

Sterilization and Microbial Inactivation Technologies for Liquid Foods: A Review of Food Safety, Shelf Life, and Food-System Resilience in Indonesia

Loso Judijanto✉

IPOSS, Jakarta, Indonesia

e-mail: losojudijantobumn@gmail.com

ABSTRAK

Liquid foods are highly susceptible to microbial contamination and quality deterioration, while distribution across geographically dispersed markets requires adequate shelf life, safety, and product stability. This article critically examines the development of sterilization and microbial inactivation technologies for liquid foods and evaluates their contribution to food safety and food-system resilience, with particular attention to Indonesia. Using a qualitative literature review, the study synthesizes peer-reviewed research published from 2020 to 2026 on thermal processes, particularly ultra-high-temperature (UHT)/aseptic processing and ohmic heating, and on non-thermal technologies including high-pressure processing (HPP), pulsed electric fields (PEF), ultraviolet-C (UV-C), and cold plasma. The synthesis shows that no single technology is optimal for every food matrix or safety target. UHT/aseptic processing remains the most established option when commercial sterility and ambient shelf stability are required, whereas HPP and PEF can provide superior retention of fresh-like quality but generally require additional hurdles when bacterial spores are relevant. UV-C performance is strongly constrained by optical properties, while cold plasma still requires broader product-specific validation, chemical-safety assessment, and scale-up evidence. For Indonesia, a portfolio approach is the most defensible strategy: optimize mature thermal and volumetric-heating platforms for mass-market products while developing targeted HPP, PEF, UV-C, and hybrid applications according to product properties, economics, regulatory requirements, and industrial capability

Keyword: liquid-food sterilization; microbial inactivation; UHT; high-pressure processing; pulsed electric field; ultraviolet-C; cold plasma; shelf life; food safety; food security.

INTRODUCTION

Food security is determined not only by the quantity of food produced but also by the capacity of food systems to maintain availability, access, safe



utilization, and supply stability over time. These dimensions are particularly important for liquid foods such as milk, fruit juices, protein beverages, and functional drinks because their high water activity and nutrient density can support microbial growth and accelerate quality deterioration. Processing technologies that control microbiological hazards while preserving nutritional value, sensory properties, and shelf life should therefore be regarded as part of food-system infrastructure rather than as isolated factory operations. This perspective is increasingly relevant as food systems are simultaneously expected to reduce losses, resource use, and environmental burdens (Gantina et al., 2020; Forde and Decker, 2022; Chung et al., 2022; Bains et al., 2024).

Terminology is critical when evaluating preservation technologies. Commercial sterilization is intended to produce a product that is microbiologically safe and stable under specified storage conditions through a validated process, including control of relevant microorganisms and, for shelf-stable low-acid foods, the risks associated with bacterial spores. In contrast, technologies frequently described as “non-thermal sterilization,” such as HPP, PEF, UV-C, and cold plasma, are more appropriately characterized under many practical conditions as microbial-inactivation or non-thermal pasteurization technologies because their effectiveness against spores depends strongly on treatment intensity, food matrix, temperature, and the use of additional hurdles. Maintaining this distinction prevents safety claims from exceeding the evidence provided by process validation (Aganovic et al., 2021; Podolak, Whitman and Black, 2020; EFSA BIOHAZ Panel et al., 2022).

Thermal processing remains the technological backbone of the liquid-food sector. Ultra-high-temperature processing combined with aseptic packaging can deliver long ambient shelf life and high throughput, but excessive thermal load may promote protein denaturation, Maillard reactions, loss of volatile compounds, color changes, and other quality defects. Advances in direct heating, more tightly controlled indirect systems, and ohmic heating aim to reduce over-processing by improving heating rate and uniformity rather than by abandoning thermal lethality. Consequently, the relevant engineering question is not simply “thermal versus non-thermal,” but how energy delivery, target lethality, matrix properties, and quality changes can be optimized together (Dumpler, Huppertz and Kulozik, 2020; Eisner, 2021; Makroo, Rastogi and Srivastava, 2020; Grossmann, Hinrichs and Weiss, 2022; Astráin-Redín et al., 2024).

At the same time, HPP, PEF, UV-C, and cold plasma have expanded the processing toolkit because they can reduce microbial loads with lower bulk-temperature increases or very short treatment times. HPP is commercially established in several food and beverage categories, whereas PEF is particularly

attractive for pumpable liquids with suitable electrical properties and is increasingly supported by mechanistic and product-specific evidence. UV-C can be comparatively simple and energy efficient, but its performance is strongly affected by absorbance, color, turbidity, and reactor hydrodynamics. Cold plasma offers broad antimicrobial mechanisms through reactive species, although reactor design, product chemistry, toxicological assessment, standardization, and industrial scale-up remain active research needs (Aganovic et al., 2021; Singh et al., 2021; Laroque et al., 2022; Bayati et al., 2024; Brito and Silva, 2024; Lytras et al., 2024).

