International Journal of Environment, Agriculture and Biotechnology
Vol-9, Issue-5; Sep-Oct, 2024
Peer-Reviewed International Journal
Journal Home Page Available: https://ijeab.com/
Journal DOI: 10.22161/ijeab

Rethinking Food Processing for a Sustainable Future: A Review of Innovative Nonthermal Technologies

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Received: 28 Jul 2024; Received in revised form: 30 Aug 2024; Accepted: 05 Sep 2024; Available online: 10 Sep 2024

Abstract— *Agricultural innovation offers a solution to mounting pressures on the global food system, which must provide safe, nutritious, and environmentally sustainable consumable goods at increasing volumes if demands are to be met. The potential of nonthermal technologies as promising alternatives to conventional thermal treatments for sustainable food processing and preservation is discussed in this review. Here we investigate four of such emerging nonthermal technologies that include High-Pressure Processing (HPP), Pulsed Electric Fields (PEF) and Irradiation, and Cold Plasma. This blog takes a deeper dive into its principles, use cases, and pros and cons. On the other hand, nonthermal technologies are energy-sparing, improve the nutritional quality of food products, and reduce loss due to processing but above all provide improved environmental performance. The energy-saving potential of these technologies can be large, while maintaining food in its original nutritive and sensory shape but with extended shelf life and lower carbon footprint. Nevertheless, scalability, cost-efficacy regulatory approval, consumer acceptance (Diaz-Ruiz Pletsch Concordet; Chellaram Barragan Maheswari), integration with the reference's infrastructure, or optimized process parameters are themselves challenging. Developing a solution to these challenges and promoting nonthermal processing technologies are strategic priorities that will be critical for future food production... With time, advances in research and developments of this important field would give rise to the wide-scale application of nonthermal processing This review aims to provide a full overview of potential benefits entailed by each innovative technique along with its limitations as well as informing stakeholders and future directions.*

