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# Next-Generation Non-Thermal Food Processing Technologies: Energy Efficiency, Food Safety, and Food Waste

# Yeni Nesil Isıl Olmayan Gıda İşleme Teknolojileri: Enerji Verimliliği, Gıda Güvenliği ve Gıda İsrafı

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**ABSTRACT**

Global food systems are currently facing a profound sustainability crisis. This crisis is driven by multiple pressures, including rapidly increasing population, the urgent need for action on climate change, and the depletion of natural resources. It has been reported that existing food production and processing technologies are insufficient to meet the world's future food demand and remain largely inadequate in managing food waste. This situation necessitates the development and implementation of innovative technologies as alternatives to conventional food processing methods. This review provides an examination of next-generation non-thermal food processing technologies, particularly High Pressure Processing (HPP), Pulsed Electric Field (PEF), Cold Plasma (CP), and lyophilization, and their transformative potential for food systems. The evaluation demonstrates that next-generation non-thermal processing methods offer benefits that extend far beyond simple food preservation. Replacing heat-intensive processes with these alternatives not only improves energy efficiency but also helps maintain the authentic quality of foods by preserving their natural nutritional value, aromas, and textures. These technologies inactivate pathogens and extend product shelf life, thereby forming the first line of defense against food waste throughout the supply chain. Furthermore, this study explains how next-generation non-thermal processing methods, when integrated with hybrid systems and digital traceability approaches, can trigger a sustainable transformation in the food industry. Supported by technological integration, these methods ensure food safety while preserving nutritional value, enabling the production of more nutritious foods with lower environmental impact. Consequently, they support sustainable food systems and contribute to global food security with a reduced carbon footprint.

***Keywords-Circular Economy, Emerging Technologies, Green Preservation, Microbial Inactivation, Novel Foods, Shelf-life Extension.***

**Highlights**

- Next-generation non-thermal food processing technologies offer greater sustainability potential compared to conventional thermal processing methods.
- HPP, PEF, CP, and lyophilization applications ensure effective microbial inactivation while preserving nutritional value and sensory quality.
- These technologies contribute to the reduction of food loss and waste by enhancing energy efficiency and extending shelf life.
- The integration of hybrid systems with digital traceability paves the way for a structural transformation in sustainable food production.
- Their industrial-scale implementation is critical for reducing the carbon footprint of food systems and strengthening global food security.

# Yeni Nesil Isıl Olmayan Gıda İşleme Teknolojileri: Enerji Verimliliği, Gıda Güvenliği ve Gıda İsrafı

**ÖZ**

Küresel gıda sistemleri bugün derin bir sürdürülebilirlik kriziyle karşı karşıyadır. Bu kriz; hızla artan nüfus, acil aksiyon alınması gereken iklim değişikliği ve doğal kaynakların tükenmesi gibi ciddi birçok baskıdan kaynaklanmaktadır. Mevcut gıda üretim ve işleme teknolojilerinin, dünyanın gelecek gıda ihtiyacını karşılayamayacağı ve gıda israfı yönetiminde büyük ölçüde yetersiz olduğu bildirilmektedir. Bu durum, geleneksel

gıda işleme yöntemleri yerine, yenilikçi teknolojiler geliştirilmesini ve kullanımını zorunlu kılmaktadır. Bu derleme, yeni nesil ısıl olmayan gıda işleme yöntemleri olan, özellikle Yüksek Basınçlı İşleme (HPP), Vurgulu Elektrik Alan (PEF), Soğuk Plazma (CP) ve liyofilizasyon teknolojilerine ve bunların gıda sistemini sürdürülebilir dönüştürme gücüne ayrıntılı olarak değinmektedir. Bu değerlendirme, yeni nesil ısıl olmayan gıda işleme yöntemlerinin gıdayı korumaktan çok daha fazlasını sağladığını göstermektedir. Yüksek ısı gerektiren işlemlerin bu alternatiflerle değiştirilmesi, enerji tasarrufu sağlamanın yanı sıra gıdanın geleneksel besin değerlerini, aromalarını ve dokularını bozulmadan koruyarak gerçek kalitesini muhafaza etmeye de katkıda bulunmaktadır. Bu teknolojiler, patojenleri etkisizleştirir ve ürünlerin çok daha uzun süre taze kalmasını sağlayarak tedarik zinciri boyunca gıda israfına karşı ilk savunma hattını oluşturur. Bu çalışma, hibrit sistemler ve dijital izlenebilirlik yöntemleriyle birleştirildiğinde yeni nesil ısıl olmayan gıda işleme yöntemlerinin, gıda endüstrisinde köklü bir dönüşümü nasıl tetikleyebileceğini açıklamaktadır. Teknolojik entegrasyonla desteklenen bu yöntemler bir yandan besin güvenliğini sağlarken diğer yandan besin değerini koruyan, daha besleyici ve çevresel etkisi düşük gıdaların üretimini mümkün kılmaktadır. Böylece sürdürülebilir gıda sistemlerini desteklemekte ve daha düşük karbon ayak iziyle küresel gıda güvenliğine katkıda bulunmaktadır.

***Anahtar Kelimeler- Döngüsel Ekonomi, Yeni Gelişen Teknolojiler, Yeşil Koruma Teknolojileri, Mikrobiyal İnaktivasyon, Yeni Gıdalar, Raf Ömrünün Uzatılması.***

**Öne Çıkanlar**

- Yeni nesil ısıl olmayan gıda işleme teknolojileri, geleneksel ısıl işlemlere kıyasla daha yüksek sürdürülebilirlik potansiyeli sunmaktadır.
- HPP, PEF, CP ve Liyofilizasyon uygulamaları, mikroorganizmaları etkisiz hale getirirken, besin değerini ve duyusal kaliteyi korur.
- Bu teknolojiler, enerji verimliliğini artırırken raf ömrünü uzatarak gıda kayıp ve israfının azaltılmasına katkıda bulunur.
- Geleneksel ve yeni nesil ısıl olmayan gıda işleme teknolojilerinden oluşan hibrit sistemler ve dijital izlenebilirlik entegrasyonu, sürdürülebilir gıda üretiminde yapısal bir dönüşümün önünü açmaktadır.
- Endüstriyel ölçekte uygulanmaları, karbon ayak izinin azaltılması ve küresel gıda güvenliğinin güçlendirilmesi açısından kritik öneme sahiptir.

