

Advanced Technologies for Food Processing and Shelf-Life Extension

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Edited by

Poonam Aggarwal and Sukhpreet Kaur

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INTRODUCTION

The global food industry is undergoing a transformative shift driven by the increasing demand for safe, nutritious, high-quality, and sustainable food. With rising consumer awareness, evolving dietary habits, and mounting environmental concerns, there is a pressing need for innovative technologies that enhance food quality, extend shelf life, and reduce post-harvest losses—without compromising nutritional and sensory attributes. This book is a comprehensive volume dedicated to exploring cutting-edge techniques and scientific breakthroughs reshaping the landscape of food science and technology.

In recent years, traditional food processing methods have been supplemented—or in some cases, replaced—by more efficient, precise, and sustainable technologies. These include both non-thermal and thermal innovations, novel extraction and separation systems, and advanced analytical tools for food quality assessment. Non-thermal preservation techniques such as high-pressure processing, pulsed electric fields, ozonation, and cold plasma technology have shown remarkable potential in microbial inactivation while maintaining the nutritional and sensory integrity of food. Simultaneously, microwave and radiofrequency heating, ohmic, inductive, and infrared heating are revolutionizing thermal processing by offering faster, uniform heating with minimized thermal damage.

One of the most impactful trends in food science is the application of membrane processing technologies such as ultrafiltration, nanofiltration, and reverse osmosis. These offer energy-efficient separation processes critical in dairy, beverages, and waste recovery. Alongside, supercritical fluid extraction has gained popularity for its ability to extract high-value bioactive compounds and flavors in an eco-friendly and solvent-free manner. Similarly, ultrasonication is emerging as a green processing technology for extraction, emulsification, and shelf-life extension.

The book also examines the role of pulsed X-ray and pulsed light technologies, which are gaining traction for their non-thermal disinfection potential, as well as advanced micronization techniques, which enable enhanced bioavailability and functional properties of food ingredients. The application of nanotechnology in food processing and packaging further opens avenues for intelligent sensing, targeted delivery of nutrients, and enhancement of food safety.

Characterization of processed foods is an equally critical aspect of modern food science. With the emergence of advanced analytical methods,

including spectroscopy, imaging, and rheological tools, researchers can now precisely understand the physical, chemical, and structural transformations occurring during processing. Complementing this, food tribology—the study of friction, lubrication, and texture perception—has added a new dimension to quality evaluation.

This book also integrates chapters on ancient food preservation methods, linking time-tested practices with modern technologies to provide context and sustainability insights. Emphasis is placed on novel drying techniques, flavor stabilization, and the role of sensors in real-time monitoring, automation, and quality control across the supply chain. Additionally, the discussion on shelf-life estimation, factors affecting food shelf life, and predictive modeling serves as a crucial reference for both researchers and industry professionals. By bridging the gap between innovation and application, the book seeks to foster a deeper understanding of modern processing technologies and inspire future directions in sustainable food production.

CHAPTER 1

ADVANCE TECHNOLOGIES IN FOOD PRESERVATION

**Nidhi Attri, Poonam Aggarwal and
Sukhpreet Kaur**

Abstract

The continuous evolution of food preservation technologies is essential in addressing the world challenges of food security, safety, and waste reduction. As global population is projected to exceed 9.7 billion by 2050, the demand for safe, healthy, and sustainable food products intensifies. Novel food preservation methods, such as plasma technology, high pressure processing, ozonation, pulsed electric fields, vacuum packaging and advanced irradiation techniques, have emerged as revolutionary solutions. These technologies extend shelf life, maintain nutritional value, and ensure microbial safety without the requirement for traditional thermal or chemical preservatives. High pressure processing effectively inactivates pathogens while conserving the organoleptic and nutritional qualities of food. Pulsed electric fields offer a non-thermal substitute to microbial control, suitable for liquid and semi-solid foods. Advanced irradiation methods, including radurization, radicidation, and radappertization, provide targeted microbial inactivation tailored to specific food safety needs.

Keywords: Preservation, irradiation, thermal processing, pressure processing

1.1 Introduction

Food preservation refers to the strategies or techniques used to control intrinsic and extrinsic factors that can cause food degradation. It involves managing and preserving food in order to avoid deterioration by blocking the growth of harmful microorganisms, reducing rancidity, and retaining the nutritional value, texture, and flavor (Ahmad et al. 2021). Traditionally food preservation methods such as drying, thermal treatments, chilling and chemical preservation have been widely employed.

However, with the worldwide population expected to exceed 9.7 billion by 2050, the food industry faces increasing demand to develop safe, healthy and sustainable commodities. While traditional preservation techniques have laid the foundation in extending the shelf life of perishable goods such as fruits & vegetables, cereal products and dairy products but modern innovations are pushing the boundaries even further. Rapid industrialization and globalization are the two primary factors for the growth of the food industry. The rapid development of advanced food preservation technologies has been crucial in addressing global challenges related to food security, safety and waste reduction. These advanced methods which includes high-pressure processing (HPP), pulsed electric field (PEF), ozonation, ohmic heating and irradiation offer wide improvements in maintaining nutritional value, organoleptic properties and overall quality of food products (Bobinaite et al. 2015). By enhancing the efficiency of preservation techniques, these technologies play an important role in meeting the growing demands of a global population while minimizing environmental impact.