Keywords— ***HPP, PEF, FAO, Cold Plasma, O2***

I. INTRODUCTION

The global food system is being shaped under intense pressure to produce enough safe, nutritious, and environmentally responsible for a world population of over 7 billion (Varzakas & Smaoui, 2024). Mechanized food processing is one solution to this problem (Zou & Mishra, 2024). Still, it inefficiently uses water and energy, providing yet another barrier to traditional farming (FAO 2017) which will be needed more than ever as the world population reaches 9.7 billion by 2050 (Nadathur, Wanasundara, Marinangeli, & Scanlin, 2024). Although these traditional thermal processing methods efficaciously guarantee the safety of food and prolong its shelf-life, they have drawbacks that further harm the sustainability of their respective food systems (Rabiepour, Zahmatkesh, & Babakhani, 2024). The thermal techniques require a lot of energy, use considerable amounts of water, and can have some changes in the food quality from nutritional (to sensorial (Fang et al., 2023). As a result, research efforts have been aimed at non-conventional and advanced technologies as promising alternatives to thermal treatments in the context of sustainable food processing and preservation (Safwa, Ahmed, Talukder, Sarker, & Rana, 2023). Nonthermal processing implies that the techniques used do not rely on heat to inactivate microorganisms, and enzymes and influence biochemical reactions taking place within food products (Allai, Azad, Mir, & Gul, 2023). Thus, these methods promise to be more energy-efficient and environmentally benign alternatives for processing food with retention of the nutritional, sensory as well and functional properties (Ali, Liao, Zeng, Manzoor, & Mazahir, 2024). In this broad review paper, we explore the nascent nonthermal technologies that are poised to change our approach to how food is processed and distributed. In this section, we will explore a wider spectrum of technologies including high-pressure processing (HPP), pulsed electric fields (PEF), cold plasma, and irradiation to understand how they work, where they are used currently or proposed in the future for positive input into promoting sustainability within our global food system. High-pressure processing (HPP) is a non-thermal technology based on the use of pressure at high levels of up to 600 MPa that inactivates microorganisms and enzymes while preserving all sensory, and nutritional qualities of food products (Keyata & Bikila, 2024). The value of this technology has been demonstrated across a range of commodities from juices, guacamole, ready-to-eat meats, and shellfish being shelf life extended without thermal pasteurization (Lohita & Srijaya, 2024). Pulsed electric fields (PEF) processing is a method using short high high-voltage electrical pulses to disintegrate the cell membranes of microorganisms by which they become inactivated (Preethi, Lavanya, Pintu, Moses, & Anandharamakrishnan, 2024). For instance, PEF has been effective in the pasteurization of liquid foods like milk or fruit juice without tremendously increasing nutrient and flavor loss when compared to conventional thermal heat treatments (Preethi et al., 2024). A non-thermal process, cold plasma is capable of inactivating a wide range of pathogens and food poisoning microorganisms on the surfaces as well as packaging material (Rahdar, 2023). It has potential application in the clean-up of produce, meat, food contact surfaces, etc. (Deliephan, Subramanyam, & Aldrich, 2023). This approach could also be utilized for the purification of environments or as a means to indirectly combat microorganisms on or within packaging materials, or under modified atmosphere packaging (MAP) conditions, thereby improving the safety and freshness of products (Barjasteh, Kaushik, Choi, & Kaushik, 2024). Irradiation, which includes the use of ionizing radiation like gamma rays, electron beams, or X-rays, can effectively reduce the microbial content in food products with little heat impulse (Bhagya, Reshmi, Waghmare, Moses, & Anandharamakrishnan, 2024). Irradiation has been approved for use in spices, poultry, and fruit as a method to maximize food safety and shelf-life (Buvaneswaran, Ukkunda, Sinija, & Mahendran, 2024). This review will focus on the benefits and sustainability of nonthermal identified technologies including energy efficiency, nutritional preservation, food waste reduction (which also includes spoilage bacteria) environmental impact. Challenges and future directions for scalability and cost-effectiveness, regulatory acceptance and consumer adoption, integration with existing infrastructure (such as providing poultry-compatible electrodes), and optimization of process parameters will be discussed. New nonthermal processing alternatives will allow us to do our part in helping create a stronger, more sustainable global food system that delivers safe and nutritious foods to the inhabitants of the world by generation.

II. NONTHERMAL FOOD PROCESSING TECHNIQUES

2.1. High-pressure processing (HPP)

High-pressure processing (HPP) is a non-thermal technology in which foods are subjected to pressures of 100-600 MPa, causing the elimination and inhibition of microorganisms with retention of sensory and nutritional characteristics that result from exposure conditions as well (Ozkan, Subasi, Capanoglu, & Esatbeyoglu, 2023). The technology has been used to generate shelf-stable food products including juice, guacamole, ready-to-eat meats, and shellfish, as well as several dairy foods without heat pasteurization for extended storage (Saifullah, Stanley, Zare, Juliano, & Hunt, 2023). During HPP, materials are subjected to high pressure which causes the proteins and enzymes in them as well as microorganisms that populate those ingredients to denature and thereby become inactive (Nath, Pandiselvam, & Sunil, 2023). The pressure is densities spread across the food product to ensure microbial inactivation throughout and minimal taste, texture, and nutritional change of foods (Lohita & Srijaya, 2024). HPP comes with a range of benefits, including improved food safety; better nutritional quality, and increased shelf-life (hence reduced wastage) (de Chiara, Castagnini, & Capozzi, 2024). On the other hand, its use is limited to huge amounts of capital and operational expenses along with lesser scalability as well as specialized equipment and facilities requirements (Moro-Visconti, 2024).

2.2. Pulsed electric fields (PEF)

Pulsed Electric Fields (PEF) - PEF is a nonthermal method that uses short high-voltage electrical pulses in the range of typically 20-80 kV/cm to disrupt cell membranes of microorganisms and thus cause a molecular leakage resulting in their inactivation (Martínez, Delso, Álvarez, & Raso, 2020). Applications Good for PEF have shown the potential for pasteurizing liquid foods such as milk and fruit juices while maintaining most of the natural nutrients, and flavor compounds that would otherwise degrade during traditional thermal pasteurization (Morales-De la Peña, Rábago-Panduro, Soliva-Fortuny, Martín-Belloso, & Welti-Chanes, 2021).