## I. INTRODUCTION

Global food systems are under increasing pressure due to the climate crisis, constraints on water and energy resources, a rapidly growing population, and structural vulnerabilities observed in food supply chains. These multifaceted stress factors directly impact not only sustainability of food production processes but also societies' access to safe and adequate food. In this context, food sustainability is considered a critical necessity for the long-term continuity of global food systems [1, 2].

The world population is expected to reach 9.7 billion by 2050, an increase projected to require approximately a 60% boost in current food production [3]. However, the urgency of transitioning to new and sustainable technologies is underscored by rising global food loss and waste, alongside the inadequacy of existing production and processing methods to meet this demand [4, 5]. Similarly, reports focusing on Türkiye indicate that food loss and waste rates are on a national upward trend, clearly demonstrating the structural limits of current production models [3].

Türkiye faces a significant risk to food security, driven by projected temperature increases of 2–3 °C by 2040 and persistent inefficiencies in irrigation systems [6]. These environmental pressures undermine national food self-sufficiency and position technological transformation as a structural necessity rather than a policy option. Food losses in Türkiye are predominantly concentrated in post-harvest and storage stages, particularly for perishable commodities such as fruits and vegetables, largely due to insufficient cold chain infrastructure and logistical constraints [3].

These structural inefficiencies further exacerbate pressures on food security by increasing resource losses along the supply chain. The urgency of this transition is reinforced by the European Green Deal, as the Carbon Border Adjustment Mechanism is projected to impose an annual economic burden of €1.1–1.8 billion on Turkish industries [7]. Within this context, non-thermal technologies, characterized by lower energy demand and reduced carbon emissions, represent a strategic pathway for Türkiye to enhance climate resilience while sustaining competitiveness in an increasingly decarbonized global economy [3, 8]. Sustainability challenges within current food systems are making technical and environmental limitations of traditional thermal processing increasingly evident. In this regard, non-thermal food processing technologies emerge as a promising alternative that redefines the balance between energy efficiency and product quality. Methods such as High Pressure Processing (HPP), Pulsed Electric Field (PEF), Cold Plasma (CP), and lyophilization are garnering growing interest in both research and industrial applications due to their low energy consumption, capacity to preserve nutrients, potential to enhance microbial safety, and ability to maintain product quality for extended periods with minimal loss [9, 10, 11, 12, 13].

Beyond process optimization, particularly through their potential to reduce food waste, these technologies are deemed as tools for structural transformation within food systems. Given that approximately 1.05 billion tonnes of food were wasted globally in 2022, meaning at least 1 billion meals a day were lost from the consumption chain, the urgency of a technological shift focused on efficiency and food safety is clear [2, 5, 9].

The aim of this review is to comprehensively and critically evaluate the effects of next-generation food processing technologies on energy efficiency, food safety, and reduction of food waste. Furthermore, by discussing the current status and future potential of these technologies within sustainable food systems, this study seeks to shed light on the transforming dynamics of the industry.

## II. SEARCH STRATEGY/ METHODOLOGY

This narrative review was conducted through structured searches in PubMed, Scopus, and Web of Science databases covering the period 2020–2026. The search strategy utilized combinations of keywords such as “non-thermal food processing,” “High Pressure Processing (HPP),” “Pulsed Electric Field (PEF),” “cold plasma,” and “lyophilization.” To ensure a comprehensive scope, additional terms including “energy efficiency,” “food safety,” “food waste,” “carbon footprint,” and “industrial applications” were incorporated. Inclusion criteria consisted of peer-reviewed original research articles, review papers, and institutional reports from FAO, WHO, and EFSA. Both laboratory and industrial-scale studies were considered to evaluate technological performance, food safety, and environmental sustainability of next-generation non-thermal technologies. Exclusion criteria included studies without sufficient methodological or technical detail on the targeted non-thermal technologies, articles not aligned with the scope of food processing applications, opinion-based publications without scientific data, and non-peer-reviewed sources lacking scientific validation. Evidence was qualitatively assessed based on study design, placing emphasis on systematic reviews and experimental studies with industrial relevance. While English-language publications were prioritized, key Turkish-language sources were included to address national regulatory frameworks and local food system contexts. Although the focus remained on this contemporary literature, seminal earlier studies provided necessary foundational scientific context.

## III. SUSTAINABILITY PERSPECTIVE

Food production systems must be addressed within a multidimensional sustainability framework where energy utilization, food safety, and food waste interact with each other. Traditional thermal processes, while standard, increase environmental pressure due to high energy requirements, often lead to nutrient degradation, and can indirectly trigger food waste by limiting product shelf life [2, 9]. Accordingly it is required that sustainable food systems focus not only on production efficiency but also on preserving nutritional value and reducing waste.

In this context, next-generation non-thermal food processing technologies can play a pivotal role in achieving sustainability goals. Methods such as High Pressure Processing (HPP), Pulsed Electric Field (PEF), Cold Plasma (CP), and lyophilization allow for the optimization of energy use while ensuring microbial safety of products and preservation of nutrients [7, 13]. For instance, PEF applications enable the inactivation of microorganisms without the need for chemical additives while limiting loss of vitamins and antioxidants; thereby contributing to reduction of food waste by extending shelf life [11, 14].

Additionally, these technologies contribute to lowering the carbon footprint through their potential to reduce energy and water consumption, while supporting environmental sustainability through minimal additive use and clean-label production approaches [1, 2]. Consequently, in this system where energy efficiency, food safety, and food waste are intrinsically linked, non-thermal technologies transcend being mere processing methods and are recognized as fundamental components of sustainable food systems.

## IV. NEXT-GENERATION NON-THERMAL TECHNOLOGIES

### *A. High Pressure Processing*

*1) Fundamental Principles and Mechanisms of Action:* High Pressure Processing (HPP) is an innovative non-thermal technology that ensures the inactivation of microorganisms and the control of enzymatic activities by exposing food products to extreme pressures ranging from 100 to 600 MPa at room temperature. Due to the instantaneous and homogeneous transmission of pressure throughout the food matrix, a uniform effect is achieved from the surface to the core of the product; thus, nutritional value, aromatic compounds, and sensory attributes are largely preserved compared to traditional thermal treatments [15]. With these characteristics, HPP stands out as a modern food processing approach that maintains "fresh-like" product quality while extending shelf life. The fundamental processing steps of the HPP system are schematized in Figure 1.

