawing, high-pressure thawing, air thawing, and water thawing** Temperature: 20°C Power: 100, 200, and 300 W Pressure: 75, 100, and 125 MPa	Product size/shape: Not specified Driving force: Pressure-induced phase transition	-» Microwave and high-pressure thawing shortened the thawing time compared to air and water thawing -» Less color change and drip loss were obtained, but the loss of vitamin C increased	Peng et al. (2022)
Mango	➢ Ultrasound thawing	Aqueous submersion Sonic wave-assisted method Environmental conditions: 4°C and 25°C Sonic energy intensity: 0.037, 0.074, and 0.123 W/mL Vibrational frequency: 28 kHz	Product size/shape: Not specified Driving force: Acoustic cavitation and mechanical agitation	-» Defrosting duration reduced by 16–64% -» Sonic waves did not adversely impact color attributes -» Sonic-assisted thawing at room temperature (25°C) yielded superior sensory characteristics compared to refrigerated conditions (4°C)	Li et al. (2019)
Apple	➢ Microwave thawing	Electromagnetic radiation exposure Vacuum-assisted electromagnetic radiation Atmospheric exposure Environmental conditions: 20°C Energy input: 300 W	Product size/shape: Not specified Driving force: Dielectric heating	-» Both electromagnetic radiation techniques accelerated the thawing process -» Vacuum-assisted electromagnetic radiation prevented sample overheating -» Vacuum-assisted electromagnetic radiation enhanced tissue firmness, as evidenced by increased breaking strain and maximum stress values	Watanabe and Ando (2021)
Potato	Microwave thawing	Ambient air exposure Electromagnetic radiation Environmental conditions: 23°C Energy input: 10%ower		-» Texture degradation in defrosted potatoes was comparable between ambient air and electromagnetic radiation methods -» Microscopic analysis revealed similar cellular structures in potatoes frozen via high-velocity air freezing (HVAF) and static air freezing, indicating maximum matrix damage in both scenarios	Phinney et al. (2017)
Spinach puree	Ohmic thawing	Electrical resistance heating Controlled low-temperature storage Electrical parameters: • Voltage gradients: 10 and 15 V/cm • Distance between electrodes: 10 cm	Product size/shape: Puree (likely uniform consistency) Driving force: Joule heating	-»Electrical resistance heating accelerated the defrosting process by 70–80% compared to controlled low-temperature storage -» Controlled low-temperature storage exhibited higher energy dissipation than electrical resistance heating -» Peak energy efficiency (64.2 ± 4.0%) was achieved with electrical resistance heating at 15 V/cm establishing it as the ideal operating condition	Çabas et al. (2022)

(Continues)

TABLE 2 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Bakery products					
Dough	➢ Ultrasound thawing ➢ Proofer thawing ➢ Refrigerator thawing ➢ Water bath thawing ➢ Ambient thawing ➢ Microwave thawing	**-Ultrasonic thawing-** Temperature: 25°C Frequency: 40 kHz Power: 60 W/L **-Proofer thawing-** Temperature: 30°C Humidity: RH 80% **-Refrigerator thawing-** Temperature: 4°C **-Water bath thawing-** Temperature: 25°C **-Ambient thawing-** Temperature and area: 25°C/air. **-Microwave thawing-** Temperature: 4°C Power: 200 W	Product size/shape: Not specified Driving force: Acoustic cavitation and mechanical agitation	-» It has been stated that ultrasonic thawing dough has better physicochemical properties than other doughs. -» It has been determined that ultrasonic thawing limits water migration of the dough, improves its rheological properties and fermentation capacity, effectively reduces the spoilage of frozen dough, and promotes the continuity and integrity of the gluten network structure of the dough, thus showing a higher specific volume and a softer texture.	Zhang et al. (2024)
Nonfermented wheat dough	➢ Refrigerator thawing ➢ Conventional thawing ➢ Microwave thawing	**-Refrigerator thawing-** Temperature: 4°C for 6 h **-Conventional thawing-** Temperature: 25°C Humidity: RH 85% for 1 h **-Microwave thawing-** Power and time: 1000 W for 25 s	Product size/shape: Not specified Driving forces: Varied (convection, conduction, dielectric heating)	-» It was found that thawing in the refrigerator (4°C) produced a dough with minimal changes in rheological properties, regardless of the duration of frozen storage. -» It was stated that microwave thawing showed lower G′ and lower zero shear viscosity ($\eta 0$) values and higher maximum creep compliance (J_{max}) and hardness. -» It was determined that combining long-term frozen storage with microwave thawing severely damaged the dough’s rheological properties, structural stability, and inner microstructure.	Yang et al. (2023)

(Continues)

TABLE 2 (Continued)

