Next-Gen Innovations in Plant-Based Milk and Meat

Next-Gen Innovations in Plant-Based Milk and Meat:

Pioneering Technologies and the Future of Food

Edited by

Kamaljit Kaur and Prabhjot Kaur

Cambridge
Scholars
Publishing

Next-Gen Innovations in Plant-Based Milk and Meat:
Pioneering Technologies and the Future of Food

Edited by Kamaljit Kaur and Prabhjot Kaur

This book first published 2026

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-6894-1
ISBN (Ebook): 978-1-0364-6895-8

TABLE OF CONTENTS

CHAPTER 1

OVERVIEW OF INNOVATIVE PROCESSING TECHNOLOGIES AND THEIR ROLE IN PLANT-BASED MILK AND MEAT ALTERNATIVES

KAMALJIT KAUR[1], HARPREET KAUR[1]
AND PRABHJOT KAUR[2]
[1]DEPARTMENT OF FOOD SCIENCE & TECHNOLOGY, PUNJAB AGRICULTURAL UNIVERSITY, LUDHIANA, INDIA
[2] DEPARTMENT OF FOOD SCIENCE & TECHNOLOGY, I.K. GUJRAL PUNJAB TECHNICAL UNIVERSITY, KAPURTHALA

Abstract

The growing global demand for sustainable and healthy food options has driven significant innovation in milk and meat alternatives. Consumers are increasingly seeking plant-based, cultured, or alternative protein products due to concerns about health, environmental sustainability, animal welfare and food security. To meet these demands, innovative processing technologies have become essential in creating alternatives that closely mimic the sensory properties (taste, texture, and appearance) of conventional milk and meat products while offering nutritional value. However, developing these alternatives poses challenges related to stability, anti-nutrient reduction, off-flavors, allergens, sensory and technological limitations. To address these issues, novel processing techniques can be employed to improve the quality of plant-based milk and meat alternatives (PBMAs). The research and market for PBMAs have seen significant growth, with innovations emerging in recent years. This chapter explores advanced food processing technologies aimed at overcoming challenges that affect the quality of PBMAs. By enhancing the sensory qualities, nutritional value, and sustainability of these products, these technologies support the growing demand for healthier,

more ethical, and environmentally friendly food choices. As these innovations evolve, they will likely play an even greater role in transforming the global food landscape.

Keywords: PBMA; Cold plasma; Extrusion; High-pressure processing; Pulse electric field

1.1 Introduction

The rising global interest in sustainability, health, and ethical food production has driven the rapid growth of the milk and meat alternatives market. Traditional methods of producing animal-based products are increasingly scrutinized for their environmental impact, inefficiencies, and ethical concerns. In response, alternative products derived from plants, microbial fermentation, and cell cultures are emerging as viable solutions. However, producing alternatives that match the taste, texture, and nutritional profile of conventional milk and meat requires advanced processing technologies. These innovative technologies are pivotal in transforming raw plant materials and cultured cells into products that closely mimic their animal-based counterparts. By enhancing texture, flavor, appearance, and nutritional content, processing innovations play a key role in driving the adoption of alternative foods by consumers. Plant-based foods have become one of the top-selling product categories in the food sector, both in Europe and globally (Blasi et al., 2023). The growth of the plant-based milk market is being driven by increasing consumer demand for sustainable and ethical food choices, as well as the rapid development of high-quality plant-based products by food companies (Zheng et al., 2021). In 2022, the global plant-based milk market was valued at $2.8 billion, and it is projected to reach $7.3 billion by 2032, with a compound annual growth rate (CAGR) of 10.3% from 2023 onwards.

Recent research highlights the significant health benefits of plant-based beverages, including their role in boosting or regulating the immune system, reducing the risk of low bone density, heart disease, digestive issues, and improving physiological functions. These beverages also have antimicrobial properties and are rich in antioxidants that can neutralize free radicals (Paul et al., 2020). Plant-based milk alternatives (PBMAs) are also suitable for individuals with hypercholesterolemia, lactose intolerance, or dairy-related allergies (Moss et al., 2022). As noted by Jaeger and Giacalone (2021), factors such as lactose intolerance, environmental concerns, health motivations, and flexitarian diets have significantly increased global consumption of plant-based beverages derived from cereals, nuts, and legumes over the past two decades.

The development of PBMAs has also been shown to positively impact the environment by reducing water usage and contributing to lower ecotoxicity and climate change potential (Plamada et al., 2023). As the plant-based milk market continues to expand rapidly, a diverse range of innovative products is being introduced to meet the evolving preferences of consumers (Tang et al., 2023).