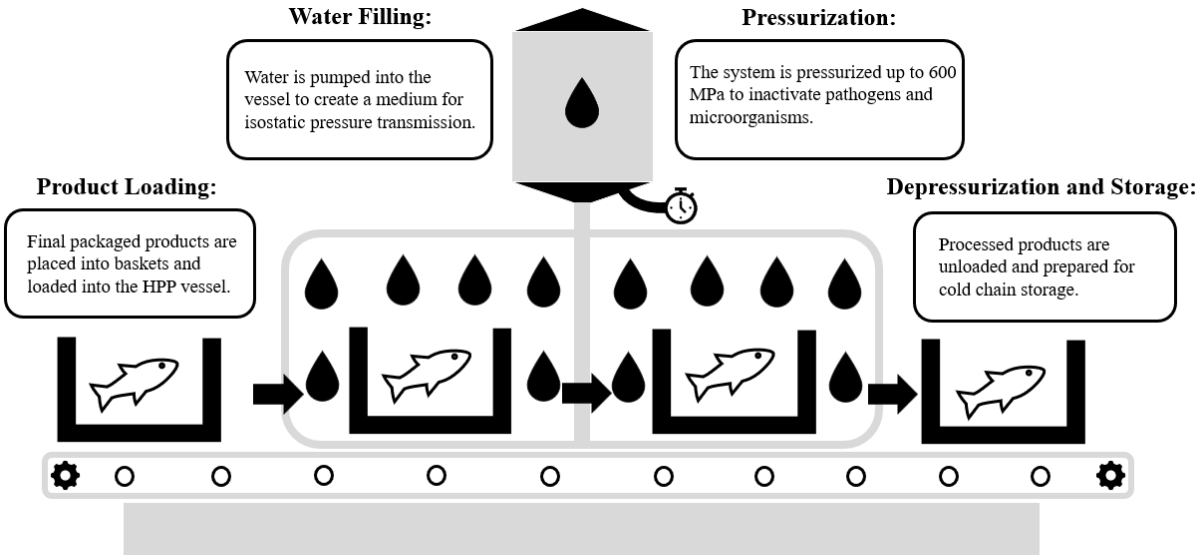



**Figure 1.** Industrial application cycle and operational stages of HPP technology

The microbial inactivation mechanism of HPP is primarily based on the structural sensitivity of the cell membrane to pressure. Under high pressure, the compression of the phospholipid bilayer disrupts membrane fluidity, leading to the leakage of intracellular components and the interruption of energy metabolism and respiratory processes. Electron microscopy studies reveal multifaceted morphological damages in pressure-exposed cells, such as surface irregularities, membrane-wall separations, cytoplasmic condensation, and ribosomal disruptions. While limited repair may be possible at low pressure levels, cellular integrity is irreversibly lost within the 200–600 MPa range, rendering viability unsustainable. In this multi-stage process, microbial sensitivity is directly correlated with cell membrane composition, membrane fluidity, and the pressure resistance of internal structures [16].

The efficacy of HPP depends not only on the pressure level but also on the pH and water activity of the food. The ionization of water under pressure lowers the pH of the medium, creating acidic conditions; this synergistically enhances inactivation, particularly in pathogens such as *Listeria monocytogenes*. Conversely, low water activity causes cell shrinkage and membrane thickening, which creates a protective barrier against the effects of pressure and limits the effectiveness of HPP. Therefore, product composition, pH, and water activity are considered critical parameters in the HPP process [16].

*2) Applications in Food Systems:* In dairy science, HPP emerges as a robust alternative to thermal pasteurization; at levels of 400–600 MPa, it effectively reduces pathogens while largely preserving protein structure, nutritional value, and sensory attributes. While pressure-induced rearrangements are observed in casein micelles and whey proteins, milk fat distribution, enzymatic activities, and emulsion stability are positively influenced. In cheeses produced from bovine and camel milk, HPP ensures microbial safety while enabling the preservation or improvement of species-specific textural properties [17, 18]. Similarly, studies on human milk indicate that HPP preserves fatty acid and triacylglycerol profiles better than Holder pasteurization, offering a reliable alternative for milk banks [19]. On an industrial scale, HPP provides a shelf life of up to 60 days for fresh cow milk while keeping vitamin and mineral losses to a minimum [20].

High hydrostatic pressure applications are also reported to offer significant advantages in plant-based and liquid food systems. In high-moisture by-products such as okara, HPP extends shelf life by enhancing microbial safety and improves functional properties through the structural modification of fiber fractions [21]. Similarly, in carrot juice, HPP enables the preservation of phenolic compounds, antioxidant activity, and β-carotene content while ensuring microbial inactivation, extending shelf life up to 15 days [22]. In systems containing pea protein concentrate and starch, HPP optimizes digestibility and techno-functional properties by inducing controlled modifications in protein structure; thus, it stands out as an effective processing technology supporting sustainable plant-based protein utilization [23]. The impact of HPP on these protein systems is characterized by an increase in surface hydrophobicity and a decrease in free sulfhydryl groups. These changes optimize protein solubility and technological functionality as a result of partial unfolding and subsequent aggregation processes occurring in protein molecules [24]. Furthermore, studies on whole pulses demonstrate that HPP application increases hydration capacity to levels as high as 93.8% and significantly shortens soaking times compared to traditional methods. Beyond enhancing the textural softness and color brightness of chickpeas, this approach maximizes nutritional quality and bioavailability by reducing antinutritional factors such as tannins and phytic acid by approximately four-fifths compared to the raw product [25].

In fish and seafood, HPP is not limited to ensuring microbial safety but offers a multi-layered protection mechanism for maintaining product quality over time. Notably, the suppression of autolytic enzyme activity and biogenic amine formation results in a significant reduction of spoilage indicators such as cadaverine and spermidine, clearly demonstrating the efficacy of HPP in extending freshness. Moreover, the improvement of tissue integrity, increased water-holding capacity, reduced drip loss, and decreased allergenicity render HPP not just a preservation technology, but a tool enabling functional product design [26]. This multifaceted impact has also been confirmed in applications for non-alcoholic beers, where HPP extended shelf life while maintaining sensory attributes, presenting a sustainable alternative to conventional thermal pasteurization [27]. Similarly, HPP exhibits high efficiency in the inactivation of polyphenol oxidase (PPO), one of the primary causes of quality loss in fruit and vegetable-based products; it is reported that heat-assisted high-pressure applications achieve more effective enzyme inactivation with a lower total energy input, generally exhibiting first-order kinetic behavior [24, 28]. These findings reveal that the advantages offered by HPP in terms of quality, energy efficiency, and product stability must be evaluated alongside the limitations and application conditions of the technology.