Food	Method	Method parameters and thawing technique	Key process parameters	Results	References
Doughs	➢ Refrigerator thawing ➢ Ambient thawing ➢ Proofer thawing ➢ Microwave thawing	**-Refrigerator thawing-** Temperature: 4°C **-Ambient temperature thawing-** Temperature: 20°C **-Proofer thawing-** Temperature: 30°C Humidity: 85% relative humidity **-Microwave thawing-** Power: 100 and 300 W	Product size/shape: Dough (likely in loaf or ball form) Driving forces: Refrigerator: Slow conduction Ambient: Natural convection Proofer: Controlled convection and humidity Microwave: Dielectric heating	-» It was found that thawing frozen dough in the microwave caused an irregular temperature profile and high weight loss. -» It was determined that the microwave shortened the thawing times and caused the dough samples to have irregular temperature distribution. -» The highest weight loss was found in samples thawed in the microwave, followed by samples thawed at ambient temperature, in the refrigerator, and in the proofing vessel. -» Dough samples thawed in the proofing vessel and in the microwave tended to have lower and higher mixing resistance, respectively. -» It was reported that thawing in the microwave produced doughs with higher storage and loss moduli, which correlated with a more complex and chewy texture. -» It was emphasized that dough thawed in the refrigerator and at ambient temperature produced bread samples with a softer texture and higher loaf volume.	Yang et al. (2020)
Other foods					
Tofu	➢ High-voltage electric field-assisted thawing	**-High-voltage electric field-assisted thawing-** Temperature: 20°C ± 1°C Distance between the electrodes: 100 mm Voltage: 28 kV	Product size/shape: Not specified Driving force: High-voltage electric field-induced heating	-» It has been emphasized that the high-voltage electric field-assisted thawing method improves the quality of thawed food.	Ding et al. (2018)

usually water. Next, we impart the pressure to the food. This technique allows frozen foods to thaw rapidly under low-temperature, high-pressure conditions, which inhibits spoilage from microorganisms and enzymes while preserving the product's quality (Köprüalan Aydın et al., 2023). A significant temperature difference between the thawing food, and its surroundings enhances the process by increasing the thermodynamic driving force (Cai et al., 2019a). Importantly, in HPT, product size and shape are critical variables that influence the effectiveness and distribution of applied pressure. Larger and nonhomogeneous products may require longer thawing times and result in increased energy consumption. Additionally, HPT has been shown to reduce ascorbic acid loss and maintain the texture and color of fruits and vegetables during thawing, improving overall product quality (Peng et al., 2022). Although HPT systems offer advantages like shorter thawing times, microbial control, and reduced drip loss, they come with downsides. These include high costs, potential changes in protein structure, and color alterations in some foods (Cartagena et al., 2020; Cui et al., 2019).

3.2.2 | Microwave thawing

Microwave thawing is a highly efficient method that offers several advantages, including reduced thawing time, energy conservation, and ease of operation, making it widely utilized in both commercial and household settings (Cai et al., 2018). This process essentially converts electromagnetic energy into thermal energy by directly interacting with the material being treated, eliminating the need for heat to diffuse from the surface inward. This allows for rapid thawing, as water molecules within the material are agitated, facilitating a more uniform energy distribution compared to conventional methods. For instance, in meat thawing, MT significantly reduces thawing time and lowers the risk of microbial contamination (Zhu et al., 2019), while enhancing the nutritional properties and acceptability in certain food products, such as meats and frozen fruits (Peng et al., 2022). However, its practical application in meat processing is somewhat limited by the microwave's shallow penetration depth, which can result in uneven heating and localized overheating, complicating the thermal conversion process (Cai et al., 2018). In order to minimize the nonuniform temperature distribution in MT, product dimensions should be optimized, and microwave energy should be evenly distributed across the sample.

Despite its advantages, the limitations associated with MT restrict its broader applicability, particularly in industrial food processing, where precision and uniformity are critical. The primary challenge lies in the uneven heating patterns caused by the microwave's shallow penetration, often resulting in partially thawed areas and localized overheating. This issue is further exacerbated in larger food items, where heat may not be uniformly distributed across the product, leading to quality degradation and compromised safety. In response to these challenges, researchers have explored the integration of microwave technology with alternative methods to enhance thawing efficiency and product quality. For instance, Cai et al. (2019b) investigated the combination of ultrasound and MT for frozen largemouth bass. Their findings indicated that the viscoelastic properties of proteins in samples thawed using this combined method were more similar to those of fresh samples, resulting in thawed products that demonstrated both protein stability and gelation characteristics. This combined approach significantly improved the texture and sensory quality of the thawed fish, making it a promising alternative for industrial applications, where protein integrity is crucial. In a similar study, Cao et al. (2018) used a combination of microwaves and magnetic nanoparticles to thaw red snapper. Their experimental findings showed that proteins in red snapper thawed with this integrated method retained stability and displayed enhanced gel properties, as well as stable secondary and tertiary structures. The use of magnetic nanoparticles facilitated more efficient heat distribution within the sample, mitigating the issues of uneven heating traditionally associated with MT. Despite the potential of these advanced methods, they remain challenging to implement in typical home kitchen thawing practices, where simplicity and ease of use are paramount. While these techniques offer promising improvements in thawing efficiency and product quality, their complexity and cost may limit their adoption to specialized industrial processes rather than everyday household use. As research in this area continues to evolve, it is expected that future innovations may address these practical limitations, potentially making microwave-assisted thawing technologies more accessible to a broader range of users (Hu et al., 2023).

3.2.3 | Ohmic thawing

Ohmic thawing is an innovative electrical heating method increasingly used for thawing various food products, offering notable advantages over conventional thawing techniques. The key principle behind this method is the passage of electrical current through the food, which generates heat internally due to its inherent electrical resistance. This process, referred to as volumetric heating, ensures more uniform heat distribution throughout the product compared to external heating methods like conventional or MT (Chen et al., 2022; Döner et al., 2024). As a result, OT greatly shortens thawing time while maintaining the quality of food products, mainly by reducing the risk of surface microbial growth and enhancing energy efficiency (Çabas et al., 2022; Fattahi & Zamindar, 2020).