In recent decades, the global meat industry has seen significant growth, with production levels reaching approximately 337 million tons by 2020—almost five times the amount produced in the 1960s. While Europe and North America initially led in meat production, Asia had become the dominant contributor by 2020, representing 41% of global output. This increase is largely attributed to both the considerable increase in the global population and significant socioeconomic developments. Looking ahead, forecasts suggest that by 2050, as the global population reaches nearly 9 billion, meat demand could potentially rise by 50–73%. This trend is driven by the growth of the population and a threefold rise in global income over the past fifty years, which has made meat more affordable and increased its consumption (Parlasca & Qaim, 2022).

The livestock sector, encompassing both meat and dairy, has considerable environmental challenges, including deforestation, greenhouse gas emissions, and water pollution. Moreover, high consumption of red meat is associated with various health risks, including cardiovascular diseases, type 2 diabetes and colorectal cancer. Traditional meat production also raises concerns over animal welfare, commonly associated with abusive practices. The challenges related to meat production and consumption are complex, impacting food security, health concerns, and animal welfare issues. Currently, around 800 million people worldwide suffer from chronic hunger, while 2 billion are affected by micronutrient deficiencies. The COVID-19 pandemic further exposed vulnerabilities in global food supply chains, emphasizing the necessity for more resilient and sustainable food systems. While meat provides essential nutrients, excessive consumption, particularly of processed meats, is associated with a range of health problems. Recognizing the unsustainability of current practices, the Food and Agriculture Organization (FAO) encourages a shift towards plant-based diets to mitigate climate change and encourage sustainable food systems. As part of this transition, innovative alternatives such as plant-based substitutes are gaining traction, providing more sustainable and ethical food choices. Plant-based meat analogs (PBMAs) have drawn attention for their potential to offer a more nutritious alternative to red meat, replicating the texture and taste of animal meats with ingredients derived from plants. However, they still face challenges in fully replicating the authenticity of conventional meat (Flint et al., 2023; Jang & Lee, 2024).

The growing demand for plant-based milk and meat alternatives (PBMAs) is driven by environmental, health, and ethical concerns, yet replicating the sensory qualities of animal milk and meat continues to be a significant challenge. This chapter aims to explore these obstacles by analyzing the current trends, ingredients and innovative processing techniques in the plant-based milk and meat alternatives sector. Table 1-1 summarizes the effect of innovative technologies on PBMAs.

Table 1-1: Impact of innovative technologies on plant-based milk and meat analogs

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Sesame milk	Cold plasma	25, 60 and 120 W corresponds to 1, 1.5 and 2 kV potential difference and 24.5, 40.3, 59.8 mA current for 5 mL/min	Lipoxygenase activity, anti-nutritional factors including phytates and oxalates decreased to 67%, 25% and 10%, respectively at 120W	Dharini et al., 2023
Sage extract added beef patties	Cold plasma	Sage extracts (0.05% and 0.075%); conventional extraction or with cold plasma assistance; 80%O_2; stored in cold conditions for 8 days	The addition of sage at 0.075% prevented hexanal formation and inhibited lipid oxidation	Pogorzelska-Nowicka et al., 2022
Ground ham with added winter mushroom powder (as an alternative to synthetic nitrite and phosphate)	Cold plasma	1% PWMP; 40°C for 30 days	Plasma-treated winter mushroom powder (PWMP) can successfully replace synthetic nitrite, but it is an insufficient substitute for phosphate in ground ham	Jo et al., 2020

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Plant-protein preparation solutions in pork sausages	Cold plasma	500 ppm nitrile; 75 ppm sodium nitrite; stored for 8 days	The addition of nitrite through solutions of plasma-activated soy and pea preparations extended the shelf life of sausages comparable to sodium nitrite, without negatively affecting the aroma	Marcinkowska-Lesiak et al., 2022
Oat milk	Cold plasma	170–230 V for an exposure time of 5–15 min.	With plasma treatment, total soluble solids (TSS), titratable acidity (TA), and solubility index (SI) increased, whereas pH, total protein content, and viscosity decreased. At an intense plasma treatment of 230 V for 15 minutes, the highest microbial log reduction of 2.18 and 1.47 in bacteria and yeast and molds, respectively, were achieved	Eazhumalai et al., 2022