Over the past few years, the application of biotechnology, material science, and engineering have resulted in the development of more advanced and effective preservation techniques. The application of these advanced technologies depends on food type, contents and the purpose of operation. For instance, the application of pulse electric fields is commonly used to process fluid foods such as fruit juices, squash, and milk. The electric field strength ranges from 20 to 80 kV/cm and kills microorganisms cell membranes in less than one second (Sharma et al. 2014; Bhavya and Umesh Hebbar 2017). Jadhav and Choudhary (2024) reported that irradiations are usually employed to solid food product. High pressure processing is used to treat huge amounts of food before packaging it. High pressure causes microbial cell membranes to permeate and disintegrate. Pressure typically ranges from 150-450 MPa at low temperatures of 40-60°C (Maitland et al. 2011). Non-thermal treatments, such as ultraviolet and cold plasma, are used to treat the outer surfaces of

raw fruits, processed food, and packaging materials (Thirumdas, Sarangapani, and Annapure 2015). These treatments are frequently combined to improve their effectiveness and increase the shelf life of foods. Non-thermal technologies, such as pulsed electric fields and cold plasma, can cause physiological changes in food ingredients, increasing functioning and expanding their applications (Jadhav and Choudhary 2024).

Emerging methods of food preservation include cold plasma treatment, edible coatings, and antimicrobial packaging (Barba et al. 2018). The key principle of food preservation underlies in deactivation of microbial cells. Novel technologies namely pulse electric field, ultrasonication, plasma technology etc., targets microbial cell wall such as creating electroporation in cell wall, DNA denaturation, protein unfolding and disrupting cellular activities (Fig 1.1). Through a comprehensive analysis of current research and innovations, this chapter aims to provide valuable insights into how these technologies can be leveraged to enhance food preservation practices worldwide.

Table 1.1: Advance technologies principle, advantages and disadvantages

S. No.	Preservation Technologies	Principle of Process	Advantages	Disadvantages	References
1.	High Pressure Processing	Intense water pressure (100-1000 MPa) inactivates pathogens and enzymes.	Minimal impact on nutrients and flavor, safe alternative to thermal processing.	High equipment cost, limited product applications (mostly liquid foods).	Bevilacqua et al. (2019)
2.	Pulsed Electric Field	Short, high-intensity electrical pulses disrupt cell membranes of microorganisms.	Retains sensory attributes (color, flavor, texture), minimal thermal impact.	Limited penetration depth (better for liquid foods) High energy consumption.	Nabilah et al. (2022)
3.	Vacuum Packaging	Removes oxygen to inhibit microbial growth and oxidation.	Extends shelf life, maintains freshness.	Requires specialized packaging Possibility for puncture and spoilage.	Shajil, Mary, and Rani Juneius (2018)
4.	Ohmic Heating	Electrical current passes through food, generating heat internally.	Uniform heating, faster processing times compared to traditional methods.	Requires specialized equipment Can cause localized overheating.	Makroo, Rastogi, and Srivastava (2020)
5.	Ultrasonication	High-frequency sound waves create cavitation bubbles that disrupt microorganisms.	Can enhance extraction of bioactive compounds, Utilization for tenderization.	Limited penetration depth non-uniform treatment Capability of negative effects on sensory qualities.	Wang et al. (2020)

S. No.	Preservation Technologies	Principle of Process	Advantages	Disadvantages	References
6.	Irradiation	Exposes food to ionized radiation to eliminate microbes and insects.	Effective for product life extension, disinfestation.	Public perception concerns Potential for nutrient loss, regulatory restrictions in some countries.	Bisht et al. (2021)
7.	Plasma Technology	Cold plasma (ionized gas) inactivates microorganisms on food surfaces.	Dry process, minimal impact on food quality.	Limited scalability, high energy consumption, research is still ongoing for food applications.	Cullen et al. (2018)
8.	Ozonation	Ozone gas (O ₃) is utilized to sanitize food surfaces and extend storage life of a product.	Efficient against a broad spectrum of pathogens, environmentally friendly (ozone decomposes back to oxygen).	Can negatively impact flavor and certain nutrients, requires careful control to avoid excessive residue.	İbanoğlu (2023)