In contrast to direct-current ohmic heating, which can lead to electrolysis, degradation of food components, and electrode corrosion, causing contamination, alternating-current OT reduces these problems. The heat generated by alternating current is inversely related to the resistance of the food material, leading to less electrolytic transformation and a cleaner heating process (Cai et al., 2019a). Consequently, OT primarily utilizes alternating current at appropriate voltage levels, where the electrical resistance of the food is transformed into heat, providing a more efficient and safer method of thawing.

A major advantage of OT is its ability to maintain the physicochemical properties of foods, such as color, texture, and lipid oxidation, due to the reduced mechanical damage associated with traditional thawing methods (Fattahi & Zamindar, 2020). Studies on minced meat and fish products have demonstrated that OT causes less drip loss and protein degradation compared to conventional methods (Cevik & Icier, 2021). Additionally, the process has been shown to be particularly effective for minimizing ascorbic acid degradation in fruit-based products when performed at lower voltage gradients, further enhancing its appeal in food processing (Mercali et al., 2012).

Despite its advantages, OT presents certain challenges, particularly in ensuring uniform electrode contact with the food, which is critical for preventing local overheating and nonhomogeneous thawing. Variations in the electrical conductivity of different regions within a food product, particularly those with heterogeneous compositions like meat, can result in uneven heating and potential cold spots (Cevik & Icier, 2021; Döner et al., 2024). This issue is exacerbated by changes in food volume during thawing, which may impair consistent contact between the electrodes and the food surface. In OT processes, the use of adaptable surfaces in electrode design for different product shapes is recommended. To address these challenges, researchers have focused on optimizing electrode designs and process conditions to ensure more uniform heat distribution (Cokgezme et al., 2021). According to Cokgezme et al. (2021), factors like the shape of the sample, voltage gradient, and the form of the electrode surface play a crucial role in determining the exergoeconomic performance of the process. Cylindrical samples, for instance, tend to experience lower exergy efficiency due to greater heat losses and poor electrode contact. Moreover, different electrode surface designs, particularly needle-type and pyramid-type electrodes, have shown improved contact, reducing inefficiencies and preventing overheating (Döner et al., 2024). Such findings underscore the importance of optimizing both equipment and process parameters to mitigate the inherent challenges of OT, ensuring better uniformity in heat distribution and enhancing overall efficiency.

Recent developments in the field have focused on the effects of various factors, such as voltage gradients and fat content, on the efficiency and quality of the thawed product. Higher fat content in meat, for example, has been associated with lower electrical conductivity, resulting in longer thawing times (Indiarto & Rezaharsamto, 2020). Similarly, the selection of appropriate voltage gradients has been shown to minimize product degradation, ensuring better retention of texture and moisture content (Cevik & Icier, 2021; Cokgezme et al., 2021). Additional research has emphasized the need for continuous and full contact between the electrodes and the food, with some studies suggesting the use of electrolytic solutions to ensure consistent contact and uniform heating (Fattahi & Zamindar, 2020). In conclusion, OT represents a promising technology in food processing, offering faster, more energy-efficient, and higher-quality thawing compared to conventional methods. While challenges related to uniform heating and electrode contact persist, ongoing research and technological advancements continue to improve the efficacy and reliability of this method across a wide range of food products, from meat to fruit purees.

3.2.4 | Acoustic thawing/ultrasound-assisted thawing

The application of acoustic energy for thawing frozen foods was explored approximately five decades ago (Cai et al., 2019a). UAT has emerged as a promising method for accelerating the thawing process while maintaining food quality. Ultrasonic technologies expedite thawing by increasing the absorption of energy, especially at the interface between thawed and frozen regions, which allows for faster heat transfer compared to conventional methods (Cai et al., 2019b). This increased efficiency stems from the cavitation effect, where ultrasonic waves cause the formation and collapse of vapor bubbles, leading to microstreaming and enhanced energy transfer to the thawing medium (Guo et al., 2021). However, the effectiveness of UAT is influenced by product size and shape, as these factors impact the transmission of ultrasonic waves and energy distribution within the product. When ultrasonic waves pass through frozen foods, like meat, an amount of the energy is converted into heat, aiding the thawing process. The surface temperature escalates rapidly, while the core temperature ascends more slowly. Upon beyond the original freezing point, the tissue next to the thawed-frozen barrier absorbs more energy, accelerating the thawing process. Ultrasound's physical effects, such as high-speed jets and uneven bubble collapse, improve heat transfer and help move the frozen-thawed boundary forward, shortening thawing times (Cai et al., 2019a). UAT has demonstrated superior performance in reducing thawing times across various food types, including mango pulp, pork, and chicken breasts, with reductions of up to 80% (Gambuteanu & Alexe, 2015; Liu et al., 2019).

Even though UAT significantly improves thawing efficiency, its impact on food quality is complex. Moderate power ultrasound enhances tenderness, improves water retention, and promotes the gelling properties of proteins, but excessive power can lead to cell disruption, degradation of pigments, and lipid oxidation, negatively affecting food texture and flavor (Guo et al., 2021). Moreover, the ultrasonic cavitation process can induce localized overheating, which may result in oxidative degradation and increased drip loss, particularly at high frequencies (Cai et al., 2018). These limitations, along with the fact that UAT generally requires a longer duration than MT, highlight the need for careful control of ultrasound parameters to minimize quality degradation (Cai et al., 2019b; Zhu et al., 2023). Despite these challenges, ultrasound has been shown to have minimal negative effects on pH and microbial growth in pork, as well as on the sensory properties of fish like Pacific cod, making it a highly viable option for food thawing, when properly optimized (Wang et al., 2022). As such, UAT continues to be a valuable tool for the food industry, offering a balance of efficiency and quality, while mitigating the risks associated with conventional thawing techniques (Qiu et al., 2020).