The processes are based on the application of high electric fields to food held between two electrodes, resulting destruction or disruption of cell membrane permeability (Demir, Tappi, Dymek, Rocculi, & Gomez-Galindo, 2023). This causes permeabilization such that the microorganisms are inactivated without significantly heating (Cui et al., 2022). The opportunity for PEF technology lies in improving food safety, a better quality of nutrients, and saving fuel as compared to traditional thermal pasteurization (Arshad et al., 2021). Nonetheless, this method encounters certain difficulties, such as the limited applicability of established food models to both solid and semi-solid food items (Kupikowska-Stobba, Domagała, & Kasprzak, 2024). Additionally, the requirement for specialized apparatus for the preparation and consumption experiments with PFMs may exceed the financial means of classroom educational settings (Ch'ng, 2024). Furthermore, there is a risk that the sensory qualities of specific food products might be adversely affected due to changes in texture or color dispersion during the chewing process.

2.3. Cold Plasma

Cold plasma is also called nonthermal plasma, produced by the ionization of gas at low temperatures usually up to atmospheric pressure (Yepez, Misra, & Keener, 2020). The technology is also known to be a powerful long-term disinfectant, capable of inactivating many microorganisms on the surfaces of food and within packaging (Shahi et al., 2021). Applications of cold plasma such as decontamination of fresh produce, meat, and food contact surfaces from pathogens (e.g., E. coli O157:H7), or in new packaging materials to improve the safety behavior along with shelf-life are very promising (Umair et al., 2023). Cold plasma provides antimicrobial activity due to generation of reactive species such as free radicals, ions, and UV photons that interact with microorganisms causing cell damage (Dharini, Jaspin, & Mahendran, 2023). Cold plasma can be made with different methods including dielectric barrier discharge, corona discharge, and also plasma jet (Anuntagool, Srangsomjit, Thaweewong, & Alvarez, 2023). As compared to traditional thermal decontamination methods cold plasma technology has several advantages improved food safety, reduced usage of chemicals, and energy conservation (de Araújo Bezerra et al., 2023). However, ultrasound for food processing also has limitations in penetration depth (independent of wavelength), possible adverse effects on food quality, and the need to study process parameters further or develop appropriate scientific knowledge/pathways behind them besides standardizing protocol components so that they comply with regulations.

2.4. Irradiation

Irradiation is a non-thermal process that leads to a significant reduction in the microbial load of food, using any source of ionizing radiation like gamma rays, electron beams, or X-rays without inducing major thermal damage (Danyo, Ivantsova, & Selezneva, 2023). Irradiation of food including spices, poultry, and fruits has been approved as a way to enhance safety (Mondal & Akhtaruzzaman, 2024). Irradiation functions by altering the molecular structure of microbial DNA resulting in loss or impairment of their reproduction, present study, and hence causes deactivation (Rai & Dutta, 2024). It is conducted in specialized facilities, with the intensity and duration of radiation specifically adjusted to achieve targeted microbial lethality without detrimentally affecting quality or safety (Chmielewski, 2023). Some of the advantages of irradiation for foods are improved food safety, shelf-life extension, and reduced chemical usage as compared to other preservation methods (Allai et al., 2023). Nevertheless, it also has drawbacks like a negative perception among consumers and to some extent, possible adverse impacts on the nutritional quality of food requirements for specialized premises and adherence with regulatory framework.