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Pork sausages added with plasma activated milk powder	Cold plasma	100 ppm sodium nitrite; 5% plasma activated milk powder ; 0.05% ascorbic acid	Sausages cured using the proposed alternative method (5% plasma activated milk powder with 0.05% ascorbic acid) exhibited higher cooking yield, lighter color, better texture, and different aroma profile compared to those cured with sodium nitrite	Marcinkowska-Lesiak et al., 2022
Vegetarian meat loaves (VMs)	Ultrasonication	Non-vacuum ultrasonic; Vacuum non-ultrasonic and Vacuum ultrasonic treatment for 20 min under an ultrasonic power of 200 W	Vacuum ultrasonic treatment improved textural qualities, promoted protein cross-links and network structure and resulted in uniform moisture distribution	Yang et al., 2021
50% reduced-phosphate frankfurters	Ultrasonication	25kHz; 240W; with 10 sec on/10 sec off cycles; 12℃ for 15, 20, 25, 30, and 35 min.	25-min ultrasound treatment significantly reduced cooking loss and enhanced emulsion stability, textural properties, and sensorial parameters of reduced phosphate frankfurters	Zhang et al., 2021
Soymilk	Ultrasonication	400 W; 25 kHz; 1-16 min	Improved protein digestibility, along with a reduction in trypsin inhibitor activity of up to 52%	Vanga et al., 2020

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Polyphenol added harbin dry sausages	Ultrasonication	150W for 15 min	At 150W for 15 min, the antioxidant capacity of ASL (*Allium senescens* L.) seed extract was the highest. A concentration of 6 g/kg of ASL seed extract was effective in inhibiting lipid and protein oxidation, as well as reducing color deterioration in dry sausages	Qin et al., 2021
Emulsion Gels (EG) made with sonicated soy protein isolate dispersions as fat replacer in frankfurters	Ultrasonication	20kHz for 30 min using a 1/2″-diameter tip operating at an amplitude of 60 μm and power input of 30–40 W	Improved fatty acid composition and fibre content and concluded that substituting pork back fat with functional EG resulted in healthier meat products	De Souza Paglarini et al., 2019

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Nano soy protein particles (SPI) and nano glycinin protein in beef burgers	Ultrasonication	20 kHz; 400 W/cm2; 40 min	High-intensity ultrasound treatments altered the structure of soy protein isolate (SPI) particles, reducing their size and causing the aggregation of glycinin (GLY) particles to the nanoscale (1-100 nm). As a result, the functional properties of both SPI and GLY particles improved. Nano soy proteins and nano glycinin can serve as functional ingredients that decrease cooking loss and shrinkage, enhance water-holding capacity, and improve the sensory attributes of beef burgers	Azab et al., 2019
Soy milk	Ultrasound	35 kHz; 20 and 40ºC; 20, 40, and 60 min	Ultrasound treatment significantly increased the protein content of extracted soymilk by nearly 6.3%	Fahmi et al., 2011

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Apple pomace (AP) and coffee silverskin (CSS) powders as phosphate replacers in Sausage	Ultrasonication	250W; 20 kHz; 30min	Addition of ultrasound- treated AP and CSS increased the water holding capacity and emulsion stability, decreased cooking loss and improved the quality of phosphate-reduced sausages whereas no significant changes were observed in color, texture and proximate content values	Thangavelu et al., 2022
Coconut milk	Ultrasonication	20 KHz for 5, 10 and 15 min	Ultrasonication positively influenced the stability of coconut milk by increasing the emulsion stability index (ESI) and reducing the creaming index. The TSS and protein content of coconut milk increased significantly by increasing the sonication time. Prolonged exposure to ultrasonication enhanced particle size reduction due to the cavitation effect	Indu et al., 2019

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Oat based beverage	Pulsed electric field	Moderate electric field strengths (9–10 kV/cm) combined with mild preheating (30–45 °C) for 25 seconds were applied across a range of specific energy inputs (77–245 kJ/L).	PEF combined with preheating reduced the levels of *E. coli* and *L. innocua* by at least 5 log units, while α-amylase activity decreased by up to 89%	Horlacher et al., 2024
Coconut milk	Pulsed electric field	2.5 kVcm; 20 pulses; 575 sec and1 Hz	Treatment with high-intensity electric field pulses under suitable conditions resulted in 20% increase in milk yield as compared to the untreated samples	Ade-Omowaye et al., 2000
Coconut milk	Pulsed electric field	High-intensity pulsed electric filed treatment: 4.25 kV/cm; 163 pulses, energy consumption less than 10kJ/kg; Thermal method: 80 °C, 15 min, energy consumption of about 200 kJ/kg	The yield of coconut milk using high-intensity pulsed electric field treatment was distinctly higher (79.68%) than untreated samples (74.03%) and slightly higher than that of thermal (78.14 %) or freeze-thaw (82.20%) pretreated samples	Eshtiaghi & Paoplook, 2013