3.2.5 | High-voltage electrostatic field thawing

Electrostatic field -assisted thawing is an innovative technology aimed at improving the quality of frozen food. Initially developed to reduce thawing losses and shorten thawing time, EF thawing has shown potential economic benefits, including reduced purge loss and faster thawing rates (Corrette et al., 2024). Qian et al. (2019) found that applying a 2.5 kV voltage to frozen beef striploins cut thawing time by 42% and reduced purge loss by approximately 20% (Qian et al., 2019). This observation was corroborated by Jia et al. (2017), who utilized EF at 20 kV on frozen rabbit meat, demonstrating a 60% reduction in thawing time and a 30% decrease in purging loss. EF-assisted thawing has shown efficacy in enhancing quality attributes, including the reduction of lipid oxidation in rabbit meat and the decrease of microbial loads in pig tenderloins (Jia et al., 2017).

HVEF thawing is an important nonthermal food processing method that has gained significant attention in recent years, primarily in research for thawing various food products such as pork, tuna, chicken, rabbit meat, shrimp, common carp, tofu, and apple tissue (Ding et al., 2018). In the literature, the application of HVEFs typically ranges from 105 to 106 V/m (Wang et al., 2019). HVEF is a novel thawing technique that has been widely used, since the 1960s for purposes such as sterilization, drying, and preserving freshness (Cai et al., 2019a). Compared to other thawing methods, HVEF thawing is faster and results in higher-quality products (Jia et al., 2018). The HVEF process works by generating an electrical wind through corona discharge, and involves the ionization of air within a needle-plate electrode setup via corona discharge. The ions produced around the needle electrodes are then accelerated by the electric field, transferring momentum to neutral air molecules, which helps move the bulk fluid toward the surface (Rahbari et al., 2018). The corona wind's ability to generate turbulence and vortices, which may improve heat transmission, causes the thawing rate to rise. Different thawing speeds may be caused by changes in voltage, the distance between the needle-shaped corona electrodes, and the spacing between the electrodes (Cai et al., 2019a).

HVEF thawing offers numerous advantages over typical thawing technologies, including decreased thawing time, preservation of food quality, prevention of microbiological development, and lower energy use. The thawing process can be conducted using either alternating current or direct current high voltages. Multipoint and plate electrode techniques are effective in expediting the thawing of frozen materials (Bai et al., 2017). HVEF thawing also provides benefits such as high efficiency, low equipment costs, and ease of operation, making it a promising area of research. He et al. (2013) found that, after 5 days of post-thaw storage, the volatile basic nitrogen levels increased from 10.64 to 16.38 mg/100 g with an applied voltage of 10 kV, while in the control group, the levels rose from 10.66 to 19.87 mg/100 g. This indicates that HVEF thawing not only accelerates the thawing process of pork but also helps extend the product's shelf life (He et al., 2013). HVEF thawing might decrease protein solubility by decreasing the electrode gap, hence amplifying the corona effect (Rahbari et al., 2018). It was stated that the utilization of HVEF for thawing pork tenderloin can decrease the duration and, consequently, impede protein oxidation and lipid peroxyl radical formation (Jia et al., 2018).

3.2.6 | Pulsed electric field thawing

Electric fields are extensively utilized in food processing, encompassing auxiliary frying, extraction, drying, and preservation. PEF treatment utilizes short voltage pulses (in microseconds) with elevated electric field intensity applied to samples positioned between two electrodes. Prior research has shown that the implementation of PEF as a treatment can enhance mass and heat transfer processes (Li et al., 2020). The primary distinction between PEF and low-voltage electric fields is the square wave nature of the PEF, which exerts stronger bioelectric effects on organisms within the electric field. As a result, PEF is commonly used for short-term sterilization or inhibiting enzyme activity (Chang et al., 2023).

PEF thawing is an energy-to-heat conversion process that does not include heat. It entails speeding the dissolution of hydrogen bonds by transferring energy from ice to water. Placing the meal between electrodes and delivering brief, high-voltage pulses is the method used (Cai et al., 2019a). The thawing durations of materials treated with PEF are much shorter than those of untreated samples (Wiktor et al., 2015). The first applications of PEF were to increase the transfer of mass in plant and animal tissues and to make liquid items last longer on the shelf. Electroporation can be classified into two categories: reversible and irreversible, depending on the optimization of electric field parameters, including intensity, frequency, pulse width, and waveform (Velickova et al., 2018). Reversible electroporation generates temporary pores that can subsequently shut, facilitating the trapping of desired components within cell membranes. Irreversible electroporation eliminates cells by irreversible membrane damage and is typically employed in microbial inactivation processes and to enhance extraction yield (Đukić-Vuković et al., 2017; Teissie et al., 2005). PEF operating settings and target meal properties primarily determine whether electroporation is reversible or irreversible. Previous research has indicated that the electrical wind produced via corona discharge can enhance the thawing rate in PEF-assisted thawing (Liu et al., 2017). Upon positioning the frozen food at the center of the stage, the corona discharge on the electrode's surface would ionize the air, augment the velocity of ions, and convey kinetic energy to the food. Simultaneously, the ions adhered to the surface, augmenting convective heat and mass transport (Jia et al., 2019). Jia et al. (2018), indicated that, in contrast to conventional air thawing, employing 10 kV HVEFs to thaw pork significantly diminishes damage to muscle proteins and preserves gel properties, softness, and water retention levels. In a study conducted with PEF-assisted thawing on duck meat, the process can successfully prevent the denaturation of duck myofibrillar protein and maintain the processing appropriateness of duck meat, including gelation and emulsification. It was demonstrated that PEF-assisted thawing is an innovative method that enhances the quality of processed meat products and minimizes processing losses (Chang et al., 2023).