*3) Industrial and Regulatory Dimensions:* In terms of energy utilization, HPP has the potential to reduce total energy consumption and carbon footprint by eliminating long-term thermal treatments, despite its requirement for high energy over short durations. By enhancing microbial safety while reducing the need for chemical additives, it contributes to the prevention of food waste and the development of clean-label products [1, 19, 29]. However, one of the significant technical limitations of HPP is its inability to independently inactivate bacterial spores, such as *Clostridium* and *Bacillus* species; therefore, for products where sterilization is the target, HPP must be combined with heat, low pH, or antimicrobials [30, 31].

It is also reported that HPP requires careful optimization regarding quality in certain product groups. In meat products, high pressure levels can accelerate lipid oxidation, thereby increasing TBARS values and leading to losses in free amino acid content. Furthermore, when applied in conjunction with high temperatures, the oxygen and water vapor barrier properties of packaging materials may weaken. Consequently, the simultaneous evaluation of HPP process parameters and packaging selection is of critical importance [32, 33].

From a packaging and regulatory perspective, the success of HPP applications depends not only on process conditions but also directly on the selection of packaging systems that are resistant to high pressure, ensured against leakage, and possess a minimal risk of migration. While biopolymer-based packaging stands out as a sustainable alternative in low-pressure applications, its loss of structural integrity under combinations of high pressure and temperature poses a significant limitation. Recognized as a technologically safe and approved process in the USA, Canada, and Australia, the evaluation of HPP under "Novel Food" legislation for certain products in the European Union underscores why technology-specific microbiological criteria, product-based risk analyses, and a clear legal framework are indispensable [34, 35]. Evaluations by EFSA indicate that, when properly optimized, HPP does not pose an additional risk to food safety and can achieve specific levels of pathogen inactivation; however, verifying this efficacy for each product individually and maintaining strict process control remains a critical requirement [36].

### *B. Pulsed Electric Field*

*1) Fundamental Principles and Mechanisms of Action:* Pulsed Electric Field (PEF) technology is an advanced non-thermal processing method based on the principle of making cell membranes temporarily or permanently permeable by applying short-duration, high-voltage electrical pulses to food products. The electroporation occurring during this process causes formation of microscopic pores in the cell membrane, leading to disruption of cellular equilibrium and inactivation of microorganisms [9, 11]. The stages of this mechanism are illustrated in Figure 2.

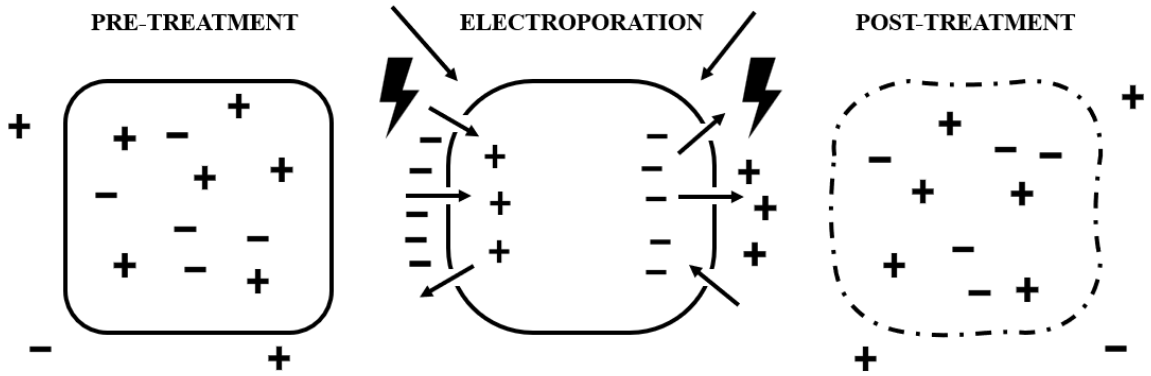



**Figure 2.** Schematic representation of cell membrane alterations during the electroporation process

Unlike thermal treatments, PEF enables the extensive preservation of nutritional components and sensory attributes by targeting cell membrane without inducing temperature-dependent structural degradation [9, 11].

*2) Applications in Food Systems:* PEF applications stand out not only as an alternative among non-thermal food processing technologies, but as a transformative approach that redefines the quality–safety balance of conventional thermal processes. Particularly effective in liquid and semi-liquid food systems, this technology is gaining increasing interest due to its industrial scalability and capacity to maintain product integrity in fruit juices, plant-based beverages, and functional liquid products. Controlled electroporation, induced by short-duration and high-intensity electric fields, enables microbial inactivation by targetingly altering the permeability of the cell membrane; since this process occurs without generating a significant thermal load, it distinguishes PEF from classical thermal treatments [37, 38].

This unique mechanism of action elevates PEF from being solely a preservation technology to a processing tool that drives functional quality. The controlled permeability created in the cell membrane enhances the release and extractability of antioxidants, phenolic compounds, and other bioactive components from within the matrix; thus, the nutritional density of the products is preserved, and in some cases, even strengthened. In the literature it is reported that vitamins, polyphenols, and aroma compounds in PEF-processed liquid foods are maintained at higher levels compared to their thermal counterparts; this characteristic offers a decisive advantage, particularly in the development of functional beverages and plant-based products [29, 38, 39].

3) *Industrial and Regulatory Dimensions:* Compared to traditional thermal treatments, PEF can achieve a significant reduction in energy consumption due to its requirement for extremely short processing times; in this regard, it stands out as a processing technology highly aligned with sustainable production goals [2]. Despite its technological advantages, the effectiveness of PEF is strongly dependent on precise optimization of operating parameters, since excessive electric field intensity can lead to irreversible electroporation, resulting in undesirable

cellular damage and potential deterioration of product quality [14]. Moreover, the high initial capital cost and the absence of fully standardized, large-scale industrial processing systems constitute major limitations that currently hinder the broader commercialization and industrial implementation of PEF technology [38, 40].

However, the industrial scale-up of PEF is determined largely by existing regulatory frameworks rather than its technical performance alone. Particularly in the European Union, non-thermal technologies are treated not merely as alternative processes but as applications that redefine the conventional concept of pasteurization, subjecting PEF to an intensive, evidence-based scientific evaluation process [38].