The topic is particularly important for Indonesia because a geographically dispersed archipelagic market requires food products that can move safely over long distances and through heterogeneous logistics systems. Longer shelf life can reduce pressure on cold-chain infrastructure for appropriate product categories, decrease spoilage during distribution, and provide greater flexibility in inventory management. Nevertheless, a technology contributes to food-system resilience only when it is technically valid, economically feasible, maintainable, and institutionally supported; expensive equipment that cannot be consistently operated or validated does not automatically improve resilience. Research on food loss and supply-chain management similarly indicates that processing technologies must be integrated with packaging, logistics, information systems, market coordination, and governance rather than treated as stand-alone solutions (Moraes, Lermen and Echeveste, 2021; Benyam, Soma and Fraser, 2021; Luo et al., 2022; Prasetya et al., 2022).

Although research on food-processing technologies has expanded rapidly, the literature is often fragmented by technology and commodity, which makes cross-technology decisions difficult. A stronger synthesis is therefore needed to connect mechanisms of microbial inactivation with quality retention, industrial readiness, validation requirements, sustainability, and food-security outcomes, particularly for developing economies and geographically dispersed distribution systems. Accordingly, this review addresses two research questions. RQ1 asks how thermal and non-thermal technologies for liquid-food sterilization or microbial inactivation compare in terms of operating principles, microbiological safety, sensory and nutritional quality, shelf life, energy implications, limitations, and industrial readiness; RQ2 asks how the selection and integration of these technologies can support Indonesian food safety and food security through longer shelf life, reduced food loss, wider distribution, and stronger industrial competitiveness. The objective is to provide an integrated conceptual synthesis, a technology-selection framework, and a practical research and implementation

agenda for Indonesia (Meijer et al., 2021; Chakka, Sriraksha and Ravishankar, 2021; Arshad et al., 2022; Cavalcanti et al., 2023).

LITERATURE REVIEW

Conceptual Boundaries: Sterilization, Pasteurization, and Microbial Inactivation

Microbiological processing objectives for liquid foods should be distinguished according to the target hazard and the intended distribution conditions. Pasteurization primarily reduces vegetative pathogens and spoilage microorganisms to a level compatible with a defined safety and shelf-life objective, commonly in combination with refrigeration or another control measure. Commercial sterilization requires a higher process target so that a properly formulated, processed, and packaged product remains safe and stable under specified ambient conditions. Technology assessment should therefore begin with the target microorganism, product characteristics, storage conditions, and required log reduction rather than with the labels “thermal” or “non-thermal” alone (Aganovic et al., 2021; Podolak, Whitman and Black, 2020; EFSA BIOHAZ Panel et al., 2022).

This distinction is especially important for low-acid products because bacterial spores are substantially more resistant than vegetative cells to many non-thermal interventions. HPP at low temperature can be highly effective against many vegetative bacteria, but reliable spore inactivation generally requires pressure combined with elevated temperature or other hurdles. PEF primarily acts through membrane electroporation and is generally more effective against vegetative cells than spores, whereas UV-C efficacy depends on delivered fluence and optical penetration and cold plasma depends on the interaction of reactive oxygen and nitrogen species with cells and food constituents. Minimal processing should therefore not be treated as equivalent to commercial sterility (Houška et al., 2022; Ghoshal, 2023; Singh et al., 2021; Varilla, Marcone and Annor, 2020; Lytras et al., 2024).

Scientific Foundations of Inactivation: Lethality, Matrix Effects, and Hurdle Technology

For thermal processes, safety design is governed by time–temperature relationships and microbial inactivation kinetics. Process effectiveness must be evaluated as integrated lethality over the complete heating history rather than from peak temperature or holding time alone, because viscosity, particle size, flow behavior, heat-transfer configuration, and thermophysical properties can create cold zones that determine process adequacy. In milk and protein-rich beverages, increasing thermal intensity also interacts with protein stability and

chemical reactions that influence color, flavor, and nutritional quality. These considerations reinforce the need to optimize the full thermal history rather than a single nominal set point (Dumpler, Huppertz and Kulozik, 2020; Eisner, 2021; Bottiroli et al., 2020).

Non-thermal technologies add process dimensions beyond bulk temperature. In HPP, pressure, holding time, initial temperature, compression and decompression rates, pH, and composition influence microbial response; in PEF, field strength, pulse width and number, specific energy, conductivity, residence time, and outlet temperature determine electroporation and associated thermal effects. UV-C performance depends on absorbance, optical path, hydrodynamics, and residence-time distribution, while cold-plasma outcomes depend on gas composition, voltage, frequency, reactor geometry, treatment time, and mass transfer of reactive species into the liquid phase. This multi-parameter behavior explains why product-specific validation is a central requirement across emerging technologies (Podolak, Whitman and Black, 2020; Arshad et al., 2020; Pierscianowski et al., 2021; Laroque et al., 2022; Zheng et al., 2024).