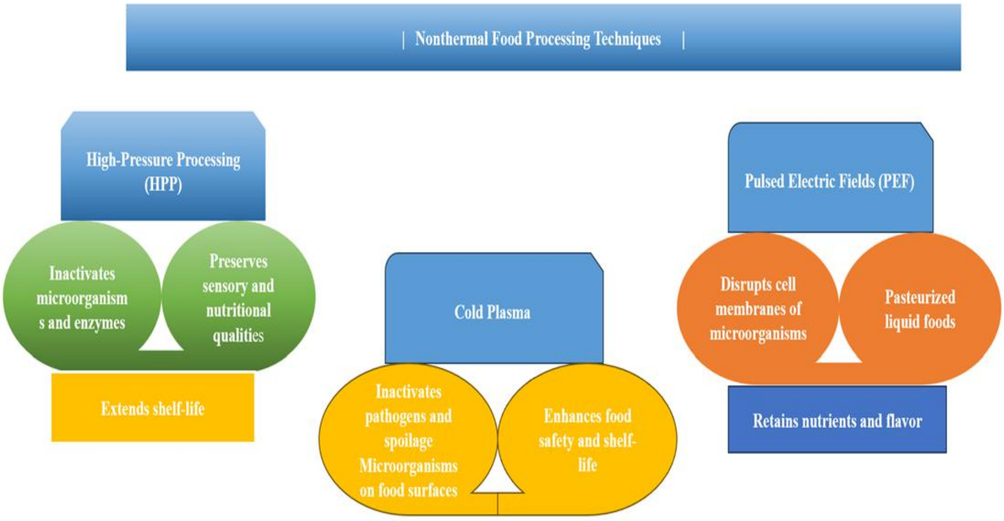

Fig.1: Nonthermal food processing techniques

III. BENEFITS AND SUSTAINABILITY CONSIDERATIONS OF NONTHERMAL FOOD PROCESSING

The non-thermal food processing technologies have been getting attention in the past few years, which is mainly due to their potential benefits as well as sustainability concerns (Bigi et al., 2023). In this review, we elaborate on the energy-saving potential and nutritional retention of nonthermal processing methods compared to traditional thermal treatment, in combination with reduced food waste as well as lower environmental impact.

3.1. Energy efficiency

Food processing by nonthermal technologies contributes to a greater energy efficiency of up to 20 times than thermal methods, such as conventional food preservation techniques (Bigi et al., 2023). Nevertheless, the reduced energy consumption associated with these methods is probably a result of the lower temperatures at which they function or the more precise delivery of energy (Amanowicz, Ratajczak, & Dudkiewicz, 2023). Consequently, HPP employs extremely high pressures (usually ranging from 400 to 600 MPa) to deactivate microorganisms and enzymes without the need for substantial heat treatment (Kateh, Purnomo, & Hasanah, 2024).

This pressure method obviates the need for high-temperature annealing, which carries a heavy toll on energy (Khanna, 2023). Likewise, PEF is another emerging technology that has been used to impact the cell membrane of microorganisms by applying low-duration voltage electrical pulses rather than long thermal processing (Poompavai & Gowri Sree, 2023). Cold Plasma processing is even better as it creates a reactive and low-temperature environment to kill food surface decontaminant so that the reliance on thermal energy can be cut off (Nwabor et al., 2022). These non-thermal processing techniques can decrease the energy requirements of food manufacturing, potentially leading to lower operational expenses for manufacturers (Pereira & Vicente, 2010). Additionally, these approaches are more environmentally benign, which suggests that their carbon emissions would be less than those of traditional thermal processing methods (S. Khan et al. 2022; Jayakumar et al., 2023). This translates directly to modified atmosphere packaged products with a dramatic decrease in O2 and an increase in CO2 (Liang et al., 2024). These intrinsic characteristics are noteworthy as they do not pose a risk of packaging leakage; instead, they can be managed throughout the nonthermal processing stage (10), which will diminish energy usage akin to conventional cooking methods—only more efficiently! (nonthermal processes require less power generation and involve lower greenhouse gas emissions).

3.2. Nutritional preservation

Non-thermal food processing excels in maintaining the food's native nutritional, sensory, and functional properties, among other significant advantages (Q. Wang et al., 2023). In recent times, non-thermal techniques have emerged as viable substitutes for traditional pasteurization or sterilization in the preservation of food, particularly for retaining heat-labile essential components—such as vitamins, minerals, and antioxidants—that are often degraded by conventional thermal treatments (Bhavya &

Hebbar, 2023; Karim et al., 2023).For instance, various studies have demonstrated that non-thermal processing methods, like pulsed electric field (PEF) treatment, result in superior retention of vitamin C, carotenoids, and polyphenols in fruit juices compared to heat-pasteurized products (Al-Juhaimi et al., 2018; Ghanem et al., 2024).