In the European Union, PEF technology is classified as an independent "processing technology," and a risk-based assessment approach is adopted to ensure product safety. Within this framework, it is mandatory to define process parameters, verify target microbial inactivation levels, and conduct detailed evaluations of process–product interactions. The necessity of proving that non-thermal processes provide a level of food safety equivalent to traditional thermal pasteurization makes validation protocols, process control mechanisms, and traceability systems core components of regulatory compliance in PEF applications. Furthermore, the evaluation of certain PEF applications under "Novel Food" legislation indicates that the technology must be addressed on a case-by-case basis, focusing not only on the process itself but also on the compositional, structural, and functional changes it induces in the product [38, 40].

In contrast, in the United States, pasteurization is defined based on targeted microbiological safety outcomes rather than a specific technology. This allows PEF to be evaluated within a more flexible and technology-neutral framework under existing food safety legislation, provided it is appropriately validated. While this approach enables faster commercialization of PEF in the US, the more cautious regulatory stance in Europe appears decisive in establishing scientific robustness and consumer confidence. Nonetheless, the lack of fully established technology-specific microbiological criteria, standardized process definitions, and internationally harmonized regulations remains one of the primary structural limitations hindering the global expansion of PEF [40]. In this context, the future position of PEF will be shaped by a holistic evaluation approach that considers multidimensional factors such as regulatory alignment, validation infrastructure, consumer trust, and industrial standardization, as consumer acceptance may be influenced by perceived risk, unfamiliarity, and concerns regarding the “naturalness” of processed foods, which can ultimately affect market adoption despite its technological advantages [38, 41].

### *C. Cold Plasma Technology*

*1) Fundamental Principles and Mechanisms of Action:* Cold Plasma (CP) technology, defined as the partially ionized gas generated through the electrical discharge of gases, stands out as an innovative method that ensures the inactivation of microorganisms at low temperatures. The primary advantage of CP is its ability to provide microbial safety without generating chemical residues in food or inducing thermal damage [42, 43].

Reactive oxygen and nitrogen species (ROS and RNS) generated during application create severe oxidative stress on the cell walls and membranes of microorganisms, disrupting membrane integrity and leading to protein and nucleic acid damage. It is reported in the literature that CP effectively reduces bacterial load without significantly increasing product temperature, thereby limiting temperature-dependent nutrient losses [44]. This non-thermal structure makes CP a sustainable alternative that can better preserve the physicochemical properties and oxidative balance of food compared to traditional pasteurization methods [42, 44]. The gas ionization process via a high-voltage source and its effects on food are illustrated in Figure 3.

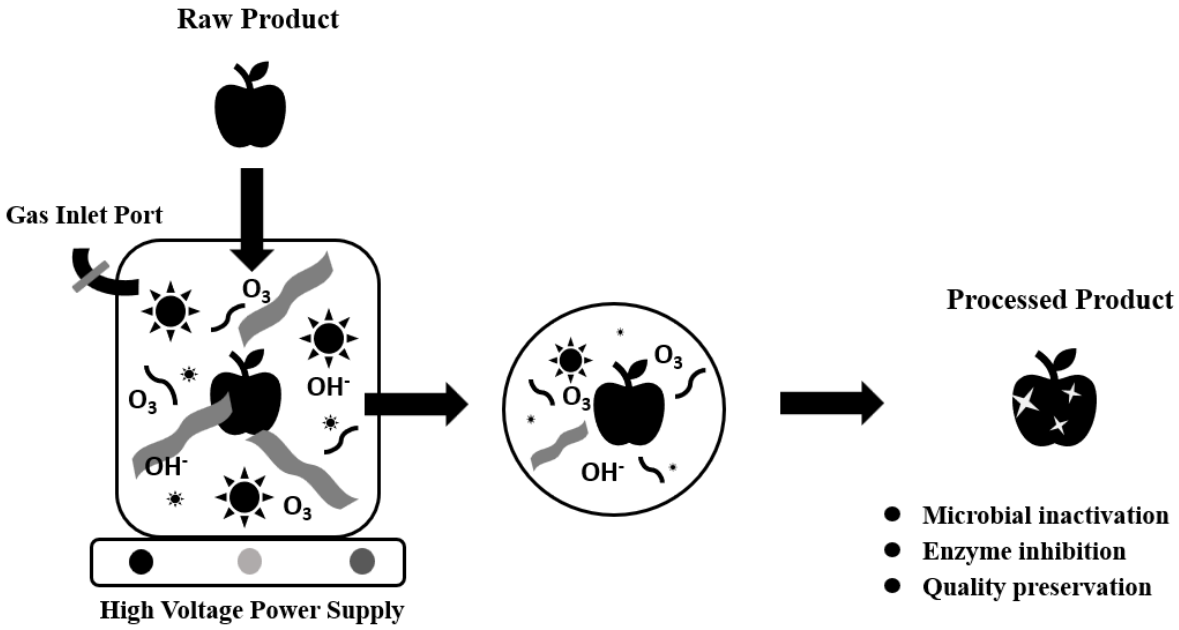



**Figure 3.** CP experimental setup and mechanism of action

*2) Applications in Food Systems:* In this context, CP technology emerges as a "gentle yet effective" surface-oriented, non-thermal sterilization method capable of inactivating microorganisms without compromising the structural integrity of the food. It is reported that CP applications enhance microbial safety, particularly in foods susceptible to surface contamination, such as fresh fruits and vegetables, meat, and seafood; additionally, it extends shelf life by improving the barrier properties of packaging materials. This multifaceted impact establishes CP as an innovative processing technology that contributes to the reduction of food waste [10, 12].

The application potential of CP is more distinctly evident in heat-sensitive and starch-based products that are difficult to preserve using conventional methods. Studies conducted on delicate foods, such as Korean rice cakes, demonstrate that in-package CP applications can effectively inactivate pathogenic microorganisms while preserving the product's color and textural attributes. This effect is based on the damage caused to the cell membrane through oxidative stress induced by reactive ions, radicals, and photons generated during plasma treatment, thereby reducing the surface bioburden; the fact that the process occurs without increasing the internal temperature of the food allows for the maintenance of sensory quality [45, 46, 47].

Originally developed for surface modification in the polymer and electronics industries, cold plasma technology has found a significant field of application in the food industry today, owing to its ability to combine high reactivity with low temperatures. Studies conducted across diverse food matrices, including cereals, dairy products, meat, fruits, and vegetables, reveal that CP applications offer distinct advantages in terms of preserving nutritional value and sensory properties compared to traditional thermal methods [48]. Nevertheless, it is reported that existing literature focuses largely on microbial disinfection, and the long-term effects of CP applications on the physical, chemical, and sensory properties of food have not yet been sufficiently elucidated. Furthermore, regarding commercial applications, more comprehensive evaluations concerning the biosafety, cytotoxic effects, and allergenicity potential of plasma-derived by-products are required [45].