Hurdle technology becomes important when a single mechanism cannot meet the desired safety target without imposing unacceptable quality changes. Moderate heating can be combined with pressure or PEF, UV-C can be coupled with reactor designs that improve exposure, and cold plasma can be integrated with complementary antimicrobial steps to increase overall inactivation. However, apparent synergy must be demonstrated experimentally because combining technologies can also increase complexity, energy use, cost, and uncertainty in process validation. The most defensible hybrid process is therefore one in which each hurdle has a clearly defined function and the combined process is validated on the actual product (Amsasekar et al., 2022; Allai et al., 2023; Chakka, Sriraksha and Ravishankar, 2021).

Thermal Technologies: UHT/Aseptic Processing and Ohmic Heating

UHT processing and aseptic packaging are mature platforms for shelf-stable liquid foods because they can deliver high microbial lethality over short heating times and then prevent post-process recontamination. Their principal strengths are industrial experience, high throughput, reproducibility, and the possibility of ambient distribution for properly designed products. The main challenge is cumulative heat damage, including protein denaturation, sedimentation, browning, flavor changes, and vitamin degradation when heating and cooling are not sufficiently controlled. Comparisons of direct and indirect heating further show that the full time-temperature profile and flash-cooling conditions can

materially affect product quality during processing and storage (Dumpler, Huppertz and Kulozik, 2020; Eisner, 2021; Bottiroli et al., 2020).

Ohmic heating generates heat volumetrically through the electrical resistance of the food, allowing potentially faster and more uniform heating than conventional surface heat transfer. It is particularly attractive for electrically conductive liquids and liquid-particulate systems and can reduce temperature gradients that lead to unnecessary over-processing. Recent evidence also emphasizes that electrical field strength, frequency, electrode material, chamber geometry, changes in conductivity during heating, fouling, and electrochemical reactions can materially affect performance and scale-up. These engineering constraints mean that the technology should be treated as a controllable thermal platform rather than as inherently uniform or automatically energy efficient (Makroo, Rastogi and Srivastava, 2020; Wattanayon, Udompijitkul and Kamonpatana, 2021; Rocha et al., 2022; Shao et al., 2021; Kuriya et al., 2020; Astráin-Redín et al., 2024).

From a sustainability perspective, thermal innovation should not be framed as an obsolete pathway that must be replaced by non-thermal processing. Heat recovery, electrification, improved heat-exchanger design, volumetric heating, and integration with low-carbon energy can reduce resource demand while preserving the major validation advantages of heat when spore control is required. Meaningful comparisons should therefore account for system-wide impacts, including downstream refrigeration, packaging, product losses, and distribution conditions, rather than only the energy consumed by the processing unit itself. Such a systems perspective is more consistent with life-cycle assessment and avoids simplistic claims that one technology class is inherently “green” (Grossmann, Hinrichs and Weiss, 2022; Chung et al., 2022; Bains et al., 2024).

High-Pressure Processing (HPP)

HPP applies high hydrostatic pressure that is transmitted rapidly and nearly uniformly through the product, typically after packaging or within a pressure vessel. The technology is highly effective against many vegetative microorganisms at relatively low temperatures and is therefore well suited to juices, smoothies, liquid sauces, and other products that seek a fresh-like sensory profile. Reviews consistently show that HPP can preserve sensory attributes and many nutrients better than intensive thermal processing, although the outcome depends on pressure, time, temperature, pH, product composition, and the target organism. Consequently, performance should be interpreted within a product-specific process window rather than as a universal quality advantage (Aganovic et al., 2021; Houška et al., 2022; Song et al., 2022).

The major microbiological limitation of low-temperature HPP is the resistance of bacterial spores and, in some products, residual enzyme activity. For low-acid products intended to be shelf stable at ambient temperature, conventional HPP conditions should not be assumed to be equivalent to commercial sterilization. Heat-assisted HPP or combinations with other hurdles can enhance spore inactivation, but these processes require integrated validation of microbiological safety, product quality, packaging performance, and economics. Safety assessments must also consider sublethal injury, potential microbial recovery, and the storage conditions applied after processing (Podolak, Whitman and Black, 2020; EFSA BIOHAZ Panel et al., 2022; Gharbi, Marciniak and Doyen, 2022).

HPP is more technologically mature than many other non-thermal options, but adoption still depends on capital cost, vessel utilization, batch or semi-continuous operation, compatible packaging, product throughput, and cost per unit of output. These factors make HPP particularly attractive for higher-value categories in which consumers or retailers reward fresh-like quality, clean-label positioning, or premium shelf-life performance. Even in such categories, structural changes in proteins, texture, and enzymatic activity must be evaluated for the actual formulation rather than assumed to be negligible. Industrial readiness therefore reflects both process maturity and a viable product-market fit (Nath, Pandiselvam and Sunil, 2023; Amsasekar et al., 2022).