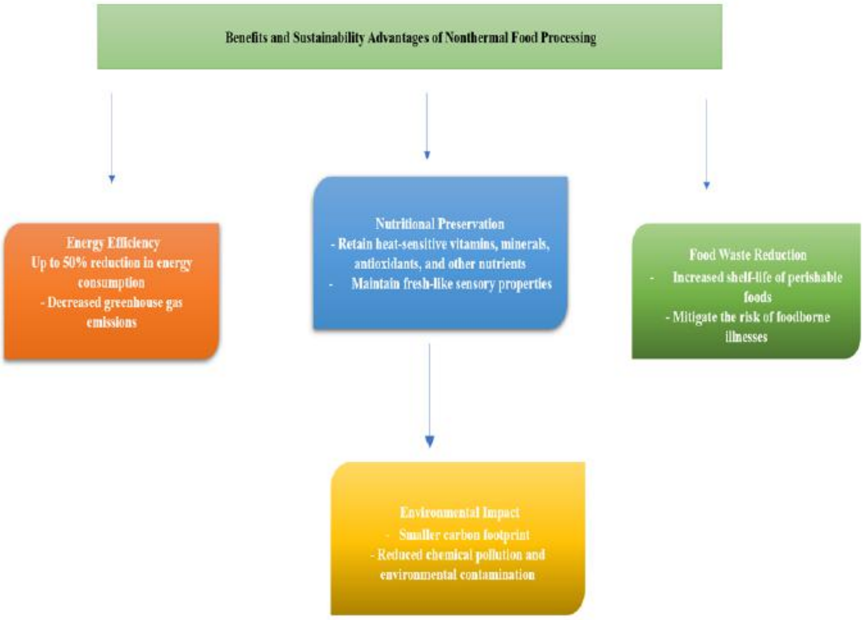

Fig.2: Benefits and sustainability considerations of nonthermal food processing

The antioxidant content in PEF-treated milk or fruit juice is comparable to that of fresh products (Šalaševičius, Uždavinytė, Visockis, Ruzgys, & Šatkauskas, 2023). Furthermore, the application of pulsed electric field (PEF) technology is linked to the conservation of flavors and fragrances that closely mimic those found in fresh food items (del Carmen Razola-Díaz et al., 2024). In a parallel manner, Cold Plasma treatment has demonstrated its efficacy in the eradication of surface pathogens from fresh agricultural products while exerting a negligible effect on the sensory and nutritional quality of the goods (Y. Wang et al., 2024). Non-thermal processing holds the promise of enhancing human health and well-being by reducing the degradation of bioactive compounds during food production and distribution while preserving the natural nutritional and functional properties of foods (Núñez-Delgado, Mizrachi-Chávez, Welti-Chanes, Macher-Quintana, & Chuck-Hernández, 2024; Sharma et al., 2024). This aligns with the growing consumer trend toward less processed, whole foods that maintain their nutritional integrity.

3.3. Food waste reduction

Nonthermal food processing technologies too, have the potential to decrease waste across the supply chain (by sustaining the shelf-life and safety of those products) (Režek Jambrak, Nutrizio, Djekić, Pleslić, & Chemat, 2021). HAPP and PEF both have the ability to inactivate spoilage microorganisms as well as enzymes, thus preserving perishable food items such as fruit juice, meat products, or dairy applications for an extended period (Amit, Uddin, Rahman, Islam, & Khan, 2017).

The longer shelf-life could mean fewer losses in storage, transportation, and retail display as well as by consumers due to spoilage (Mortazavi, Kaur, Farahnaky, Torley, & Osborn, 2023). Furthermore, enhancing the microbial safety of foods processed without heat can help decrease the incidence of foodborne illnesses and as a result, lower the amount of waste caused by product recalls or consumers' reluctance to purchase affected items following outbreaks (Islam et al., 2022; Wansink, 2004). Nonthermal processing can help support the broader sustainability of the food system by reducing food waste (Djukić-Vuković, Mladenović, Pejin, & Mojović, 2022). Less food waste means better use of resources, lower environmental impacts, and more available food - all essential for improving global sustainability of the world's environmental challenges, as well to ensure long term availability.