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Oat beverage	Pulsed electric field	10–24 kV/cm; 110–115 kJ/L; 80–522 µs; 35℃ inlet temperature	Log10 reductions ≥5.7 of L. plantarum was achieved	Thamsuaidee et al., 2024
Soy milk	Pulsed electric field	20–40 kV/cm; 450, 1350, and 2250 ms	PEF treatment reduced soymilk allergenicity, LOX activity, and trypsin inhibitor activity to 38.99 ±17.7, 79.26±3.74, and 91.71±10.64%, respectively.	Anbarasan et al., 2023
Soy milk	Pulsed electric field	40 kV/cm; 0 to 547 µs	PEF inactivates *E. coli*, *S. aureus*, and SLOX (soybean lipoxygenase) without affecting the quality characteristics of soymilk	Li et al., 2013
Olive oil and soy sauce added chicken breast meat	High-pressure processing	300 or 600MPa	The combination of HPP with the addition of soy sauce or olive oil is an effective technology for enhancing the chemical, health and sensory qualities of chicken breast meat	Kruk et al., 2014
Pork myofibrillar protein with soy protein isolate (SPI)	High-pressure processing	200MPa;10 min	The addition of 2% SPI enhanced the gel characteristics and water-holding capacity of pork myofibrillar protein under 200 MPa	Li et al., 2021

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Sage powder added beef burgers	High-pressure processing	300 MPa for 10 min, at 9.9 °C and 600 MPa for 10 min at 10.2°C	Burgers exposed to 600 MPa retained acceptable microbial quality after 60 days	Mizi et al., 2019
Soy protein-based high moisture meat analogs	High-pressure processing	200, 400 and 600 MPa; 5, 10 and 15 min	Products treated with high-pressure (600 MPa) showed the highest reductions in microbial growth but the aroma of the beans became more pronounced	Limsangouan et al., 2024
Soymilk	Microwave heating	2450 MHz; 70°C–100°C; 2 to10 min	Increased digestibility up to 93% at 85°C after microwave processing for 10 min	Vanga et al., 2020
Beef and vegan burgers	Microwave processing	1–1.15 min each side at 900 W	After microwave processing, vegan burgers showed similar protein content, less fat content and lower energy values along with higher antioxidant capacity parameters than beef burgers. During *in vitro* digestion, lipid oxidation was more pronounced in vegan samples than in beef products	Ariz et al., 2024

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Almond and hazelnut milk	High-pressure homogenization	62, 103 and 172 MPa; 121°C and 85°C for 15 and 30 min, respectively	The combination of high homogenization pressure and low heat treatment (172 MPa at 85°C for 30 minutes) significantly enhanced the appearance and physical stability of almond and hazelnut milk	Bernat et al., 2015
Soy milk	High-pressure homogenization	207 and 276 MPa; 0.75 and 1.25 L/min; 121 and 145°C	No lipoxygenase activity was detected and treated soy milk remained stable for 28 days	Sidhu & Singh, 2016
Whole Peanut milk (WPM)	Microfluidization	0–120 MPa	At 120 MPa, WPM showed good stability without separating for 67 hours, with smaller, uniform particles and higher viscosity. The proteins formed a network around oil droplets, and whole peanut milk processed at 120MPa had the highest flavor content.	Dai et al., 2022
Soy Protein Meat Analog	High-moisture extrusion	Moisture contents of 60%, 65%, and 70% and cooking temperatures of 138, 149, and 160 °C	Lower moisture during extrusion led to higher temperature and pressure, resulted in tougher and more fibrous products, while higher moisture and temperature improved water absorption.	Lin et al., 2000

Milk/Meat analogs	Technology applied	Processing parameters	Observations	References
Fibrous meat analogs from blends of oat-pea proteins	Low-moisture extrusion	Oat and pea protein blends at ratios- 20:80, 30:70, 50:50, and 70:30; screw speed of 200–1200 rpm; barrel temperatures of 135–160 °C and moisture content from 25 to 35%	Increasing oat content in the blend improved the fibrous texture of meat analogs, while the water holding capacity decreased, moistness and mild flavor remained consistent. This study concluded that blends of oat and pea proteins serve as a viable alternative to soy and gluten for producing meat substitutes.	Kalenda et al., 2021
Meat analogues from hempseed protein concentrate and oat fibre residue	High-moisture extrusion	Moisture contents (60, 63, 66%); screw speeds (500, 700, 900); temperature profiles (40-70-110-130 °C and 40-70-120-150 °C)	Meat analogues made from hempseed protein exhibited a fibrous structure and improved texture when processed at higher temperatures, despite experiencing a decrease in hardness and chewiness due to higher moisture content.	Zahari et al., 2023

1.2 Cold Plasma

Cold plasma is gaining attention as an innovative, non-thermal processing technology, with potential applications in plant-based meat and milk alternatives. Its growing appeal in the food industry, particularly for heat-sensitive products, comes from its nonthermal, versatile, and eco-friendly properties (Mollakhalili-Meybodi et al., 2021; Kopuk et al., 2022). In the food and agriculture sectors, it is mainly used for packaging modification, seed germination enhancement, microbial inactivation and the degradation of pesticides and mycotoxins (Mehta et al., 2022; Thirumdas et al., 2017). Recent studies have also shown that cold plasma treatment can activate antioxidant enzymes and inactivate undesirable oxidative enzymes, depending on the treatment properties of cold plasma, which can thereby improve the shelf life of foodstuffs (Bangar et al., 2022).