3.2.7 | Radio frequency thawing

Electromagnetic waves with frequencies below 100 kHz are absorbed by the Earth's surface, whereas those above 100 kHz can propagate through the atmosphere. Radiofrequency waves are a kind of electromagnetic radiation that have wavelengths between 300 kHz and 300 GHz. The creation of an alternating field between the two electrodes causes bipolar molecules, such as charged ions in water and food components, to become polarized. As a result, the molecules continually reposition themselves toward the poles. Radio frequency and microwave systems are similar, although radiofrequency applications have deeper penetration (Zhang et al., 2022). The thawing technologies utilizing the electromagnetic wave-heat conversion mechanism generally encompass radio frequency thawing and MT, which vary in frequency and the method of electromagnetic wave creation. RFT could penetrate frozen muscle foods more effectively, offering superior potential for uniform heating of food products due to its narrower frequency range (1–300 MHz), compared to MT (300 MHz–300 GHz) (Huang et al., 2016; Ramírez-Rojas et al., 2020).

When food products are subjected to RFT, polar molecules initiate dipole rotation in response to the changing field, thereby converting electromagnetic wave energy into heat, resulting in the thawing of frozen food. Applying alternating electrical fields to frozen food causes the dissociated ions to vibrate, producing heat through molecular friction (Cai et al., 2019a). To create the induction coupling, the load material and electrodes come together. According to Guo et al. (2019), in order to align the load materials with the generator's resistance and establish a constant coupling of radio frequency energy, the automated tuning adjusts the total impedance to 50 ohm.

Thawing processes increasingly utilize radiofrequency technologies. The volumetric heating properties of radiofrequency technology facilitate expedited thawing durations and consistent temperature distribution during the RFT of food items. This provides an advantage for defrosting larger quantities of food (Zhang et al., 2022). The RFT procedure utilizes the electromagnetic field generated by parallel electrodes to facilitate thawing (Köprüalan Aydın et al., 2023). Recently, the commercial application of radio frequency for thawing frozen blocks of meat and seafood has been implemented by companies like SAIREM SAS (France), SONAR (Türkiye), Stalam (Italy), and Yamamoto Vinita (Japan), offering many advantages over conventional thawing methods and microwave applications. These advantages encompass decreased thawing duration and reduced product quality degradation due to the volumetric heating property with extended penetration depth. The radio frequency technique enables deep penetration, attributed to its longer wavelength (about 11 m at a frequency of 27.12 MHz), and facilitates the heating of food materials even within their packaging. Radio frequency technology has the drawback of causing uncontrolled heating when used for thawing. The analysis suggests that runaway heating is linked to food composition, with high-fat diets being the most problematic (Llave & Erdogdu, 2022). Moreover, the constraints of the radiofrequency application arise from the uneven distribution of heat throughout the product, especially at the edges, corners, and surfaces (Wu et al., 2017).

3.2.8 | Other new thawing technologies

In recent years, research has increasingly concentrated on physical field techniques to enhance freezing and thawing effects through rapid freezing, including ultrasound, microwave, far infrared, high pressure, electric field, magnetic field, and radio frequency. In comparison to rapid freezing and thawing alone, the utilization of effective physical field aid or combined processes may improve the quality of frozen products and decrease energy usage. Additional potential benefits of effective physical field aid are progressively becoming apparent (Jiang et al., 2023). Fan et al. (2020) developed an innovative technique of osmotic-dehydrofreezing utilizing ultrasound for kiwifruit. The utilization of ultrasound decreased freezing duration, minimized drip loss, and successfully preserved the characteristics of kiwifruit (Fan et al., 2020).

Thermal processes, including microwave, dielectric, and resistive thawing, offer the advantages of speed and simplicity; however, they present issues such as unequal heating, favored surface warming, and elevated energy usage. Although nonthermal methods such as vacuum thawing, ultra-high pressure, and ultra-high ultrasound may lessen denaturation of food quality, they can be difficult to apply, do not always permeate samples, and can cause physiochemical changes and microbial growth (Cai et al., 2019a). Numerous novel thawing technologies, including hybrid or combination procedures, have been developed and studied in order to solve the limitations associated with various thawing techniques. Most of them are laboratory-scale and lack commercial applicability.

Thermal and nonthermal thawing methods can be combined for enhanced results. For instance, in order to defrost red seabream fillets, it is possible to combine suction with microwave or ultrasound (Cao et al., 2018). Vacuum thawing can mitigate some of the side effects of microwave and ultrasound therapies by keeping the temperature down. The findings demonstrated that the combination of these strategies was more effective than each strategy alone in preserving actin's thermal stability and tertiary structure. To address the uneven temperature distribution often seen during MT, various techniques can be employed to reduce significant temperature variations. Combining MT with conventional heating can lead to more uniform heating, and using air jet impingement or infrared heating alongside MT can also help reduce temperature disparities (Cai et al., 2018).