It is reported that CP technology is being investigated for microbial inactivation, shelf-life extension, and quality preservation in various foods, particularly dairy products. Research indicates that CP applications suppress the growth of pathogenic microorganisms and delay the increase in acidity; meanwhile, the risk of lipid oxidation associated with traditional thermal treatments remains more limited in CP applications. Lower peroxide values and increased oxidative stability, along with the extension of induction periods, demonstrate the products'

enhanced resistance to oxidation; this supports the view of CP as a sustainable technology that not only ensures food safety but also contributes to the reduction of food waste by extending shelf life [44].

*3) Industrial and Regulatory Dimensions:* When evaluated in terms of energy efficiency, CP technology offers a sustainable processing profile with lower energy consumption compared to traditional thermal treatments. Additionally, it contributes to reducing the environmental footprint by decreasing water usage and the demand for chemical additives during processing [1, 2]. These characteristics position CP a strategic technology not only for microbial control but also for achieving energy efficiency, quality preservation, and sustainable production goals. It is reported that holistic solutions supporting environmental sustainability, while enhancing food safety and shelf life, can be provided, particularly through hybrid systems integrated with other non-thermal methods [45, 47, 48].

In the field of food processing, CP technology is among the promising non-thermal methods for reducing the immunoreactivity of allergenic proteins. Various studies in the literature demonstrate that CP can significantly reduce IgE-binding capacity, particularly in highly allergenic food matrices such as peanuts and egg whites. This effect is reported to be associated with the structural changes induced in protein structures by the reactive oxygen and nitrogen species generated during the plasma process. However, when evaluating the potential of CP, oxidative side reactions and undesirable modifications in protein structure that may arise depending on processing intensity and duration must also be considered. Furthermore, the fact that the effect of CP is largely limited to the surface may restrict the achievement of sufficient immunological modification in the internal parts of some food matrices. Therefore, there is a general consensus in the literature that process parameters must be carefully optimized in the evaluation of CP technology regarding food safety and biosafety [28].

Furthermore, although CP technology holds significant potential for food preservation, shelf-life extension, and the protection of bioactive components, it is still considered an evolving process in terms of safety and regulatory dimensions. Secondary by-products generated during plasma production, such as ozone, ultraviolet radiation, and reactive oxygen species, are among the fundamental factors determining the application limits of the technology in the food industry. In the literature, it is emphasized that although CP applications are increasingly being adopted by the food sector, the long-term effects of reactive species formed during processing on food components and packaging materials have not been fully elucidated. In this context, the transfer of CP to large-scale commercial applications and its acceptance by both consumers and industry stakeholders depend on a comprehensive evaluation and regulatory clarification of the gases used, packaging–plasma interactions, and the biosafety of post-processing by-products [49].

### *D. Lyophilization*

*1) Fundamental Principles and Mechanisms of Action:* Lyophilization stands out as an advanced dehydration technology based on the initial freezing of food, followed by the removal of water through direct transition from the solid state to the gas phase (sublimation) under low pressure, without passing through the liquid phase. Carrying out the process under low temperature and vacuum conditions minimizes the loss of heat-sensitive components, such as vitamins, antioxidants, phytochemicals, and aroma compounds, while allowing for the long-term preservation of the sensory attributes of products, including taste, texture, and color [9, 11]. The fundamental phases of the lyophilization process, beginning with the freezing stage and concluding with sublimation and desorption, are illustrated in Figure 4.

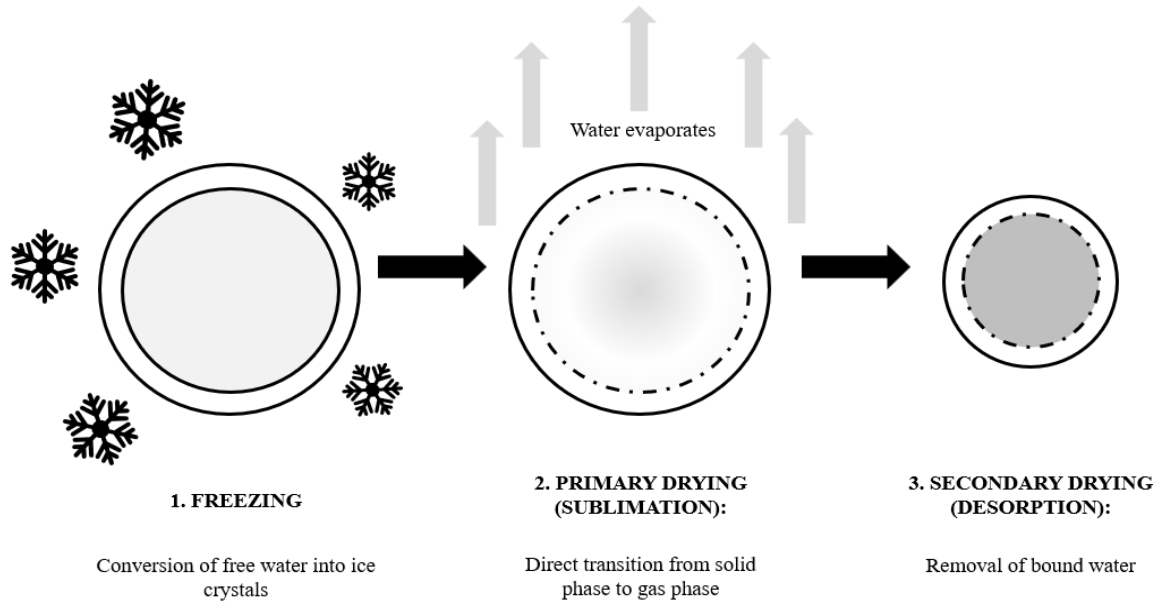



**Figure 4.** Fundamental phases of the lyophilization process: Freezing, sublimation, and desorption

The protective effect of lyophilization is not limited solely to the advantage of low temperatures but is also directly related to the unique microstructure formed within the food matrix. The high porosity resulting from the removal of ice crystals after sublimation enhances the oxidative stability of bioactive components and maximizes rehydration capacity. This structure preserves the quaternary configuration and catalytic activity of heat-sensitive enzymes, such as diamine oxidase, while suppressing enzymatic degradation processes. Indeed, studies conducted on legume sprouts demonstrate that when lyophilization is combined with frozen storage, the enzymatic activity responsible for histamine degradation can be maintained stably for up to 12 months [50].