Plasma, as a unique state of matter, mainly contains a complex mixture of electrons, positively and negatively charged ions, ground or excited states of molecules, free radicals, neutral atoms, heavy particles, UV–visible light photons, heat and electromagnetic radiations (Bayati et al., 2024). According to Nikmaram & Keener (2022) plasma consists of an ionized gas mixture of ions, free electrons, atoms and molecules. When plasma discharges occur in open-air atmospheres, the primary active agents produced are reactive oxygen species (ROS) and reactive nitrogen species (RNS). Numerous plasma sources are employed in food treatment including plasma jets, dielectric barrier discharges (DBD's), microwave discharges and corona discharges. The effectiveness of plasma treatment on food, such as milk, is influenced by several factors, including device geometry, electrode design, voltage, pressure, exposure mode, treatment time, humidity, gas type, and sample volume.

Among the different types, atmospheric cold plasma is most commonly applied to fresh produce at ambient temperatures to eliminate microorganisms and toxins. Depending on the mode of excitation, it can be classified into dielectric barrier discharge (DBD), radio frequency discharge (RF) and microwave discharge systems (Chen et al., 2020). Sruthi et al. (2022) reported that cold plasma processing is a technique that applies electricity and reactive carrier gases, including oxygen, nitrogen and helium, to inhibit enzymes, kill microorganisms and preserve food quality without the use of chemical antimicrobial agents. Additionally, it enhances the barrier properties of packaging materials and provides antimicrobial benefits. In sesame milk, cold plasma reduced antinutritional factors and allergenicity (Dharini et al., 2023) and reduced *Listeria innocua* in ready-to-eat meat (Ekezie et al., 2017). Its application in plant-based meat alternatives has shown promising results. For instance, Gao et al. (2021) demonstrated that incorporating antioxidants such as BHT, carnosine, and plant extracts from rosemary, pomegranate, and pine bark into CP-treated patties not only enhanced microbial inactivation but also inhibited lipid oxidation. This combination of cold plasma treatment with antioxidant supplementation helps maintain product quality and extends shelf life, making it a valuable tool in producing plant-based meat and milk products.

1.2.1 The Mechanism of Plasma Action on Food Pathogens

The presence of plasma-charged particles and reactive species is primarily responsible for microbial inactivation in food systems. When the outer part of the cell wall is bombarded with charged particles produced by cold plasma, the accumulated charges cause the transmembrane potential to rise to a critical level. This rise deforms the shape of ion channel proteins, allowing specific anions and cations, such as chloride, sodium, potassium, and calcium to pass through the ion channels.

If the electric field intensity produced by the charged particles is sufficiently high, it can vary the three-dimensional structure of proteins in such a way that it detaches from the cell membrane, resulting in the formation of larger pores in the membrane and its subsequent weakening. Therefore, charged particles produced in cold plasma penetrate cells, affecting enzyme activities and protein functions. The formation of pores in the membrane results in cytoplasm leakage and cell death (Bayati et al., 2024).

In addition to this, the ions generated during gas ionization possess significant kinetic energy. This energy contributes to structural damage within the cell through direct bombardment of cellular components, leading to further physical disruption. The combination of this mechanical damage and chemical interactions effectively neutralizes microorganisms, ensuring enhanced food safety and prolonging the shelf life of products (Lunov et al., 2016).

Cold plasma, therefore, acts as a multifaceted approach to microbial inactivation by inducing both physical and biochemical damage to cells. This innovative technology is becoming increasingly important in the food industry as it offers a non-thermal method for improving microbial safety without compromising the nutritional and sensory properties of food.

1.3 Ultrasonication

Ultrasonication is considered as a green technology due to its potential to produce environmentally friendly products (Rao et al., 2021). It is one of the fast, versatile, emerging, and promising non-destructive green technologies used in the food industry from last few years (Majid et al., 2015). As a green and non-thermal processing method, ultrasound has the advantage of improving processing efficiency and reducing processing costs (Li et al., 2024). The typical frequency range that is usually used in ultrasound applications varies between 20 kHz and 500 MHz (Al-Juboori et al., 2015). Ultrasonication is used in the quality control of fresh vegetables and fruits in both pre-harvest and post-harvest, cheese processing, commercial cooking oils, bread and cereal products, bulk and emulsified fat-based food products, food gels, aerated, and frozen foods.