Pulsed Electric Field (PEF)

PEF exposes liquid foods to short pulses of high electric field, with irreversible electroporation of microbial cell membranes as the principal inactivation mechanism under non-thermal or mildly thermal conditions. Continuous-flow configurations make the technology particularly attractive for juices, dairy beverages, liquid egg, and other pumpable products with suitable electrical properties. Microbial inactivation is influenced by field strength, pulse shape, treatment time, specific energy, conductivity, temperature, microorganism characteristics, and product composition, and insufficient treatment may leave sublethally injured cells. Recent mechanistic reviews therefore emphasize that electrical and microbiological parameters must be reported together to support process comparison and validation (Niu et al., 2020; Arshad et al., 2020; Ghoshal, 2023; Cavalcanti et al., 2023; Lytras et al., 2024).

A major advantage of PEF is its ability, under appropriately optimized conditions, to retain color, aroma, vitamins, and other heat-sensitive compounds while providing meaningful microbial and enzymatic inactivation. The technology can also modify protein functionality and enhance extraction from plant materials and processing side streams, which broadens its relevance to

resource efficiency and circular processing. Nevertheless, spore inactivation is limited under conventional PEF conditions, and treatment can become less predictable in highly conductive or compositionally complex systems, particularly when particles, gas bubbles, or electrode reactions affect field distribution. Evidence from fruit and vegetable juices confirms that optimization must integrate electrical parameters, microbial targets, physicochemical stability, and sensory quality rather than maximizing field intensity alone (Taha et al., 2022; Xi, Li and Fan, 2021; Brito and Silva, 2024).

PEF is often described as an energy-efficient and sustainable process because treatment times can be very short and continuous integration is feasible. Such claims, however, are meaningful only when technologies are compared using the same functional unit, for example energy per liter of microbiologically safe product that achieves a specified shelf life. Pulse generators, treatment chambers, electrode durability, high-voltage safety, maintenance, and operator expertise remain important determinants of commercial feasibility. Industrial deployment therefore requires combined microbiological, engineering, and techno-economic evidence, especially for lower-acid and compositionally complex products (Arshad et al., 2021; Chakka, Sriraksha and Ravishankar, 2021; Arshad et al., 2022; Lytras et al., 2024).

UV-C and Cold Plasma

UV-C inactivates microorganisms primarily through photochemical damage to nucleic acids and can support continuous processing with little bulk heating when the liquid is sufficiently transparent. Its effectiveness is nevertheless strongly constrained by optical properties because absorbance, turbidity, color, suspended particles, and fouling can shield microorganisms and create non-uniform dose delivery. Reactor designs that generate thin films, controlled turbulence, secondary flow, or repeated passes are therefore required to ensure that the actual delivered fluence can be validated. UV-C should consequently be regarded as a matrix-dependent process in which optical characterization and hydrodynamics are as important as nominal lamp power (Singh et al., 2021; Pierscianowski et al., 2021; He et al., 2021).

Evidence from fruit- and vegetable-based products indicates that UV-C can preserve many quality attributes when dose and exposure time are optimized, but the technology is not universally suitable for all beverages. Studies on UV and pulsed-light processing also demonstrate trade-offs among microbial dose, photochemical degradation of sensitive compounds, and light distribution through heterogeneous matrices. For this reason, UV-C is best positioned as a product-specific technology or part of a validated hurdle strategy rather than as a direct replacement for UHT across the entire liquid-food sector. The same

caution applies when laboratory performance is extrapolated to industrial flow rates and larger optical path lengths (Esua et al., 2020; Dhar, Basak and Chakraborty, 2022; Darré et al., 2022; Yemmireddy, Adhikari and Moreira, 2022).

Cold plasma generates electrons, ions, photons, and reactive oxygen and nitrogen species that can damage microbial membranes, proteins, and genetic material. The technology can be applied to surfaces, packaging, process air, or liquids through direct plasma exposure or plasma-activated media, and its relatively low process temperature makes it attractive for heat-sensitive products. However, the same reactive chemistry responsible for microbial inactivation can oxidize lipids, pigments, vitamins, proteins, and aroma compounds, which means that product chemistry must be assessed alongside log reduction. Recent research has therefore shifted from reporting antimicrobial efficacy alone toward characterizing chemical reaction products, sensory changes, and the safety implications of plasma-generated species (Varilla, Marcone and Annor, 2020; Warne et al., 2021; Saremnezhad et al., 2021; Laroque et al., 2022; Katsigiannis, Bayliss and Walsh, 2022; Bayati et al., 2024).