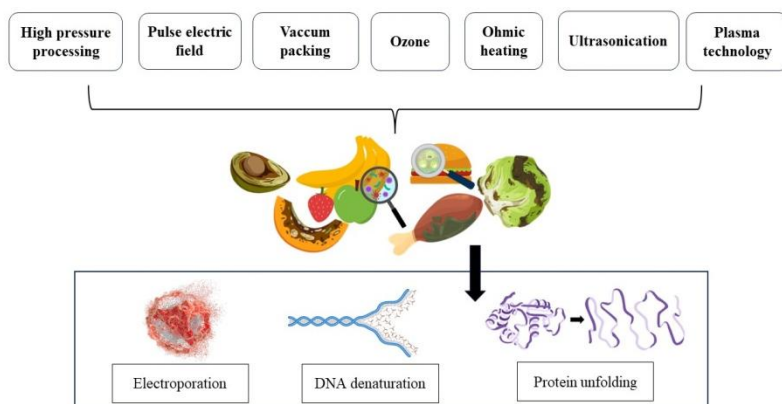


Fig 1.1: Novel technologies in microbial cell inactivation

Food Preservation Technologies

1.2 High pressure processing (HPP)

High Pressure Processing is a non-thermal food preservation method that utilizes extremely elevated pressure up to 900 MPa to kill pathogens and spoilage germs in food products. This processing method has received a prominent attention in past years because of its capability to retain the nutritional and sensory characteristics of food, which are usually compromised by traditional heat processing techniques like pasteurization and sterilization (Amit et al. 2017). By applying pressures from 100 to 600 MPa, HPP successfully eliminates microbial cells without the use of high temperatures, keeping food freshness, flavour, and nutritional integrity (Zhang and Mittal 2008). High pressure processing can be implemented in multi phase system which includes repetitive high pressure treatment for various cycles. Bulut and Karatzas (2021), reported that high pressure treatment with combination of freezing at 600 MPa pressure for 15 minute resulted in reduction in E.coli present in orange juice. Similarly, Gouvea et al. (2020) noticed that high pressure treatment at a pressure of 400 MPa for 3 minutes resulted in degradation of microorganisms in Acai juice (pH 4 and soluble solids 2.9°B).

The inactivation varies with the type of microorganism present in food. Some are resistant to the treatment with low pressure like prokaryotes, yeast and molds can withstand up to 400 MPa of pressure compared with the eukaryotes and parasites (Grundy, Lapsley, and Ellis 2016; Rendueles et al. 2011).

1.2.2 Principle of food preservation

The basic principle of high pressure processing method is the uniform application of pressure to product, often in a water-filled chamber. This applied pressure damages the cellular structures of bacteria, causing them to become inactive, while the food itself remain undamaged (Balakrishna, Wazed, and Farid 2020). HPP deactivates pathogens by disrupting their cell membranes and inactivating enzymes (Zhang and Mittal 2008). Cell membranes are phospholipid bilayers, which means they have a double layer of fat molecules with phosphate heads on the outside and tails on the inside. These fat molecules are not much soluble in water, which helps to keep the inside of the cell separate from the outside environment. When the high pressure is applied, the intense pressure disrupts the arrangement of the fat molecules in the cell membrane, making it more permeable. This allows water and other molecules to enter the cell, which can disrupt the cell's internal environment and essential functions. In addition, HPP can also inactivate enzymes by causing changes in their protein structure (Bevilacqua et al. 2019). Enzymes present in microorganisms are essential for all living organisms, including microbes, because they speed up chemical reactions that are necessary for life. When an enzyme is inactivated, it can no longer perform its function, which can lead to the death of the microbe. HPP techniques inactivates the enzymes essential for functioning reducing their load in food products (Sehrawat et al. 2021).

This makes HPP ideal for storing temperature-sensitive products including fresh juices, guacamole, and ready-made meals. Furthermore, because method has no influence on the organoleptic features of food, high pressure processing treated items keep their original flavour, colour, and texture, which is highly prized by consumers looking for high-quality, fresh-tasting food options.

1.2.3 Mechanism

A high pressure processing instrument has a pressure chamber for food storage, a pressure generating structure and a system for process control. The pressure range for food is 250-650 MPa (Sevenich, Rauh, and Knorr 2016). Food is placed inside the pressure chamber and the lid is closed from above. The medium used to generate pressure is generally water and may contain minor amounts of soluble oil. Water is pumped into the compartment from the bottom, leading to compression of food. The appropriate pressure is achieved and maintained during the process (Shajil, Mary, and Rani Juneius 2018).

1.2.4 Advantages

- I. Prolonged product life and food safety:** HPP technique extends the product life cycle by deactivating spoilage causing microbial cells and enzymes.
- II. Nutrients and flavour preservation:** Unlike thermal processing, HPP maintains the nutritional value, colour and flavour of food since it does not involve high temperatures.
- III. Minimal effect on texture:** HPP has minimal effect on food texture, making it acceptable for variety of items such as juices, meats, and shellfish.
- IV. Clean label:** HPP enables manufacturers to produce "clean label" foods with fewer additives, which appeals to health-conscious customers.
- V. Environmental benefits:** HPP is an energy-efficient procedure that generates less waste than certain older processes, helping to create a more sustainable food production system.

1.2.5 Disadvantages

High initial investment: The equipment needed for HPP is costly, which might be a substantial obstacle for small and medium-sized food producers.

Operational costs: Although HPP is energy-efficient, its operational expenses, including maintenance and labour, may be higher than traditional preservation methods.

Batch processing: HPP is typically a batch process, which has lower throughput and scalability than continuous processing methods.

1.3 Pulse Electric Field (PEF)

Pulsed Electric Field is another non-thermal food preservation technique that uses high voltage electric fields to deactivate microbes and enzymes present in food. This new technique has a considerable advantage over typical thermal processing processes since it successfully preserves the sensory and nutritional attributes of food products while assuring microbiological safety (Raso et al. 2022). PEF involves the use of electric fields from 10 to 80 kilovolts per centimeter, delivered in microsecond pulses, to rupture the cell membranes of bacteria and other pathogens which results in their inactivation (Nabilah et al. 2022; Arshad et al. 2021).