In the category of plant-based meat alternatives, ultrasonication has shown significant potential. Yang et al. (2021) reported that vacuum ultrasonic treatment effectively enhanced the production of vegetarian meatloaves made from textured wheat protein, achieving a texture and sensory quality comparable to traditional beef patties. This innovation demonstrates the capability of ultrasonication to optimize the sensory attributes of plant-based products, thereby improving consumer acceptance. In addition to meat alternatives, ultrasound technology has been utilized to enhance the quality of plant-based milk. Dai et al. (2020) have provided a great deal of research achievements about the application of ultrasound technique in dairy processing such as enhancement of dairy ultrafiltration, modification of functional dairy protein ingredients, improvement of dairy physicochemical properties, dairy ingredients processing, cleaning of ultrafiltration membranes and sterilization.

Furthermore, ultrasonic-assisted extraction techniques have been employed to maximize the antioxidant potential of ingredients used in plant-based products. A study on the extraction of total polyphenols from *Allium senescens* L. (ASL) seeds was conducted and found that applying ultrasound at 150 W for 15 minutes yielded an extract with significant antioxidant efficacy. The resulting ASL seed extract demonstrated the ability to inhibit lipid and protein oxidation, thereby preserving the quality of Harbin dry sausages (Qin et al., 2021). Overall, ultrasonication represents an innovative approach to improving the quality and sustainability of food products.

1.3.1 Mechanism

The mechanism of ultrasonication is primarily based on acoustic cavitation, which involves the formation, growth, and collapse of bubbles in a liquid medium. This process is driven by the propagation of ultrasound waves, leading to a range of mechanical, thermal, and chemical effects that influence biological systems, particularly in food processing.

During acoustic cavitation, the high temperatures and pressures that develop can break down water molecules into free radicals, such as hydrogen (H^+) and hydroxyl (OH^-) ions. These radicals accelerate specific chemical reactions, facilitating the disruption of plant cell walls and altering enzymatic activity. As ultrasound waves propagate, the oscillation and collapse of bubbles generate localized hotspots with extreme conditions—temperatures reaching approximately 5,000 K and pressures around 1,000 atm. These extreme conditions produce free radicals that enhance reaction rates (Soria & Villamiel, 2010). These free radicals can interact with various components, such as enzymes, potentially affecting their structure and function by scavenging amino acids, which are vital for structural stability and catalytic functions (Kutlu et al., 2022).

The mechanical effects of ultrasonication include collapse pressure, turbulence, and shear stress, all of which contribute to the physical disruption of cells. This mechanical action is essential for breaking down cell walls, and facilitating the release of intracellular components. As ultrasound waves propagate, they create alternating positive and negative pressure cycles, causing the material to expand and compress. This process leads to cell rupture and promotes mass transfer (Al-Juboori et al., 2015). Additionally, the heat generated by the collapsing cavitation bubbles and the absorption of sound energy by the medium contributed to localized and overall temperature increases. These transient high temperatures can damage the structures of microorganisms and inactivate key enzymes, making ultrasonication a valuable non-thermal sterilization technique for food processing (Zhang et al., 2021).

Cavitation bubbles generated by ultrasound are categorized into two types: stable (steady-state) and transient (inertial). Stable cavitation involves the oscillation of bubbles without collapse, resulting in gradual energy release and the formation of eddy currents in the surrounding medium. In contrast, transient cavitation occurs when bubbles rapidly expand and collapse under low-frequency ultrasound (20–100 kHz). This violent collapse releases significant energy, producing intense shear stress and turbulence, which leads to the generation of free radicals (Ercan & Soysal, 2011). The combined mechanical and chemical effects disrupt the structural integrity of microbial cells, facilitating their inactivation. By employing these processes, ultrasonication acts as a highly efficient non-thermal method in food processing, ensuring enhanced microbial safety and longer shelf life while preserving the integrity of the food.

1.4 Pulsed Electric Field

Pulsed electric field (PEF) is considered as an innovative non-thermal approach for preserving foods and enhancing their quality. This technology involves the use of electric field pulses of short duration, from several nanoseconds to several milliseconds with an electric field strength of 0.1–80 kV/cm applied to a food positioned between or passed through two electrodes (Bhat et al., 2019). PEF treatments are carried out at ambient, sub-ambient or slightly above ambient temperatures for a shorter period (milliseconds), ensuring minimal energy loss due to heating of the food matrix (Odriozola-Serrano et al., 2013).

PEF is regarded as more effective than traditional thermal processing and preservation methods as it minimizes adverse effects on food quality and nutritional value while preserving the physical and sensory attributes of products. Its applications extend across a wide range of food types, including liquid and semi-solid foods, as well as solid foods. This non-thermal technique involves applying short bursts of high-voltage electric fields, allowing for effective food preservation at lower temperatures and shorter residence times, thereby retaining the fresh-like character and nutritional integrity of the products.