Cold-plasma readiness for liquid-food applications remains lower than that of HPP and established thermal technologies. Differences in plasma sources, gas composition, frequency, electrode distance, liquid-gas mass transfer, reactor geometry, and definitions of effective dose make cross-study comparison difficult. Reviews published from 2022 onward show promising retention or apparent enhancement of selected bioactive compounds under some conditions, while simultaneously documenting oxidation risks and the need for more rigorous toxicological assessment and scale-up studies. Progress toward commercial liquid processing will therefore depend on standardized reporting, chemical-safety characterization, process monitoring, and reproducible reactor design (Zhang et al., 2022; Sruthi et al., 2022; Oner et al., 2023; Dharini, Jaspín and Mahendran, 2023; Bayati et al., 2024; Zargarchi et al., 2024; Xiang et al., 2023).

Quality, Shelf Life, Consumer Trust, and Sustainability

Microbiological safety is the minimum requirement for preservation, but commercial success also depends on quality changes during processing and storage. UHT products may continue to undergo flavor, color, and protein-stability changes during shelf life; HPP often preserves fresh-like characteristics but can leave residual enzyme activity or alter texture; and PEF, UV-C, and cold plasma can preserve heat-sensitive compounds while introducing process-specific chemical or physical changes. Shelf-life evaluation must therefore integrate microbiology, chemical stability, sensory quality, nutritional markers, and the possibility of microbial recovery under realistic storage conditions. A process that performs well immediately after treatment cannot be assumed to

remain optimal throughout distribution (Bottiroli et al., 2020; Song et al., 2022; Warne et al., 2021; Brito and Silva, 2024).

Consumer acceptance of new processing technologies is not determined by technical performance alone. Consumers also evaluate perceived naturalness, degree of processing, expected benefits, uncertainty, risk, and the credibility of information supplied by producers, scientists, and regulators. European evidence indicates that transparent communication of both benefits and limitations is important for acceptance of non-thermally processed foods. Industrialization strategies should therefore combine scientific validation with accurate labeling and communication, including avoidance of the term “sterile” when a process has only been validated as pasteurization or microbial inactivation (Meijer et al., 2021; Song et al., 2020).

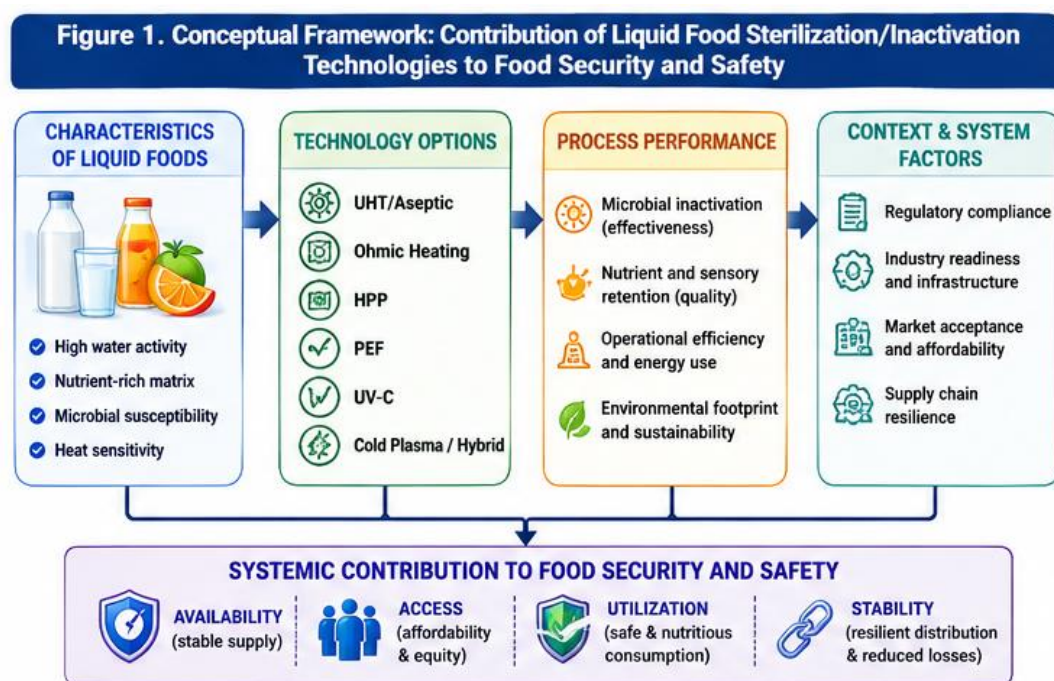
From a sustainability perspective, lower-temperature technologies may reduce specific energy demands or better preserve the economic value of sensitive ingredients, but meaningful assessment requires a whole-system boundary. HPP uses specialized pressure equipment; UHT requires heat but can eliminate cold-chain needs for appropriate products; PEF relies on high-power electrical pulses but can operate for very short treatment times; and UV-C can be efficient when optical conditions are favorable. Credible comparisons should therefore include shelf life, food losses, water, packaging, distribution, refrigeration, equipment utilization, and the carbon intensity of energy rather than presenting process energy alone as evidence of environmental superiority. Recent circular-bioeconomy analyses reinforce the value of using life-cycle and resource-efficiency metrics when comparing emerging processing technologies (Chung et al., 2022; Chakka, Sriraksha and Ravishankar, 2021; Grossmann, Hinrichs and Weiss, 2022; Bains et al., 2024).