The increasing attention in PEF processing stems from its capacity to address customer desires for minimally processed, clean-label foods that preserve their natural properties. Furthermore, PEF has various operational benefits, such as energy efficiency, shorter processing times, and the possibility of continuous processing, which can boost productivity and lower costs (Arshad et al. 2020). The technological breakthroughs and practical uses of PEF in the food sector have laid an emphasis on its potential to alter food preservation techniques (Nabilah et al. 2022; Bobinaitė et al. 2015; Plaza et al. 2011).

1.3.1 Principle of food preservation

As discussed earlier, the main principle in food preservation is the deactivation of pathogens. Pulse electric field is a technique which deactivates pathogens by electroporation, a process in which high-intensity electric fields produce pores in microorganism cell membranes (Raso et al. 2022). When a high-voltage electric pulse is employed to a food, the charged particles (ions) inside the microbial cells experience a strong force. This force can be strong enough to pull the ions across the cell membrane, creating microscopic pores in the membrane. These pores can disrupt the cell's essential functions, such as nutrient transport and waste removal, leading to cell death. The effectiveness of this technology relies on various factors which include the strength and duration of the electric pulse, the conductivity of the food, and the type of microbe (Raso et al. 2022; Nabilah et al. 2022). PEF is more effective against simpler organisms like bacteria than against more complex organisms like spores.

Also, as PEF functions at very low temperatures, it reduces thermal damage to food components, retaining their original taste, colour, and nutritional profile (Jadhav and Choudhary 2024). This makes PEF ideal for liquid foods like dairy products, fruit juices and liquid egg products, where quality and freshness are essential.

1.3.2 Mechanism of PEF

The system generally includes a treatment chamber, an energy supply unit, and a surveillance system (Buchmann, Bloch, and Mathys 2018). The success of PEF treatment is heavily determined by the treatment chamber design, which typically consists of two stainless steel electrodes. The food material is positioned between these electrodes and the energy supply unit generates a high-voltage pulse (10-90 kilovolts per centimeter). The food is exposed to this pulse for a short period of time, usually between microseconds and milliseconds. This short exposure duration reduces

unwanted changes in the food, keeping its inherent properties (Novickij et al. 2020).

For liquid foods, the flow pattern of liquid inside the treatment chamber is critical for attaining maximal disinfection. Stream line flow of liquid can cause unequal treatment, in order to achieve maximum deactivation pulse intensity or frequency is regulated (Novickij et al. 2020). Turbulent flow, on the other hand, improves the mixing of liquid layers and increases microbiological exposure to electric fields. Turbulence can be created naturally or artificially using a variety of means, such as adding barriers or changing flow rates (Kanduđer et al. 2017; Novac et al. 2014).

The energy supply unit is a vital component of PEF systems, as it generates the high-voltage pulses. This system is complex and expensive to design and maintain, making large-scale adoption of PEF technology difficult.

1.3.3 Advantages

- I. Non-Thermal Processing:** PEF is a food preservation technology which inactivates microorganisms without causing significant heating, preserving the organoleptic and nutritional quality of food better than traditional thermal methods.
- II. Energy Efficiency:** PEF uses less energy consumption as compared to other thermal processes like pasteurization or sterilization, thus making it more environmentally friendly.
- III. Nutrient Preservation:** Due to no involvement of high temperature in processing, this technique retains more vitamins, antioxidants, and other heat-sensitive nutrients.
- IV. Enhanced Extraction Processes:** PEF can improve the extraction of juices, oils, and other valuable components from plant materials, increasing yield and efficiency.
- V. Minimal Impact on Food Quality:** PEF maintains the color, flavor, and texture of foods, making it ideal for products where sensory attributes are crucial.

1.3.4 Disadvantages

- I. High Initial Cost:** The setup and equipment costs for PEF systems are relatively high which may be prohibitive for small or medium-sized enterprises.

- II. **Limited Application:** PEF is most effective for liquid or semi-liquid foods. Its application to solid foods or complex food matrices is limited and challenging.
- III. **Technical Challenges:** PEF technology requires precise control of process parameters such as electric field strength and pulse frequency and duration, which can be complex and require specialized knowledge.
- IV. **Regulatory Approval:** In some regions, regulatory approval for PEF-treated foods may be slow or complicated due to the relatively new adoption of the technology.
- V. **Maintenance and Wear:** The electrodes in PEF systems are subject to wear and require regular maintenance or replacement, adding to operational costs.
- VI. **Consumer Acceptance:** As a relatively new technology, there may be some consumer skepticism or resistance to products processed with PEF, requiring education and marketing efforts.

1.4 Vacuum Packaging

Vacuum packaging is a popular food preservation technique that enhances the product life of food perishable products by excluding air from the packaging environment (Rocha, Coulon, and Morais 2003). This method entails placing food in a plastic film packaging, extracting the air, then sealing the box to form a vacuum. Vacuum packaging reduces the oxygen which retards the production of aerobic microorganisms such as bacteria, yeast and mould, both of which contribute considerably to food degradation (Lorenzo and Gómez 2012). This approach is especially successful for keeping the freshness, flavour, and nutritional value of a wide variety of food products. Vacuum packaging works by creating an anaerobic atmosphere, which reduces oxidation and the growth of spoiling organisms. According to Rocha et al. (2003), vacuum packaging reduces air exposure, which helps to retain moisture, prevent freezer burn and maintain overall food quality. Furthermore, vacuum packaging can be used with other preservation techniques, such as refrigeration or sous-vide cooking, to enhance the food safety and quality of food goods, such as meats, cheeses, vegetables and prepared meals.