The application of PEF in food preservation offers tremendous potential for extending shelf life without the need for heat treatment, enabling effective and rapid control of microbiological spoilage. Studies have demonstrated its effectiveness in inactivating microorganisms in various liquid foods, including milk, dairy products, and juices, while simultaneously enhancing energy efficiency in an economical manner. In the field of meat processing, PEF can be utilized for multiple purposes, including the enhancement of cell permeation to increase tenderness, the attenuation of microbial load to improve the shelf life and the maintenance of volatile profile of meat during storage (Syed et al., 2017; Toepfl et al., 2005). PEF treatments could also be used to modify the rheological and color properties of soy milk during the processing and manufacturing of certain food products (Xiang et al 2011). As consumer demand for high-quality, minimally processed foods continues to grow, PEF technology represents a promising solution for maintaining product integrity and sustainability in the meat and dairy industries.

1.4.1 Mechanism

Pulsed Electric Field (PEF) technology is gaining significant attention due to its effective lethality against microorganisms and remarkable extraction efficiency for valuable components. The mechanism of PEF technology involves delivering pulsing power to the product placed between two electrodes that enclose the treatment area of the PEF chamber.

The typical PEF system has a pulse generator that produces high-voltage pulses, a treatment chamber designed to hold the product associated with controlling and monitoring devices. The food product is placed within the treatment chamber, where electrodes are connected by a non-conductive material to prevent electrical flow between them. When the system is activated, high-voltage pulses are generated and applied to the product. As the product undergoes these pulses, it experiences an electric force per unit charge, which causes electroporation, a phenomenon where the cell membranes of bacteria are disrupted. This effect significantly reduces the microbial load and enhances the extraction of valuable compounds from the food matrix (Mohamed and Eissa, 2012; Syed et al., 2017). Overall, PEF technology offers a promising, non-thermal method for enhancing food safety and improving the extraction of bioactive compounds, making it a valuable tool in food processing.

1.5 Radiofrequency and Microwave Heating

Microwave (MW) ranging from 300–300,000 MHz, and radio frequency (RF) waves from 0.003 to 300 MHz are part of the electromagnetic (EM) spectrum and play a significant role in modern food processing. Generally, two frequencies—915 MHz and 2450 MHz—are employed in microwave food processing, while RF heating utilizes three frequencies: 13.56 MHz, 27.12 MHz, and 40.68 MHz (Stefanoiu et al., 2016).

In the food sector, MW heating is widely applied in food processing operations such as tempering meat or fish blocks and precooking bacon or meat patties, while RF heating is commonly utilized for drying freshly baked products. These technologies expedite processing times, save floor space, and enhance product quality compared to conventional methods (Ramaswamy & tang, 2008).

Previous research has shown that the use of longer wavelengths in RF heating does not cause interference or adverse effects on food products. In contrast, microwave heating can lead to uneven heating patterns, resulting in cold and hot spots. RF-treated meat exhibits enhanced quality and coagulation, resulting in a product that maintains an appealing taste and appearance. This technology not only elevates the quality of meat but also proves beneficial in the dairy sector. Specifically, RF heating is effective in yogurt pasteurization, eliminating harmful microorganisms in both liquid and solid foods. Inactivation of *Bacillus subtilis* spores in soybean milk by radio-frequency flash heating at 28MHz by heating up to 115ºC for 0.4sec was studied by Uemura et al. (2011). This dual application emphasizes the versatility of RF heating in improving the safety and quality of both meat and milk products (Altemimi et al., 2019).

1.5.1 Mechanism

RF and MW heating are advanced thermal processing methods in the food engineering field. Both RF and MW heating are mainly applied to target dielectric materials (Jiao et al., 2014), with dipole rotation and ionic conduction serving as the dominant mechanisms for heat generation.

When foods having polar molecules, such as water, are subjected to an alternating electric field, dielectric heating occurs. These polar molecules possess electric dipole moments, which leads to a lack of alignment between their negative and positive charge centres when placed in an electric field, while the molecules themselves align with the field. Polarization is caused due to the migration of positive and negative charges to opposite ends of the molecules. Furthermore, polar molecules continuously rotate to align with the alternating electric field, a phenomenon known as dipole rotation (Altemimi et al., 2019). In this process, the friction between surrounding molecules transforms electromagnetic energy into heat, leading to a temperature increase in the treated materials.