Theoretical Link between Processing Technology and Food Security

The contribution of sterilization and microbial-inactivation technologies to food security occurs through intermediate mechanisms rather than through processing alone. Effective microbial control improves food safety and reduces spoilage; a longer stable shelf life increases the available distribution window and inventory flexibility; reduced spoilage and rejection can decrease losses along the chain; and consistent safety and quality can strengthen market access and consumer confidence. These pathways can support the four conventional dimensions of food security – availability, access, utilization, and stability – but their magnitude is conditioned by processing cost, infrastructure, operating capability, logistics, regulation, and governance. Technology should therefore be conceptualized as an enabling capability whose food-security effects depend on

the wider system in which it is embedded (Moraes, Lermen and Echeveste, 2021; Benyam, Soma and Fraser, 2021; Luo et al., 2022; Gantina et al., 2020).

Figure 1 summarizes the causal pathway used as the conceptual framework for this review. It places liquid-food characteristics and technology selection upstream, links them to microbiological and quality outcomes, and then connects those outcomes to shelf life, distribution performance, food losses, and food-security consequences. This structure prevents technology from being treated as an end in itself and instead positions processing as one component of food-system capability. The framework is subsequently used to interpret technology trade-offs in the Results and Discussion section (Arshad et al., 2022; Magalhães et al., 2021).



Source: Synthesized by author based on Gantina et al. (2020), Moraes, Lermen and Echeveste (2021), Luo et al. (2022), and Arshad et al. (2022).

Figure 1. Conceptual framework: contribution of liquid-food sterilization/inactivation technologies to food security and safety.

Source: author's synthesis based on Gantina et al. (2020), Moraes, Lermen and Echeveste (2021), Luo et al. (2022), and Arshad et al. (2022).

Figure 1 emphasizes that microbiological success alone is insufficient to demonstrate a food-security benefit. A technology creates system-level value only when improved safety, quality, or shelf life is translated into a wider distribution radius, lower losses, improved supply flexibility, or stronger market access at an affordable total cost. The framework therefore provides a disciplined bridge between processing performance and the broader outcomes examined in

this review. It also makes explicit that the same technology may have different food-security implications under different infrastructure and market conditions (Chung et al., 2022; Benyam, Soma and Fraser, 2021).

Table 1. Terminological boundaries and process-validation implications for liquid foods

Term	General objective	Storage implications	Validation considerations
Pasteurization / vegetative-cell inactivation	Reduction of vegetative pathogens and spoilage microorganisms to a defined target.	Generally requires refrigeration or another hurdle, depending on product formulation and target shelf life.	The target organism, required log reduction, matrix, process conditions, and shelf-life regime must be specified.
Commercial sterility	Validated safety and stability of a shelf-stable product under specified conditions.	Ambient storage is possible when formulation, processing, aseptic conditions, and packaging meet the validated requirements.	For low-acid foods, spore resistance is a central concern; validation cannot be generalized across products.
Non-thermal processing	A category of technologies in which bulk heat generation is limited or deliberately controlled.	Storage requirements vary, and many applications still require refrigeration.	“Non-thermal” is not synonymous with “sterile”; microbial efficacy must be demonstrated for the actual product.
Hurdle / hybrid processing	Combination of complementary control factors to achieve a safety target without relying on extreme intensity from a single process.	Storage conditions vary according to the combined hurdles and the validated shelf-life design.	Synergy must be verified experimentally, and quality, energy, complexity, and regulatory implications must also be assessed.

Source: author’s synthesis based on Aganovic et al. (2021), Podolak, Whitman and Black (2020), EFSA BIOHAZ Panel et al. (2022), and Allai et al. (2023).

METHODOLOGY

This article uses a qualitative literature review (QLR), also described as a qualitative or narrative review, to develop a conceptual and interpretive synthesis of the literature on liquid-food processing. This approach is appropriate because the research questions are broad and integrative, spanning process mechanisms, product quality, industrial readiness, sustainability, and food-security implications rather than a single homogeneous outcome suitable for meta-analysis. QLR is treated here as an iterative process in which research questions, searching, critical reading, comparison, and the development of analytical categories inform one another. The approach therefore prioritizes conceptual integration and explanatory depth while retaining transparency about the limits of coverage (Juntunen and Lehenkari, 2021; Sukhera, 2022; Furlong and Lester, 2023).