Prior research indicated that components such as free radicals, active oxygen, and active nitrogen present in plasma-activated wate can degrade the lipids and proteins of microorganisms (Thirumdas et al., 2018), thereby exhibiting a potent bactericidal effect that effectively inactivates *Salmonella*, *Staphylococcus aureus*, *Escherichia coli*, and other food spoilage and pathogenic bacteria. Nonetheless, the investigation into PAW predominantly centers on the immersion and sterilizing of fruit and vegetable items. To solve the issues of microbial contamination and protein degradation associated with traditional thawing methods, a novel frozen meat thawing medium was employed to decrease the effects of microbial contamination on chicken and enhance the properties of PAW and ultrasound (Qian et al., 2022).

A study explored the use of slightly acidic electrolyzed water thawing combined with ultrasound to assess its impact on the quality, nutrients, and microstructure of frozen meat. The samples were thawed in an ultrasonic bath containing 12.5 L of SAEW, and the samples were placed in a wash basket. The ultrasound, operating at a frequency of 80 kHz and an output power of 300 W, was applied within a low-frequency range (20–100 kHz) and high intensity (10–1000 W/cm^2). The ultrasound-assisted slightly acidic electrolyzed treatment effectively controlled lipid oxidation in the samples and minimized nutrient loss during thawing. Additionally, the microstructure of the meat treated with UAET remained more intact and compact compared to those thawed using traditional methods. Overall, UAET proved to be a promising thawing technique that helps preserve the quality, nutritional value, and microstructure of thawed meat products (Kong et al., 2023).

The temperature during thermal thawing methods, including microwave, RF, and OT, is nonuniform, resulting in warm areas becoming focal points for increased power dissipation. Excessive heating may lead to overcooked areas of food that are not fully thawed. Prior research on biomaterials resulted in swift and uniform heating by the integration of radiofrequency and magnetic nanoparticles (Eisenberg et al., 2016; Manuchehrabadi et al., 2017; Wang et al., 2016). Magnetic nanoparticles transition to a paramagnetic state upon heating, hence enhancing heat conduction due to the vigorous motion of polar molecules in, for instance, fish tissue. Magnetic nanoparticles utilized alongside microwave or far-infrared thawing resulted in more consistent thawing (Cai et al., 2019a).

Chen et al. (2023) conducted a study to enhance the novel vacuum sublimation–rehydration thawing method to ensure superior quality of thawed meat, optimize the thawing rate, and reduce energy consumption, thereby offering innovative insights for the advancement of high-efficiency thawing apparatus. The results indicated that the developed regression equations closely aligned with the experimental values (Chen et al., 2023). Vacuum steam thawing technology is a technique that utilizes latent heat from the condensation of water vapor to heat frozen goods. The process entails heating a water tank to temperatures ranging from 7°C to 90°C, resulting in vaporization into steam. The steam then infiltrates the frozen meat, condensing and emitting heat. VSTT is recognized for its superior production efficiency, little energy usage, and capacity to inhibit oxidative damage, in contrast to microwave or high-frequency thawing techniques (Chen et al., 2020).

A different study explored the use of multi-frequency ultrasonic thawing on pork, examining the effects of ultrasonication on thawing rate, physicochemical properties, water migration, distribution, and microstructure with various frequency combinations (mono-, dual-, or tri-frequency in sequential and simultaneous modes). The results showed that ultrasonic-assisted thawing increased the thawing rate and reduced thawing time by 26.72–64.99%, compared to water immersion thawing, while also helping to reduce lipid oxidation. The optimal ultrasonic frequency and power are essential for preserving the quality of thawed food and accelerating the procedure. The frequency and intensity of ultrasound dictate the development and potency of ultrasonic cavitation. Contemporary studies concentrate on UAT at various power levels; nevertheless, there is a paucity of study about the impacts of temperature, combinations of ultrasonic frequencies, and operating modes (Chen et al., 2024). The impact of IRT + MT on frozen pork was compared to fresh air thawing, IRT, and MT. The IRT + MT was identified as an exceptional thawing technique, demonstrating high thawing efficiency, while inflicting minimal damage to product quality. The IRT + MT demonstrates superior performance in the quality of thawed pork. The dimensions and volume of the samples significantly influence the quality of thawed pork. Consequently, additional studies must be undertaken to validate the commercial application of IRT + MT (Hu et al., 2023).

4 | COST EFFECTS OF DIFFERENT THAWING TECHNIQUES IN FOOD PRODUCTS

The cost of thawing food can vary significantly depending on the method. Conventional thawing methods like air, vacuum, and water thawing are often costly and inconvenient. They can also degrade food quality and accelerate microbial growth under suboptimal conditions (Qiu et al., 2020; Zhang et al., 2023a). Innovative technologies like OT, MT, UAT, RFT, PEF, high-voltage electrostatic field, magnetic field, and HPT can provide viable, cost-effective solutions that offer rapid thawing and improved quality, while minimizing nutrient and quality loss (Chen et al., 2024; Mohsenpour et al., 2023; Xiao et al., 2024; Zhang et al., 2021b). However, their initial investment, operational, and maintenance costs may present a barrier, emphasizing the need for a balanced, cost-effective approach to food thawing (Balthazar et al., 2024). While these costs vary across techniques, strategically integrating these methods can reduce energy consumption and processing times, promoting sustainability and lowering operational costs in the food industry. An industrial technique should consider economic cost, energy consumption, efficiency, throughput, and practicality. Therefore, assessing the costs of these thawing methods is crucial to determining the most suitable option for different food types (Köprüalan Aydın et al., 2023).