When evaluated in terms of energy consumption, the high energy requirement of freezing and vacuum systems in the initial stages is seen as a disadvantage. However, its ability to significantly extend product shelf life, reduce food losses due to spoilage, and enable the production of lightweight, compact products for logistical processes transforms lyophilization into a sustainable preservation technology in terms of total environmental impact [1, 2]. In this regard, particularly in the production of fruits, vegetables, plant extracts, and functional foods, lyophilization is considered not only a method that preserves microbial safety and nutritional quality but also a strategic process that directly contributes to sustainable food systems by reducing food waste.

*2) Applications in Food Systems:* In the food industry, lyophilization is regarded as a reference method in the literature for processing fruits with rich lipid profiles and heat-sensitive bioactive components, such as avocados, due to its potential to minimize quality losses. Beyond extending shelf life, this methodology demonstrates a distinct superiority over conventional thermal drying techniques in terms of preserving phenolic composition and maintaining radical scavenging capacity. Studies focusing on process optimization reveal that controlled management of the heating plate temperature can accelerate drying kinetics by 48–60% while enabling high-level retention of antioxidant activity. Despite variations observed in the browning index within the matrix structure, the resulting highly porous structure ensures the bioaccessibility of nutritional micro-components and the techno-functionality of the products [51].

The protective effect is further supported by innovative applications involving the use of lyophilized vegetable and fruit powders in functional product development. A study in the literature evaluated the nutritional and bioactive properties of eight different functional beverage formulations created from lyophilized powders of carrot, zucchini, lentil sprouts, raspberry, strawberry, and apple; these formulations were reported to exhibit high antioxidant activity, phenolic content, and vitamin C levels. Raspberry-containing mixtures exhibited strong antioxidant capacity, and in vitro digestion models revealed that these products offer satisfactory bioaccessibility of bioactive fractions, particularly phenolic components. Additionally, these formulations are stated to possess functional value due to their starch and protein content [52].

Beyond plant matrices, the protective effect of lyophilization is also clearly reported in heat- and oxidation-sensitive animal-derived bioactive products. In this context, research on royal jelly shows that the freeze-drying process not only provides moisture removal but also plays a critical role in maintaining the stability of functional components [53]. In constructing sustainable food systems, transforming meat industry by-products into value-added ingredients has similarly become a strategic necessity. A study demonstrated that sheep and pig by-products (liver, kidney, heart, and lung), which constitute approximately one-third of the live animal weight, can be converted into high-nutritional functional food ingredients using lyophilization technology. It has been proven that this advanced drying technique can stabilize the essential amino acid profiles and sensitive fatty acid compositions, such as Omega-3/Omega-6, of animal tissues without significant loss; particularly, freeze-drying organs like sheep liver provides a reliable raw material source for next-generation dietary supplements that retain their bioactive value [54].

Within the scope of modern food biotechnology, lyophilization is synergistically integrated with microencapsulation technologies to enhance the viability of probiotic microorganisms in the gastrointestinal tract. During this integration process, the method allows sensitive strains such as *Lactobacillus acidophilus* to maintain structural integrity within wall materials based on soy protein isolate (SPI) or sodium alginate (SA). Empirical data reveal that lyophilized microcapsules stabilize sensory attributes in fermented dairy matrices like yogurt over a 21-day storage period and provide significantly higher viability compared to free cells. Specifically, encapsulation efficiencies reaching 92–95% with SPI and SA combinations make lyophilization an indispensable stabilization step in the development of functional food formulations [55].

Lyophilization also plays a critical role in stabilizing lipid fractions rich in omega-3 fatty acids, such as fish oil, which are highly susceptible to autoxidation, within protein matrices. In this process, the method can physically mask the characteristic volatile aroma compounds and oily texture of fish oil, entrapping them within matrix-type microspheres. Although lyophilization offers higher solids recovery yield compared to other drying methods, the resulting porous microstructure and increased specific surface area bring a risk of oxygen penetration. Due to this structural paradox, while lyophilization exhibits superior performance in preserving the physical configuration of heat-sensitive protein-lipid emulsions, it requires meticulous optimization of protein/oil ratios and atmospheric packaging conditions to maximize oxidative stability [56].

*3) Industrial and Regulatory Dimensions:* Despite providing high-quality and functional products, lyophilization entails certain structural limitations inherent to the method. The high porosity and large specific surface area formed after drying can create a disadvantage, particularly in the encapsulation of oxidation-sensitive lipid fractions such as fish oil. This porous structure facilitates oxygen penetration, thereby increasing free radical formation and potentially accelerating lipid oxidation during storage. Indeed, it is reported in the literature that lyophilization may exhibit lower encapsulation efficiency in some systems compared to alternative methods like spray drying. This necessitates more rigorous monitoring of shelf-life tests and quality parameters regarding the oxidative stability of post-lyophilization products [56].

Furthermore, while the holistic evaluation of plant tissues offers a significant advantage in terms of reducing food waste, certain technological constraints are reported in the development of lyophilized powder-based products. These include the inability to fully mask raw material-derived off-flavors with fruit components and the potential for high rehydration temperatures to adversely affect sensory quality. Overall, such studies reveal that lyophilized vegetable and fruit powders possess substantial potential as high value-added ingredients in the

functional food industry; however, they demonstrate that sensory optimization and rehydration conditions are critical parameters for product success [52].

While lyophilization offers high efficiency in stabilizing natural antioxidants derived from industrial by-products, their performance under high-temperature applications is not always predictable. Although it is reported that lyophilization processes combined with acid hydrolysis can delay the oxidative degradation of refined oils during frying, they may exhibit limited effects on advanced thermal degradation indicators, such as conjugated triene formation [57]. These findings emphasize that in the evaluation of lyophilized natural antioxidants, not only their initial antioxidant capacities but also their stability under conditions of high temperature and oxidative stress must be considered. From a regulatory and food safety perspective, this necessitates the clear and verifiable definition of optimum utilization concentrations and processing conditions when incorporating lyophilized ingredients into food matrices. To establish a sustainable safety management system for healthy oil production, it is of critical importance to evaluate the behavior of lyophilized ingredients under challenging process conditions, alongside their functional efficacy, within regulatory frameworks [57].