Advances in vacuum packaging technology, such as the creation of more durable and flexible packaging materials have increased the effectiveness and versatility of this method. Furthermore, vacuum

packaging promotes sustainability by eliminating food waste and the need for preservatives.

1.4.1 Principle of food preservation

Vacuum packaging is a food preservation technique in which air is removed from a sealed package prior to sealing it. This procedure produces a low-oxygen environment, which limits the growth of microbes like bacteria and mold (Özogul, Polat, and Özogul 2004). Removing oxygen from the package drastically decreases the reproduction of aerobic microbes, which require oxygen to survive. This method can also aid in regulating moisture levels within the box. This is because the lack of oxygen slows the evaporation process and keeps the food from drying out. A vacuum-packed environment slows or prevents oxidation, a chemical reaction that can destroy food quality.

1.4.2 Mechanism

- i) **Air Removal:** A vacuum pump is used to remove air from the packaging. The pump generates a low-pressure condition within the chamber, forcing air to be pulled out.
- ii) **Sealing:** After achieving the necessary degree of vacuum, package is sealed airtight. This stops oxygen from re-entering the package. The sealed package creates a low-oxygen environment, inhibiting the growth of aerobic bacteria, molds, and yeasts. These microbes need oxygen to metabolize and proliferate.
- iii) **Prevention of Oxidation:** Oxidation, a chemical reaction that can reduce food quality, is slowed or prevented in a vacuum-packed atmosphere. This helps to keep the food fresh, flavorful, and colorful.

Table 1.2: Types of vacuum packaging

Sr. No.	Type of vacuum packaging	Functions	Applications	Advantages	Disadvantages
1	Edge Sealers (External Vacuum Sealers)	Removes air by placing the open end of a pouch over a sealing bar.	Home use, small businesses, flat/pre-formed pouches	Suitable for small scale use, relatively inexpensive	Not ideal for liquids or uneven surfaces, limited seal strength compared to chamber machines
2	Chamber Vacuum Sealers	Places the entire pouch inside a chamber, where air is removed before sealing.	Industrial kitchens, restaurants, liquids, marinades, delicate items	Stronger seals, suitable for uneven surfaces and liquids, allows for MAP	More expensive, larger footprint, slower than automatic belt sealers
4	Single Chamber	Simpler design, product remains in the chamber after sealing.	Smaller scale industrial kitchens, restaurants	Cost-effective for smaller operations	Lower throughput compared to double chamber
5	Double Chamber	Higher throughput, one chamber for sealing while the other is being loaded/unloaded.	Larger scale industrial kitchens, restaurants	Higher throughput, efficient for larger volumes	More complex, higher cost than single chamber
6	Automatic Belt Vacuum Sealers	Continuous operation with a conveyor belt that feeds pouches through the sealing process.	High-volume production lines, pre-made pouches	Fastest sealing speeds, suitable for large-scale, automated production	High initial investment, requires more space
7	Thermoforming Vacuum Packaging Machines	Creates custom-shaped packages from plastic film rolls, followed by vacuum sealing.	Flexible packaging for specific product shapes, fresh produce, meat	Customizable packages, maximum product visibility, often used with MAP	High cost, complex machinery, best for specific product types

1.4.3 Vacuum and modified atmosphere packaging (MAP)

Modified atmospheric packaging (MAP) is a food conservation method that modifies the composition of gases within a package. This involves replacing ambient air with a gas combination matched to the product being packaged, such as increased amounts of carbon dioxide and decreased levels of oxygen (Lorenzo and Gómez 2012). By combining vacuum packaging with modified atmospheric packaging, food manufacturers can enhance the preservation effects. The vacuum condition reduces oxygen levels, and the specifically prepared gas combinations in MAP can further suppress microbial growth and oxidative activities. This synergy extends the product life such as seafood and other perishable commodities, preserving their freshness and quality. For instance, studies have shown that applying MAP at 90% CO₂ can markedly improve the preservation of vacuum packed fish during refrigerated conditions (YILMAZ et al. 2009).

1.4.4 Advantages

- I. Extended Shelf Life:** Vacuum packaging significantly extends the shelf life of perishable foods by retarding the growth and reproduction of bacteria, mold, and yeast that require oxygen to survive.
- II. Preservation of Freshness and Flavor:** By removing air, vacuum packaging helps to preserve the flavor, texture, and freshness of food products especially for items like meats, cheeses and coffee.
- III. Reduced Food Waste:** The extended shelf life means less food spoilage, which can help reduce food waste both at home and in commercial settings.
- IV. Protection Against Freezer Burn:** Vacuum packaging minimizes the risk of freezer burn, which can occur when food is exposed to air during freezing.
- V. Space Efficiency:** Vacuum-packed items take up less space in storage, whether in the refrigerator, freezer, or pantry, allowing for better organization.
- VI. Improved Product Safety:** The absence of oxygen reduces the risk of contamination by aerobic microorganisms, leading to safer food storage.
- VII. Enhanced Marination:** Vacuum packaging can be used to marinate foods faster and more effectively as the absence of air allows the marinade to penetrate the food more deeply.

VIII. Versatility: Vacuum packaging is suitable for a variety of products, including solid foods, liquids (with careful handling), and even non-food items like clothing or electronics.