OT, for example, offers a sustainable and cost-efficient solution in food processing, providing a faster, energy-efficient alternative to traditional methods. It reduces thawing times by 64–87% for frozen minced beef, while minimizing protein denaturation and enhancing physicochemical, sensory, and textural qualities. Despite these benefits, high initial costs, uneven heating for irregularly shaped products with varying conductivity, and risks of metal contamination may limit the widespread adoption of OT (Balthazar et al., 2024).

MT offers faster heating, improved energy efficiency, and greater throughput, which helps reduce labor costs and processing time compared to traditional methods. While high upfront equipment costs and surface heating inconsistencies can affect cost-effectiveness in large-scale operations, many models are relatively affordable to manufacture, making them accessible for both home and commercial use. However, the need for specialized equipment can result in higher initial setup expenses (Icier et al., 2017; Mao & Zhu, 2024). UAT ensures uniformity, affordability, and efficiency, making it a highly effective method for speeding up the thawing process. It is considered cost-effective due to its low energy consumption and reduced processing times. While initial equipment costs may vary depending on the system's complexity, its ability to reduce thawing time and energy usage can lead to overall savings, especially in medium- to large-scale operations (Kong et al., 2023; Sarıoğlu et al., 2024). A recent study by Sarıoğlu et al. (2024) found that UAT reduced the thawing time by 80%, compared to static freezing and thawing methods without adversely affecting the quality of product. Ultrasound at 40% amplitude yielded more effective results than at 100% amplitude. For extraction processes, ultrasound at 100% amplitude not only failed to provide a significant advantage in meat quality but also increased energy consumption. While ultrasound effectively accelerated thawing and protected food quality, 100% amplitude did not offer a notable advantage in the quality characteristics of the samples.

RFT is increasingly used to thaw a variety of foods, including meat, seafood, and even strawberries, offering several advantages over traditional methods, such as more consistent thawing and reduced labor costs (Gao et al., 2023). Although RFT devices are designed to provide rapid and uniform heating, leading to potential time and energy savings, the technology requires a significant initial investment. The cost of RFT is influenced by factors like equipment design, energy consumption, and operational efficiency, with operational costs varying depending on the specific design and application. Despite these challenges, RFT can be cost-effective in the long run. However, the high upfront costs and the technology's complexity have slowed its adoption in the food industry. In large-scale operations, the benefits of improved product quality and reduced waste may make the initial investment worthwhile. Despite its potential, the high price of RFT equipment has limited its use, especially since the technology is controlled by only a few companies, making it less accessible compared to more established methods like hot air/water or microwave heating (Gao et al., 2023; Liu et al., 2024; Llave & Erdogdu, 2022).

PEF thawing systems require a substantial initial investment due to the high-voltage equipment and complex configurations involved. Ongoing operational expenses depend on factors like energy use, system design, and operational scale. Although PEF offers greater energy efficiency than traditional thawing methods, the significant upfront and maintenance costs pose challenges, particularly for smaller businesses. However, for larger operations, the potential for faster processing, better product quality, and reduced waste might make PEF thawing a more cost-effective option over time (Rondineli & Silva, 2024; Wu et al., 2024; Yang et al., 2024). For instance, PEF-assisted thawing has demonstrated a significant reduction in thawing time by up to 50% and minimized quality degradation in food products, like duck meat compared to conventional methods (Lung et al., 2022; Wu et al., 2024). Similar outcomes were observed for porcine meat (Yang et al., 2024). Despite these advantages, the cost of PEF thawing remains relatively high, due to the specialized equipment involved. These expenses, particularly in industrial settings, continue to be a key factor limiting the widespread adoption of this technology (Rondineli & Silva, 2024).

High-voltage electrostatic field thawing can accelerate the thawing process, especially in muscle foods, but it may also cause issues like oxidation and thawing loss, which could impact the overall quality of the product (Dalvi-Isfahan et al., 2016). The high output voltage of HVEFT systems not only poses safety risks for operators, but also requires careful optimization of factors like needle distance, electrode spacing, and applied voltage to enhance efficiency and control energy consumption. The substantial capital costs and varying energy demands, depending on operation scale and equipment efficiency, create significant cost barriers, hindering large-scale implementation (Lin et al., 2024; Zhang et al., 2023a).

Magnetic field thawing accelerates thawing using magnetic fields but requires specialized equipment, resulting in high initial and maintenance costs. These costs vary with equipment size, scale, and complexity, posing a significant challenge for small-scale businesses and limiting broader adoption (Wang et al., 2024). Magnetic field thawing offers rapid thawing with energy-saving, environmentally friendly benefits while minimizing ice crystal damage to muscle fibers and preventing thawing loss. It maintains stable product temperatures, even at high intensities, and is free from chemical residues. This efficient, safe method preserves food quality, indirectly reducing waste and lowering costs by enhancing process efficiency (Jiang et al., 2022; Wang et al., 2024).