3.4. Environmental impact

The use of nonthermal food processing technologies can save significantly more energy and offer greater environmental benefits compared to thermal methods for the preservation of foods other than dehydrated products (Zou, Khan, et al. 2024; Boateng, 2024). Low power use:

This is the most critical pro of using renewable energy while it performs (Jenkins & Ekanayake, 2024). Nonthermal techniques such as high-pressure processing or pulsed electric fields typically function at a lower temperature; thus the minimum stress is needed for heating and cooling steps accompanying them providing essential energy-saving (Bigi et al., 2023; Brito & Silva, 2024). Meaning, lower greenhouse gas emissions and carbon footprint for food processing facilities (Zou, Hussain, et al. 2024; Shabir et al., 2023). In nonthermal processing, heat-induced nutrient and quality degradation can also be minimized thus further raising yield while reducing food wastage along the supply chain (Safwa et al., 2023). Decreased food waste contributes to reduced resource inefficiency and the environmental impact of wasted food that is generated, transported, and disposed of (Onyeaka et al., 2023). Other nonthermal technologies (ie, UV light; cold plasma) also have the potential to minimize water consumption and wastewater generation in comparison with traditional cleaning and sanitization methods (Gururani et al., 2021; Mumtaz et al., 2023). These technologies can support food processing sustainability, for the international community as well by conserving water and reducing the load on wastewater treatment infrastructure (Javan et al., 2023; Obaideen et al., 2022). "Moreover, the incorporation of nonthermal technologies can facilitate the development of closed-loop or circular production systems, where waste streams and byproducts from high-value processing steps are effectively utilized, thereby minimizing the environmental footprint associated with food processing operations." (Almaraz-Sánchez, Amaro-Reyes, Acosta-Gallegos, & Mendoza-Sánchez, 2022; Kabir, Akter, Huang, Tijing, & Shon, 2023; Paini et al., 2022). This also validates the broader pivot towards a more circular food economy, which minimizes waste and resource consumption (Zhang, Dhir, & Kaur, 2022). In sum, the environmental advantages of nonthermal food processing technologies i.e. low energy consumption along with reduced footprint in terms of greenhouse gas emissions; potential to combat waste across various stages from farm-to-fork and value realization opportunities for water streams/wastes is a sustainable route toward future safe food manufacturing strategies.

IV. CHALLENGES AND FUTURE DIRECTIONS

4.1. Scalability and cost-effectiveness

Despite the environmental and quality benefits, large-scale implementation of nonthermal food processing technologies in the industry is challenging from a scalability perspective as well as cost-effectiveness (Chacha et al., 2021). A significant hurdle to the widespread adoption of nonthermal technologies is the substantial upfront investment required for specialized equipment and infrastructure needed for industrial-scale production (Rajabloo, De Ceuninck, Van Wortswinkel, Rezakazemi, & Aminabhavi, 2022). Nonthermal processes may require more complex and elegant machinery relative to conventional thermal processing systems rendering such apparatus costly especially for smaller-scale food industries (Keşa et al., 2021; Noble, Todorova, & Yarovsky, 2022). Further, full-scale finite element nonthermal models have yet to be developed based on model parameter selection accompanied by process simulations along with the assessment of operational costs against all other forms or terms comprises an appropriate challenge (Duchnowski & Brown, 2024; Melchiorri, 2024). For these reasons, practical and economic evaluations of waste-water treatments with ozonation are necessary in terms of energy consumption, throughput rates, and integration into existing processing lines (Monje et al., 2022; Thakur et al., 2023). In turn, researchers and food industry stakeholders aim to overcome these challenges through the inclusion of different methods to increase quality assurance while minimizing defects (Antony et al., 2024; I. Khan et al. 2023). This has included the design of more compact, modular equipment as well as adjusting process parameters to improve energy efficiency and throughput in all different temperature ranges (Allouhi, Rehman, Buker, & Said, 2023; Tilahun, 2024). Collaborative industry-academia partnerships and supportive policies, and incentives can encourage the deterrence of financial constraints faced by industries in adopting these non-thermal technologies into their processing lines thus helping to invest substantially in scaling up research and development (Wyns, Khandekar, & Groen, 2019). Still, as that technology develops and economies of scale benefit the industry at large; nonthermal will become increasingly cost-competitive with thermal standards in terms of both capital and operating costs - making these sexy solutions ever more viable for broad adoption across food.