In addition to dipole rotation, ionic conduction also contributes to heating. Unlike polar molecules, dissociative ions in foods exhibit motion in response to an applied electrical field. Similarly, the direction of their motion varies with alternating electrical fields. Heat is produced within the material due to the friction among molecules caused by the back-and-forth oscillation of ions. This mechanism is known as ionic conduction. These advanced thermal processing methods, through their unique mechanisms, offer efficient, targeted heating solutions that enhance product quality and safety in various food applications.

1.6 High-Pressure Processing

High-pressure processing (HPP) is an innovative, non-thermal food processing technique that applies pressures ranging from 50 to 1000 MPa to both liquid and solid foods, whether packaged or unpackaged (Tao et al., 2014). This innovative technique enhances food preservation while maintaining the quality of fresh products, proving effective for food preservation with minimal impact on nutritional and sensory qualities (Chandrajith et al., 2019). HPP, also referred to as high hydrostatic pressure processing and ultra-high-pressure processing, preserves the sensory attributes of food compared to traditional thermal sterilization methods (Muntean et al., 2016; Yordanov & Angelova, 2010).

HPP has emerged as a non-thermal preservation technology with the potential to extend the shelf life of food products, including milk, by effectively inactivating spoilage and pathogenic microorganisms. For raw milk, HPP has been shown to reduce the total viable count (TVC), Enterobacteriaceae, lactic acid bacteria (LAB), and *Pseudomonas* spp., thereby enhancing both its safety and shelf life (Stratakos et al., 2019). This technology has been successfully applied to inactivate soybean trypsin inhibitors and lipoxygenase, enhancing the quality and nutritional value of plant-based products (Ven et al., 2005). In the context of dairy processing, HPP offers several advantages, including maintaining the sensory and nutritional quality of milk while ensuring microbial safety. Its application in the dairy industry holds promise, particularly as consumers demand minimally processed, safe, and nutritious milk products.

HPP has shown remarkable potential in the meat industry for microbial control and food safety. Studies have demonstrated that pressure levels of 400, 600, and 900 MPa can effectively reduce pathogenic bacteria, such as *Salmonella enterica, Staphylococcus aureus* and *Listeria monocytogenes,* to almost undetectable levels in various meat products (Abera, 2019). This microbial inactivation not only extends the shelf life of meat products but also preserves their sensory and nutritional properties, making HPP a valuable tool in maintaining food quality and safety.

1.6.1 Mechanism

High-pressure processing (HPP) is governed by three fundamental principles, as described by Yordanov & Angelova (2010). The first is Le Chatelier’s principle, which states that any equilibrium process (such as a chemical reaction, phase transition, or conformational change) that involves a reduction in volume can be enhanced by pressure, thereby favoring reactions that lead to a volume decrease. The second principle, known as the isostatic principle, asserts that during compression, pressure is transmitted uniformly from all directions, allowing the product to retain its shape after decompression and facilitating the development of commercially successful processes (Kumar et al., 2019). This principle also clarifies that in high-pressure applications, where packaged food is surrounded by a pressurizing fluid, the pressure effects are distributed quasi-instantaneously and uniformly throughout the food, irrespective of its geometry and size. However, since air and water are compressed differently, the structure and shape of foods containing air pockets may be altered during pressure treatment unless they are perfectly elastic. Lastly, the principle of microscopic ordering, suggests that an increase in pressure at constant temperature enhances the molecular ordering of materials by restricting rotational, vibrational, and translational motion, ultimately increasing molecular order (Sehrawat et al., 2021; Martínez-Monteagudo & Balasubramaniam, 2016). Together, these principles clarify HPP’s underlying mechanisms and its potential to enhance food quality and safety.

1.7 Ultra High-Pressure Homogenization

Ultra-high pressure homogenization (UHPH) is an advanced food processing technique that significantly enhances the quality and stability of liquid products. By applying extremely high pressures, typically above 100 MPa (approximately 14,500 psi), UHPH effectively reduces particle sizes and creates stable emulsions, leading to improvements in texture, flavor release, and nutrient availability. One of its key advantages is its ability to enhance the stability of plant-based milk emulsions and their physicochemical properties with minimal effect on nutritional content (Munekata et al., 2020). UHPH-treated beverages exhibit superior colloidal stability, primarily achieved by reducing particle size and promoting new particle interactions. For instance, a treatment of 300 MPa resulted in the greatest reduction in peroxidase activity, whereas fat oxidation reactions were most stable at 200 MPa (Codina-Torrella et al., 2017).

Furthermore, high-pressure homogenization (HPH) can improve the functional and rheological properties of other food matrices, such as mechanically deboned chicken meat proteins. HPH improves protein structure and texture, making it a valuable technique for improving the quality of processed meat products (Saricaoglu et al., 2018). Overall, UHPH and HPH offer versatile solutions for improving food quality, enhancing texture, stability, and safety across a wide range of food products, from plant-based beverages to protein-rich foods.