HPT requires a significant initial investment, with equipment costs ranging from \$600,000 to \$4 million, depending on the size of the vessel and the level of automation (OSU, 2024). Operational costs are influenced by factors such as energy use, maintenance, and equipment efficiency (Döner et al., 2024). Despite these high upfront costs, HPT offers rapid thawing while preserving food quality and minimizing microbial risks, making it a viable solution for large-scale industrial applications, particularly for high-value products (Devaraj et al., 2024). However, its widespread adoption for thawing in smaller operations is limited, due to the considerable investment required (Li, 2024; Xiao et al., 2024).

Zhang et al. (2023a) compared the energy costs of various thawing techniques, ranking them in the following order: refrigerated thawing > ultrasonic thawing > MT > RFT > OT > water thawing. Although these emerging thawing technologies involve significant equipment costs and higher energy use, they offer the advantage of faster thawing times. On the other hand, water thawing is energy-efficient, but slower. Despite varying initial costs, integrating these emerging technologies can help reduce energy use and processing times, support more sustainable practices, and lower operational expenses in the food industry. Moreover, further research is necessary to optimize and improve their cost-effectiveness for large-scale applications by determining the key parameters.

5 | CONCLUSION AND FUTURE RESEARCH

The comprehensive review of traditional and novel thawing methods for frozen foods highlights the significant advancements in food preservation and processing technologies. Traditional thawing methods, while still widely used, are gradually being complemented or replaced by innovative techniques that offer improved efficiency, quality retention, and food safety. Innovative thawing techniques, such as HPT, MT, OT, UAT, HVEFT, PEF thawing, and RFT, have demonstrated positive outcomes across a range of food applications. These methods typically provide quicker thawing times, more consistent temperature distribution, and enhanced preservation of food quality compared to conventional thawing approaches.

The application of these thawing methods across different food categories, including meat products, fruits and vegetables, seafood, bakery products, and other foods, demonstrates their versatility and potential for widespread adoption in the food industry. However, the effectiveness of each method varies depending on the specific food product, its composition, and the desired quality attributes. Optimal thawing methods vary by food type, with high-pressure and electric field-assisted techniques (low/high-voltage, pulsed) being most effective for meat, while fruits and vegetables benefit from specific methods like high-pressure and UAT for mangoes, which reduce thaw time and preserve sensory qualities. Seafood thawing methods vary by species, with UAT being ideal for shrimp and sea cucumber, saline solution effective for cuttlefish, and OT efficient for tuna. For doughs and bakery items, UAT is superior for improving properties and fermentation, refrigerator thawing (4°C) is safe for long-term storage and quality maintenance, while MT is fast but should be used cautiously due to potential quality issues.

Future research in this field should focus on:

- ✓ Optimizing HPT parameters for different meat cuts to minimize protein denaturation and maintain texture,
- ✓ Investigating PEF thawing for reducing thawing time, while maintaining meat quality, especially for poultry and pork products,
- ✓ Evaluating UAT's effectiveness in maintaining cellular structure and reducing drip loss in various fruits and vegetables,
- ✓ Exploring OT's potential for uniform thawing of pureed or cut vegetables, while preserving nutritional content,
- ✓ Investigating RFT's efficacy in rapid, uniform thawing of various seafood products, particularly for large fish fillets and shellfish,
- ✓ Developing MT protocols to prevent localized heating and maintain the delicate texture of fish and shellfish,
- ✓ Researching HVEFT's potential to maintain gluten network integrity in frozen doughs,
- ✓ Investigating UAT's effects on yeast activity and dough rheology during the thawing process of bakery products,
- ✓ Exploring synergistic effects of combining different thawing techniques (e.g., ultrasound with ohmic heating) for enhanced efficiency and quality preservation,
- ✓ Conducting comparative studies on the energy consumption of various novel thawing methods across different food categories,
- ✓ Investigating the challenges and opportunities in scaling up promising thawing technologies for industrial applications,
- ✓ Conducting comprehensive studies on the effects of different thawing methods on nutrient retention, especially for fruits, vegetables, and seafood.

By focusing research efforts on these priorities, the food industry can work toward developing more effective, efficient, and product-specific thawing solutions. This targeted approach will help in addressing the unique challenges posed by different food types and accelerate the adoption of optimal thawing technologies in various sectors of the food industry.

AUTHOR CONTRIBUTIONS

Gülşah Çalışkan Koç: Conceptualization; writing—original draft; writing—review and editing; supervision. **Azime Özkan Karabacak**: Writing—original draft; writing—review and editing. **Özge Süfer**: Investigation; writing—review and editing; writing—original draft. **Samiye Adal**: Writing—original draft; writing—review and editing. **Yasemin Çelebi**: Writing—review and editing; writing—original draft. **Berrak Delikanlı-Kıyak**: Writing—original draft; writing—review and editing.

Sebahat Öztekin: Visualization; writing—review and editing; writing—original draft.

ACKNOWLEDGMENTS

Graphical abstract and all figures were created by Biorender.com.

Open access funding provided by the Scientifc and Technological Research Council of Türkiye (TÜBİTAK).

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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How to cite this article: Çalışkan Koç, G., Özkan Karabacak, A., Süfer, Ö., Adal, S., Çelebi, Y., Delikanlı Kıyak, B., & Öztekin, S. (2025). Thawing frozen foods: A comparative review of traditional and innovative methods. *Comprehensive Reviews in Food Science and Food Safety*, *24*, e70136. https://doi.org/10.1111/1541-4337.70136