4.2. Regulatory approval and consumer acceptance

Such nonthermal processing methods may find a variety of potential applications in the food industry, but regulatory approval and consumer acceptance can be obstacles to their implementation (Zhao, de Alba, Sun, & Tiwari, 2019). Regulatory bodies must establish rigorous guidelines for the approval of new processing technologies, and food safety as well as product quality are always priority concerns (Okpala & Korzeniowska, 2023). Nona thermal processing technologies such as high-pressure, pulsed electric fields, cold plasma, etc., require an adequate amount of research and testing to ensure pathogens' inactivation along with retention of food quality (nutritional), preservation attributes (Delbrück, 2022; Galanakis, 2015).Therefore, the information about processes needed for certification under different storage events could be a laborious job for stakeholders) Regulations in different countries and regions differ (Zeberer), which makes the uptake of these technologies more difficult Aside from regulatory clearance, consumer liking must pave the way for a successful deployment of nonthermal processing (Hassoun et al., 2023). Many consumers are not familiar with or misinformed about these new technologies, and communication and education programs may be needed to clarify the facts accurately so that confidence can grow (Allchin, 2023). Managing the level of consumer regard to food safety, nutrition, and transparency is key for overcoming apprehensions about nonthermal-processed food products (and another study focused specifically on APP-treated beef); Nevertheless, a long-term sustainable partnership among food industry stakeholders together with regulators and consumer groups is essential to accelerate the acceptance process and also provide mechanisms for enhancing consumer awareness regard nonthermal methods that would increase trust in such technologies.

4.3. Integration with existing infrastructure

Integrating nonthermal processes into current food manufacturing sites and the logistics of the supply chain may be quite challenging (Chakka, Sriraksha, & Ravishankar, 2021). The incorporation of these new technologies may necessitate large investments, in terms of changes to current processing setups infrastructure, equipment upgrades, and modifications to existing workflows (Atkinson, Gesing, Montagnat, & Taylor, 2017). Nonthermal processing methods can require food manufacturers to retrofit their sites for niche equipment and operating systems (Hussain et al. 2024; Aguilar et al., 2019). Examples of such adjustments include the retrofitting or reconfiguration of production lines, as well as updating storage and transportation systems to accommodate these changes in processing techniques (Carman, 2002) (Krishnan, Yonca, & Comes, 2023; Moreno-Rangel & Dalton, 2023). In addition, any nonthermal approaches must be economically viable and suitable for implementation further downstream within the wider food supply chain to ensure that they are generic enough concerning packaging, distribution, or retail handling (Sovacool et al., 2021). There are also the logistics, e.g. cold chain or batch sizes - which means careful planning and implementation are required here as well (Richards & Grinsted, 2024). To combat integration problems, food processors and equipment makers are starting to work more closely together as they develop new modular nonthermal processing systems that can be easier to integrate into operations (Picart-Palmade, Cunault, Chevalier-Lucia, Belleville, & Marchesseau, 2019). Current research and development in that area are focused on the creation of these solutions which can significantly reduce any potential impact on existing food processing procedures while helping to smoothen both integration and acclimatization processes for non-thermal technologies (Bigi et al., 2023; Picart-Palmade et al., 2019).