## V. COMPARATIVE ASSESSMENT OF TECHNOLOGIES

Next-generation non-thermal food processing technologies exhibit varying performances in terms of energy consumption, food safety, quality preservation, and food waste reduction, depending on their processing principles and target product groups. HPP provides a high level of food safety by effectively inactivating microorganisms while allowing for the extensive preservation of nutrients; it stands out for its lower energy utilization compared to traditional thermal treatments [2, 9]. PEF technology, particularly in liquid and semi-liquid products, extends shelf life by increasing cell permeability, supports the preservation of nutritional value, and offers advantages in terms of energy efficiency [1, 39]. CP applications provide high microbial safety without leaving chemical residues in products requiring surface sterilization, contributing to sustainable production goals through optimized energy use [10, 42]. Lyophilization significantly extends shelf life, especially in fruit and vegetable-based products, by largely preserving nutritional value and aroma compounds, thereby playing a direct role in reducing food waste [11, 13]. Overall, these technologies offer distinct advantages regarding energy efficiency, quality preservation, food safety, and waste reduction, demonstrating a strong alignment with sustainable food production goals [2, 9]. A comparative analysis of the examined next-generation non-thermal technologies in terms of energy, safety, quality, and operational limitations is summarized in Table 1.

Despite their differing technological characteristics and application areas, the industrial implementation of these non-thermal technologies also requires appropriate regulatory evaluation and food safety oversight. In the Turkish regulatory framework, applications involving HPP, PEF, and CP are evaluated within the scope of the Turkish Food Codex Novel Foods Regulation, which requires a pre-market safety assessment by the Ministry of Agriculture and Forestry [58]. Since these non-thermal technologies do not yet have technology-specific regulatory frameworks, they are assessed through a risk-based food safety approach that considers chemical, microbiological, and process-related factors associated with emerging food processing methods [58]. In contrast, lyophilization is recognized as a conventional dehydration technique under the Turkish Food Codex and is therefore regulated according to product-specific food category provisions rather than under novel food legislation [59].

**Table 1.** Literature-based conceptual comparison of non-thermal food processing technologies

| Technology | Energy Utilization | Food Safety | Quality Retention | Shelf Life | Key Limitations |
|---|---|---|---|---|---|
| **HPP** | ● | ↑ | ↑ | ↑ | High initial equipment and capital investment costs |
| **PEF** | ↓ | ● | ↑ | ● | Limited to liquid and semi-liquid products |
| **Cold Plasma** | ↓ | ↑* | ↑ | ● | Regulatory uncertainty and industrial scalability |
| **Lyophilization** | ↑↑ | ● | ↑↑ | ↑↑ | High energy requirements and prolonged processing times |

**Note:** Symbols represent; ↓: low, ●: moderate, ↑: high, ↑↑: very high effect/level.
*In Cold Plasma (CP) applications, the food safety effect is predominantly limited to surface sterilization.
**Source:** Prepared by the author based on data from [9, 10, 34, 36, 38, 51].

## VI. FUTURE PERSPECTIVES

In a future perspective, the integration of next-generation non-thermal food processing technologies into hybrid systems offers significant opportunities for sustainable food production. The combined use of HPP and PEF technologies maximizes the bioavailability of nutrients while enhancing microbial safety through synergistic effects created in the cell wall structure [9]. Similarly, the combination of CP and lyophilization provides effective surface sterilization, particularly in products containing fruits, vegetables, and delicate proteins, while offering the advantages of extended shelf life and minimal nutrient loss [10, 11]. Such hybrid approaches enable the development of optimized processes in terms of energy efficiency and product quality by overcoming the limitations of standalone technologies, thereby contributing directly to goals aimed at reducing food waste [2]. Indeed, literature and industrial applications demonstrate that these systems are highly aligned with sustainable production and circular economy targets [1].

However, the integration of next-generation and hybrid food processing technologies into sustainable food systems is not limited solely to technical and environmental advantages; consumer perception, trust, and acceptance also play a decisive role in this transition. The literature emphasizes that individual differences, such as perceived naturalness, trust in the food industry, and food neophobia, are critical factors in the adoption of these technologies. Therefore, it is noted that the dimension of social acceptance must be systematically considered during the early development and market introduction stages of these technologies [41].

The integration of digital traceability and energy management stands out as another fundamental component that strengthens the efficiency and sustainability potential of hybrid systems. Through sensor-based data collection, Internet of Things (IoT) applications, and smart energy management systems within the food supply chain, energy consumption can be monitored in real-time, production processes can be optimized, and critical control points for waste prevention can be identified more effectively [13, 42]. Furthermore, the origin, processing history, and quality parameters of products can be transparently tracked through blockchain-based digital recording systems; this both increases consumer confidence and strengthens the traceability of the sustainable food supply chain [9]. When all these developments are evaluated together, it is predicted that the integration of hybrid technologies and digital traceability will play a critical role in the transformation of sustainable food production models centered on energy efficiency, quality assurance, and food waste reduction [39]. Nevertheless, for these systems to be widely implemented, research focused on process standardization, regulatory compliance, and industrial scalability must be intensified.

## VII. CONCLUSION

In conclusion, next-generation non-thermal food processing technologies represent a key component of sustainable food systems, particularly in relation to energy efficiency, food safety, and food waste reduction [1]. Technologies such as HPP, PEF, CP, and lyophilization not only optimize processing conditions but also help preserve nutritional quality, extend shelf life, and reduce product losses [1, 51]. When integrated with hybrid processing systems and digital traceability tools, these technologies can enable a more holistic transformation of the food supply chain. This transformation spans energy management, quality assurance, and waste minimization [1, 2]. In this context, reducing industrial carbon footprints and improving process efficiency are essential for large-scale implementation [2, 7].

However, the successful adoption of these technologies requires more than technological advancement. Interdisciplinary collaboration between food scientists, engineers, and industry stakeholders should be strengthened to accelerate innovation and application [7, 40]. In addition, pilot-scale validation studies and industrial demonstration projects are necessary to bridge the gap between research and commercialization [34, 40]. From a policy perspective, the development of harmonized regulatory frameworks and standardized processing guidelines is crucial to ensure safety, reproducibility, and international compatibility [36]. Financial incentives and support mechanisms may further facilitate industrial investment, particularly for small and medium-sized enterprises [7, 8].

Overall, the future of food processing will depend not only on technological innovation but also on its effective integration into industrial systems supported by science-based regulation and cross-sector collaboration [1, 34, 40]. Sustainable food production has therefore shifted from an optional approach to an essential requirement for global food security and resource sustainability [4, 5].

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