1.4.5 Disadvantages

- I. Not Suitable for All Foods:** Some foods, such as soft or delicate items (e.g., berries, leafy greens), can be crushed during the vacuuming process. Additionally, foods with high moisture content may require pre-freezing to avoid liquid extraction.
- II. Potential for Anaerobic Bacteria Growth:** While vacuum packaging inhibits aerobic bacteria, it can create an environment conducive to the growth of anaerobic bacteria, such as *Clostridium botulinum*, if not properly stored.
- III. Limited Packaging Material:** Only specific types of bags or materials can be used with vacuum sealers, which may add to the cost and limit options.
- IV. Need for Proper Storage Conditions:** Vacuum-packed foods still require refrigeration or freezing. Without proper storage, the vacuum seal can fail, leading to spoilage.
- V. Time-Consuming Process:** The vacuum packaging process can be time-consuming, especially if packaging large quantities of food.
- VI. Environmental Impact:** The plastic bags used for vacuum packaging are often single-use and contribute to plastic waste, raising environmental concerns.

1.5 Ohmic thermal processing

Ohmic heating is a technique which involves passing of electrical current in food's components (Kaur and Singh 2016). This method rapidly and uniformly raises the internal temperature of the food by transforming electrical energy supplied into thermal energy. Kubo et al.(2020) highlighted that this method heats food products by generating heat in the food material itself because of electrical resistivity risen due to passing of electric current. Ohmic heating is an advanced method that lowers the thermal damage to food while ensuring quick and even heating. This process, also referred as internal thermal energy generation technology, produces heat internally due to the resistance to the current flowing.

In the food industry, a wide range of products, specifically plant-origin foods like processed fruits and vegetables are processed using this

advanced heating method (Jan et al. 2021). Ohmic heating is valued for its low entry barrier, high energy efficiency, and technological simplicity (Makroo, Rastogi, and Srivastava 2020). It is also referred to as electroconductive heating, electrical resistance heating and Joule heating. The concept of ohmic heating has been applied to food preparation since the 19th century, starting with the pasteurization of milk (Alkanan et al. 2021). The first law of thermodynamics states that energy cannot be created or destroyed but can only change forms. Ohmic heating is a prominent application of this principle, converting electrical energy into thermal energy. Food products having an electrical conductivity of 0.1 to 10 Siemens per meter are appropriate for ohmic heating with electric fields less than 100 volts per centimeter (Guo et al. 2017).

1.5.1 Principle of food preservation

The basic principle of ohmic heating is based on Joule's equation, which depicts that the heat generated in a conductor is directly proportional to the square of the current, the material's resistance, and the time the current is applied (Kaur and Singh 2016). The mathematical expression for this is:

Ohm's Law : $V=I \cdot R$

Joule's Law: $P=I^2RT$

Where, P= Powder generated

I= current

R=resistance

T=time period

The principle behind microbial inactivation is protein denaturation (Kubo et al. 2020). Heat generated by electric current disrupts and denatures proteins in microbial cells. Proteins are essential components of cell membranes and many other cellular structures. When proteins are exposed to heat, they can unfold and lose their ability to function properly. This can damage the cell wall which results in leakage of cellular contents and results in death of cell. Additionally, heat can also denature enzymes, which are proteins that speed up chemical reactions in cells. When enzymes are denatured, they can no longer perform their functions, which can disrupt essential metabolic processes in microbes and lead to cell death (Kumar 2018; Makroo, Rastogi, and Srivastava 2020; Jaeger et al. 2016).

1.5.2 Mechanism

A food product is subjected to an electrical current from generator, usually between electrodes immersed in a conductive fluid (such as water or salt solution). As the electrical current passes through the product, it faces resistance from the molecules present in composition of a product (Aurina and Sari 2022). This resistance of molecules transforms electrical energy into heat, causing the food to heat up. Unlike typical heating methods, ohmic heating distributes heat evenly throughout the meal, resulting in consistent pasteurization or cooking. This is because the electrical current flows through the full volume of the meal, heating it from the inside out.

1.5.3 Advantages

- I. Uniform Heating:** Unlike conventional heating methods, ohmic heating distribute heat equally throughout the food product. This reduces the risk of overheating or undercooking, especially for foods with complex structures.
- II. Rapid Heating:** It is a fast technique as the heat is produced internally within the food material, reducing the overall processing time. This is particularly beneficial for heat-sensitive foods.
- III. Nutrient Retention:** The rapid and uniform heating minimizes exposure to high temperatures, helping to preserve heat-sensitive nutrients, vitamins, and flavors in the food.
- IV. Reduced Thermal Damage:** The precise control over heating reduces the likelihood of thermal damage, maintaining the food's sensory qualities such as texture, color and flavor.
- V. Microbial Inactivation:** Ohmic heating is effective at inactivating pathogens and spoilage causing microorganisms, ensuring food safety and extending shelf life without the need for preservatives.
- VI. Minimal Fouling:** Since ohmic heating does not rely on hot surfaces, there is less fouling or scaling, which reduces maintenance and cleaning requirements.

1.5.3 Disadvantages

- I. High Initial Cost:** The set up investment in ohmic heating equipment could be high which results in less adoption of technique by small bussinesses.