The literature search was purposive and iterative and focused primarily on peer-reviewed articles published from 2020 to 2026. English and Indonesian search terms covered liquid-food sterilization, commercial sterility, UHT, aseptic processing, ohmic heating, high-pressure processing, pulsed electric field, UV-C, cold plasma, microbial inactivation, shelf life, food loss, food safety, and food security. Priority was given to recent reviews, relevant experimental studies involving liquid foods, and reputable journals for which the DOI or publisher record could be verified. Sources were retained when they were directly relevant to the research questions, described methods sufficiently to support interpretation, and contributed to technology comparison or food-system analysis; the review was not designed as a systematic literature review, did not claim exhaustive retrieval, and did not apply PRISMA or publication-count procedures (Sukhera, 2022; Yadav, 2022; Furlong and Lester, 2023).

Analysis was conducted through thematic synthesis. Evidence was organized into six themes: target organisms and inactivation mechanisms; nutritional and sensory effects; shelf life and distribution requirements; industrial readiness and scale-up constraints; energy, resource use, and food-loss implications; and relevance to the Indonesian food system. Cross-technology comparison was then used to address RQ1, while relationships between process performance and supply-chain outcomes were used to address RQ2. Interpretive validity was strengthened through comparison of review evidence with primary studies, conservative use of terminology, and explicit acknowledgment when results were strongly matrix- or condition-dependent. Because the review is purposive rather than exhaustive and the evidence base is heterogeneous, the resulting rankings and frameworks should be interpreted as qualitative

syntheses rather than pooled effect estimates (Yadav, 2022; Juntunen and Lehenkari, 2021).

RESULT AND DISSCUSION

Evolution of the Processing Paradigm: From Microbial Lethality to Multi-Criteria Optimization

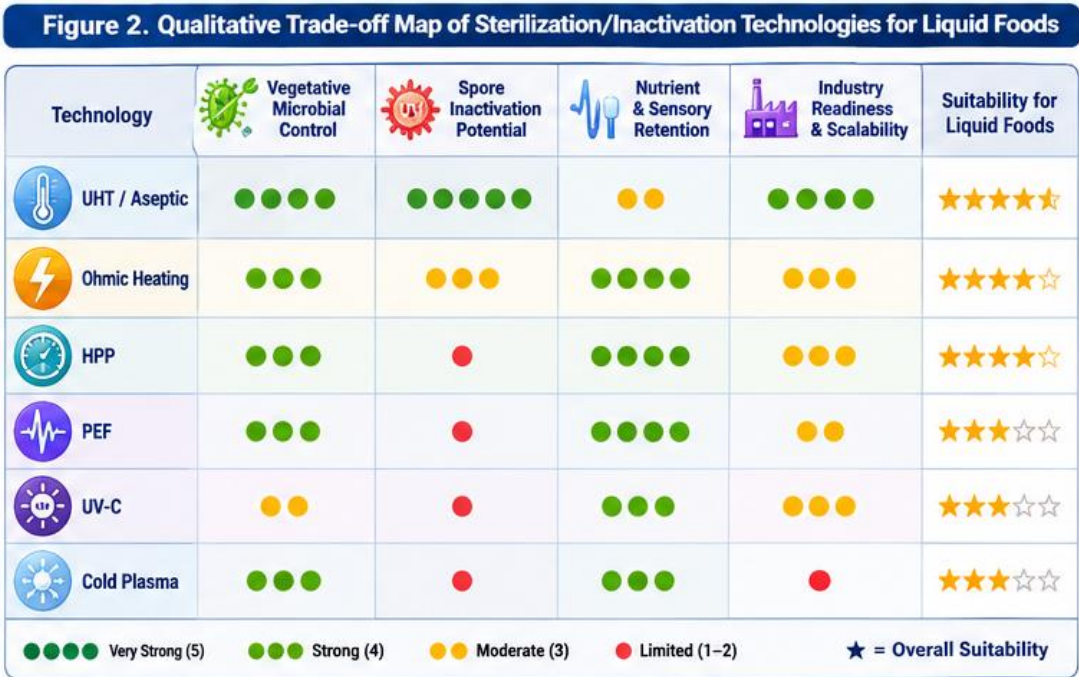
The literature shows a clear shift from a processing paradigm dominated by microbial lethality toward one that optimizes multiple outcomes simultaneously. Contemporary process design considers safety, sensory quality, nutrient retention, energy use, throughput, product flexibility, packaging, equipment compatibility, and sustainability rather than treating quality as a secondary consequence of safety. This shift does not reduce the importance of thermal processing; instead, it has stimulated more precise direct heating, improved heat recovery, volumetric heating, and hybrid approaches that can achieve an adequate safety margin without unnecessary over-processing. UHT, direct steam heating, and ohmic heating therefore continue to evolve in parallel with HPP, PEF, UV-C, and cold plasma rather than being displaced by them (Eisner, 2021; Makroo, Rastogi and Srivastava, 2020; Farahnaky, Majzoobi and Gavahian, 2022; Astráin-Redín et al., 2024; Zheng et al., 2024).