4.4. Optimization of process parameters

Integrating nonthermal processes into current food manufacturing sites and logistics of the supply chain may be quite challenging (Kumar, Panghal, & Garg, 2024). The incorporation of these new technologies may necessitate large investments, in terms of changes to current processing setups infrastructure, equipment upgrades, and modifications to existing workflows (Luna, 2024; Shukla & Dubey, 2024). Nonthermal processing methods can require food manufacturers to retrofit their sites for niche equipment and operating systems (Luna, 2024). Examples of such adjustments include the retrofitting or reconfiguration of production lines, as well as updating storage and transportation systems to accommodate these changes in processing techniques (Carman, 2002) (Moreno-Rangel & Dalton, 2023). In addition, any nonthermal approaches must be economically viable and suitable for implementation further downstream within the wider food supply chain to ensure that they are generic enough concerning packaging, distribution, or retail handling (Sovacool et al., 2021). There is also the logistics, e.g. cold chain or batch sizes - which means careful planning and implementation are required here as well (Altekar, 2023). To combat integration problems, food processors and equipment makers are starting to work more closely together as they develop new modular nonthermal processing systems that can be easier to integrate into operations (Bramsiepe et al., 2012). Current research and development in that area are focused on the creation of these solutions which can significantly reduce any potential impact on existing food processing procedures while helping to smoothen both integration and acclimatization processes for non-thermal technologies.

4.5. Future perspectives

In this ever-changing global scenario of the food industry, innovative nonthermal processing technologies discussed in the review could play a major role and are very promising to bring revolution in food materials treatments. One clear direction for the future is increasing the scalability and cost-effectiveness of nonthermal systems. Future work should focus on accelerating R&D, to refine the design and manufacturing of these technologies so that they can eventually be fully integrated within the fabric of existing food processing infrastructure at a cost-performance level competitive with traditional thermal methods. Advances in system engineering, materials science and in process automation will be necessary for the scale-up of non-thermal technologies to their full potential. Next to the technical improvements, nonthermal processing will have to be widely introduced as part of an integrated chain in close collaboration between researchers, regulatory bodies and the food industry. The task of setting rigorous standards around safety and quality (health considerations aside), as well as, education knowing that this is happening are some immediate areas for necessary attention. Because consumer acceptance is key to adopting new food technologies, strategic communication and transparency will be essential in earning the confidence needed for nonthermal processing methods to attain more widespread use within our mainstream food supply chains. The continuous optimization of process parameters and investigation of alternative nonthermal methods will overcome these potential issues to deliver products with replicable product quality, safety, and sensory attributes. By examining the synergistic effects associated with combining different nonthermal technologies, new areas could be targeted for diversifying applications and broadening horizons towards revolutionary food processing solutions. It would also consider the logistical challenges of integrating nonthermal technologies into current food supply chains. New ways of transportation and storage solutions along with the establishment of decentralized processing facilities will inevitably play a part in revising current bottlenecks - via its seamless inclusion into the supply chain. In short, progress in nonthermal food processing will not work without the multi-topic and transdisciplinary detail gaze. Interdisciplinary connections between food scientists, engineers (from process to material science), and sustainability experts can help catalyze the translation of novel concepts from ideas into practical solutions. The combined effort from both organizations will play a critical role in leading the evolution of the food system to become even more sustainable, resilient, and climate-friendly moving forward.

V. CONCLUSION

Recent years have seen nonthermal processing methods such as High-Pressure Processing (HPP), Pulsed Electric Fields (PEF), and Cold Plasma surfaces, providing alternative solutions to sustainability issues in food production and supply chains. All of these emerging technologies provide a range of benefits to create more sustainable and resilient global food systems. These methods of nonthermal processing maintain the nutritional and quality properties of food products which are susceptible to degradation by heat process, consequently enabling producers to prepare healthier as well as more pleasurable food items. Besides, these efforts display exceptionally good energy efficiency as compared to traditional thermal processing reducing the related power usage and greenhouse gas emissions by a large factor. This improved energy efficiency and minimized environment impact fits right within global efforts to combat climate change, and its built around new sustainable methodologies. Moreover, the use of non-thermal technologies helps to prevent food waste along the supply chain thanks to prolonged shelf-life for perishable foods with controlled essential attributes. This comprehensive use of the cutting-edge technology will be instrumental to ensuring that food production and consumption become more sustainable in order to meet global concerns about resource conservation, environmental integrity and depletion or shortage.

ACKNOWLEDGEMENTS

The authors acknowledge the College of Food Science, Southwest University, Chongqing for the support. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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