- II. Limited Conductivity Range:** The effectiveness of the technique depends on factors such as the electrical conductivity of the food material. Foods with very low or very high conductivity may not heat efficiently, limiting the range of suitable products.
- III. Complex Control Requirements:** Ohmic heating systems require precise control of electrical parameters such as voltage, current, and frequency to ensure uniform heating, which can be technically challenging.
- IV. Potential for Electrochemical Reactions:** At the electrodes, there is a risk of electrochemical reactions that can cause changes in food product or contamination, especially if improper electrode materials are used.
- V. Regulatory Challenges:** As a relatively new technology, ohmic heating may face regulatory hurdles in some regions, and there may be a lack of established standards or guidelines for its use.
- VI. Safety Concerns:** The use of high voltages requires strict safety measures to protect operators and ensure the safe operation of the equipment.
- VII. Limited Consumer Awareness:** As ohmic heating is not widely recognized by consumers, there may be some resistance or skepticism regarding products processed using this method.

1.6 Ultrasonication

Ultrasonication is also referred as high-intensity ultrasound (HIU) or high-power ultrasound (HPU), is another potential food preservation method which uses high frequency sound waves typically above the hearing range (typically above 20 kilohertz) to inactivate microbes and to enhance food quality and to increase food safety (Wang et al. 2020). This technology is acquiring significance in the food sector due to its capacity to preserve nutritional and organoleptic qualities of food products while increasing shelf life and assuring safety. Ultrasonication is a technology that can be used alone or can be combined with other food preservation techniques, providing a diverse approach to current food processing (Gao, Lewis, and Hemar 2016). Fan, Zhang, and Jiang (2019) reported that ultrasonication at a frequency of 20 KHz for 10 minutes using direct sonication and probe results in increased shelf life of cucumber.

Ultrasonication can be operated at three frequency ranges: 10-100 kHz (low frequency), 100-1 MHz (mid frequency) and 1-10 MHz (high frequency). While low-frequency ultrasonication creates larger cavities

that collapse with high energy and high-frequency ultrasonication creates smaller cavities, medium-frequency ultrasonication creates cavities of the right size for the generation of chemical radicals. High-power ultrasound technology have been proven to pasteurize fruit juices. Its benefits in food processing and preservation include reduced energy consumption, increased homogeneity, less flavor loss in liquid foods, and disruption of bacterial agglomerates (Sango et al. 2014).

However, the chemical radicals created by medium-frequency ultrasonication might cause unwanted modifications in food products, rendering it unfit for use in the food business (Ranjha et al. 2021).

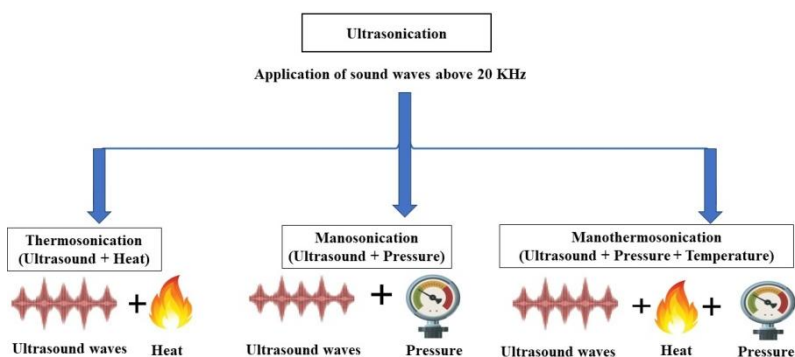


Fig 1.2: Ultrasonication types

Several authors have reported the use of ultrasonication with combination with other technologies. Ultrasonication when combined with pressure is known as manosonication (Rathnakumar et al. 2023; Lv et al. 2019). Režek Jambrak et al. (2018) noticed that manosonication at 20 KHz frequency for 6 and 9 minutes at 60 °C resulted in complete deactivation of bacteria in fruit juices (cranberry, apple, blueberry) . Ultrasonication when combined with heat is known as thermosonication. Thermosonication is used for sterilization and pasteurization of different food items. This technology when employed on mung bean protein at 20 KHz frequency for 4 different time period (5,10,20,30 minutes), at 70 °C temperature resulted in reduction in particle size and increase in hydrophobicity (Zhong and Xiong 2020). Also, this technology have resulted in increment in protein solubility at double times. Ultrasound can be applied with two parameters also and is known as manothermosonication (ultrasound + pressure + temperature) (Fig 1.2).

1.6.1 Principle of food preservation

The key principle in microbial inactivation in ultrasonication is a phenomenon called cavitation (Rathnakumar et al. 2023; Lin et al. 2019). In a liquid food, high-frequency sound waves create tiny air bubbles. These bubbles rapidly grow and collapse, produces intense shockwaves and localized heating (Zhu et al. 2017). The collapsing bubbles generate strong shear forces which can disrupt the cell membranes of microbes. This allows essential cellular components to leak out, leading to cell death. The shockwaves can also travel through the liquid and directly damage internal structures of microbes, including DNA and proteins. This can interrupt vital cellular processes and lead to cell lysis.

1.6.2 Mechanism of ultrasonication

Ultrasonication works by generating high-frequency sound waves, typically above 20 kHz, which are then transmitted into a liquid medium via a transducer. These ultrasonic waves cause alternate cycles of compression and rarefaction which results in the production, growth and collapse of bubbles, a process known as acoustic cavitation. The sudden collapse of these cavitation bubbles creates localized extreme conditions such as intense heat, high pressure, and powerful shear forces (Dolas, Saravanan, and Kaur 2019). These conditions facilitate a variety of effects, including particle dispersion, mixture emulsification, cell wall breakdown, and chemical reaction enhancement through increased mass transfer rates and energy input. This cell wall breakdown in pathogens results in sterilized conditions.

1.6.3 Advantages

1. **Efficient Mixing and Homogenization:** Ultrasonication can create uniform dispersions, emulsions, and mixtures by breaking down particles and droplets into finer sizes, making it ideal for sample preparation.
2. **Enhanced Reaction Rates:** The process generates cavitation, which can increase the rate of chemical reactions by providing localized high energy, improving reaction efficiency and yields.
3. **Nanoparticle Synthesis:** Ultrasonication is commonly used to create nanoparticles by breaking down bulk materials into smaller particles or by aiding in the precipitation of nanoscale materials.
4. **Cell Disruption and Extraction:** Ultrasonication can effectively break cell walls, making it useful for extracting intracellular compounds, such as DNA, proteins, and enzymes.

5. **Environmental Benefits:** It can be an eco-friendly alternative to chemical methods for processes like cleaning, degassing, and pollutant degradation, as it often requires fewer chemicals and less energy.
6. **Non-Thermal Processing:** In some applications, ultrasonication can be used for processes that require minimal heat, preserving the quality and activity of sensitive compounds.

1.6.4 Disadvantages

1. **Localized Heating:** Ultrasonication can cause localized heating due to the intense energy generated, which can degrade sensitive materials or cause unwanted side reactions.
2. **Equipment Wear and Tear:** The process can cause wear on the ultrasonic equipment, particularly the probe, leading to contamination of the sample with metal particles over time.
3. **Energy Consumption:** High-power ultrasonication requires significant energy, which can be costly, especially for large-scale applications.
4. **Limited Penetration Depth:** Ultrasonic waves may not penetrate deeply into thick or highly viscous samples, limiting the effectiveness in certain applications.
5. **Cavitation Erosion:** Prolonged ultrasonication can cause erosion of the reactor walls and other surfaces due to the cavitation bubbles, potentially contaminating the sample and requiring maintenance.
6. **Potential for Overprocessing:** Excessive ultrasonication can lead to the breakdown of desired structures, such as over-shearing of particles or denaturation of proteins.

1.7 Irradiation

Food irradiation is a technique which improve food product life, food safety and reduce food waste by using ionising radiation to eradicate pathogens, insects, and spoilage microorganisms (Sakare et al. 2020). This technique includes subjecting food products to doses of X-rays, gamma rays or electron beams, which effectively disrupt the DNA of harmful organisms, causing them inactive. Food irradiation is recognised for its efficacy and versatility. According to the Codex General Standard for Irradiated Foods, safe ionizing radiations for food treatment include X-rays with 5 MeV or less energy, accelerated electrons with 10 MeV or less energy, and high-energy gamma rays (^{60}Co and ^{137}Cs) (CX-STAN 106-

1983 2003). Food irradiation could be categorized into radurization, radicidation, radappertization (Table 1.3). Microbial inactivation using irradiation is influenced by various factors such as radiation type, dose and the target microorganism. While X-rays and gamma radiation possess high penetrating power, accelerated electrons have a more limited range, suitable for treating foods with lower moisture content. For instance, Jan et al. (2020) have demonstrated the positive effects of irradiation on physical, chemical and sensory attributes of brown rice. Treatment with 0-10 kGy improved brown rice's physical, chemical, and sensory properties, as well as antioxidant activity and phenolic content. However, these effects reduced with storage time.

The effectiveness of irradiation varies among different types of microorganisms, with yeasts, viruses and certain fungi exhibiting higher resistance than bacteria. There are three types of irradiation used in food industry i.e., low, medium and high. Low-dose irradiation (below 1 kGy) is generally employed as a preventive measure, delaying sprouting and maturation while preventing microbial growth in fresh vegetables and eggs. Medium-dose irradiation (1-10 kGy) is used to kill harmful bacteria and improve the overall quality of food, especially meat and meat products. High-dose irradiation (over 15 kGy) is used to achieve higher degrees of microbial inactivation, which is necessary for astronaut food and other extremely sensitive items (Jadhav and Choudhary 2024). X-rays (0.75 kGy) with 125 keV energy and gamma radiations (9.1 kGy) effectively kill pathogenic microorganisms like *E. coli*, *Salmonella*, and *Listeria* in food. Irradiation is also useful in killing fungus in fruit juices (Begum et al. 2020).

1.7.1 Principle of food preservation

The irradiation principle is based on ionizing radiation's ability to penetrate food materials and disrupt the molecular structures of bacteria, viruses, and pathogens (Halford 1957; Ramaswamy, Krishnamurthy, and Jun 2012). This method not only kill microbial cells but also prevents ripening and sprouting in fruits and vegetables, extending freshness. Unlike thermal treatments, irradiation occurs at ambient or sub-ambient temperatures, preserving the texture, flavour, and nutrient content of treated foods. This non-thermal property makes irradiation particularly advantageous for heat-sensitive products, providing a sturdy alternative to traditional pasteurization and sterilization procedures (Roberts 2014).