A second finding is that technologies must be differentiated by function and validated outcome rather than by novelty. HPP and PEF have strong evidence for vegetative-cell inactivation and retention of fresh-like characteristics in appropriate products, but neither should be treated as a universal substitute for UHT in low-acid shelf-stable beverages. UV-C can be highly effective when optical properties allow uniform dose delivery, while cold plasma offers multiple antimicrobial mechanisms but remains less standardized for liquid applications. The evolution of preservation technology should therefore be understood as an expansion of the process portfolio, not as a linear migration from thermal to non-thermal processing (Aganovic et al., 2021; Ghoshal, 2023; Singh et al., 2021; Bayati et al., 2024; Lytras et al., 2024).

Technology Trade-offs and the Answer to RQ1

To answer RQ1, the literature was compared across five dimensions: control of vegetative microorganisms, potential for spore control, quality retention, industrial readiness, and suitability for liquid foods. Figure 2 presents a qualitative evidence map rather than a meta-analytic score, and the categories should be interpreted as broad tendencies that can shift with formulation and process conditions. A “conditional” rating indicates that performance depends strongly on the food matrix, operating parameters, storage conditions, or combination with another hurdle and therefore cannot be used as a generic safety

guarantee. This interpretation is consistent with recent evidence showing that matrix properties and process intensity are central determinants of emerging-technology performance (Aganovic et al., 2021; Arshad et al., 2020; Laroque et al., 2022; Lytras et al., 2024).



Source: Synthesized by author based on Dumpler, Huppertz and Kulozik (2020), Aganovic et al. (2021), Arshad et al. (2021), Singh et al. (2021), Houska et al. (2022), and Bayati et al. (2024).

Figure 2. Qualitative trade-off map of sterilization/inactivation technologies for liquid foods.

Source: author’s synthesis based on Dumpler, Huppertz and Kulozik (2020), Aganovic et al. (2021), Arshad et al. (2021), Singh et al. (2021), Houška et al. (2022), and Bayati et al. (2024).

Figure 2 indicates that UHT/aseptic processing retains the strongest position when the principal objective is a shelf-stable product with validated spore control, although sensitive formulations can experience greater sensory or nutritional changes. HPP is highly attractive for fresh-like quality and has strong commercial readiness in selected categories, but its limited low-temperature efficacy against spores and frequent dependence on refrigerated distribution constrain its role as a substitute for commercial sterilization. PEF offers continuous processing and high quality retention for appropriate liquids, whereas UV-C is constrained by optical properties and cold plasma remains more suitable as an emerging platform or additional hurdle until product-specific validation and standardization become more mature. The comparison therefore supports a portfolio strategy in which technology selection follows the

safety target, matrix, distribution model, and value proposition rather than a universal ranking (EFSA BIOHAZ Panel et al., 2022; Song et al., 2022; Ghoshal, 2023; Singh et al., 2021; Laroque et al., 2022; Brito and Silva, 2024).

Table 2. Comparative matrix of processing technologies for liquid foods

Technology	Dominant mechanism	Principal strengths	Critical limitations	Strategic status	Most plausible applications
UHT + aseptic	High-temperature, short-time heating followed by prevention of post-process recontamination.	Commercial sterility, high throughput, ambient distribution.	Thermal damage, fouling, aseptic-system complexity.	Mature / core	UHT milk, protein beverages, and low-acid shelf-stable liquids.
Ohmic heating	Volumetric heating generated by electrical resistance.	Rapid heating, potentially improved uniformity, lower over-processing.	Electrical conductivity, electrode reactions, fouling/corrosion, scale-up.	Emerging to maturing	Conductive liquids and liquid-particulate products requiring rapid thermal processing.
HPP	High hydrostatic pressure.	Fresh-like quality and strong efficacy against many vegetative microorganisms.	Spore and enzyme resistance, batch operation, capital cost, packaging requirements.	Commercially mature in selected categories	Juices, smoothies, sauces, and premium beverages, often with chilled distribution.
PEF	Irreversible membrane electroporation.	Continuous processing, short treatment time, strong quality retention.	Spore resistance, conductivity constraints, chamber design, high-voltage safety.	Commercial / emerging	Pumpable juices and beverages with suitable electrical characteristics.
UV-C	Photochemical damage to microbial nucleic acids.	Relatively simple systems and potentially low process-energy demand.	Turbidity, absorbance, shielding, fouling, and delivered-fluence validation.	Commercial / emerging niche	Clear or relatively transparent liquids and validated hurdle applications.

Technology	Dominant mechanism	Principal strengths	Critical limitations	Strategic status	Most plausible applications
Cold plasma	Reactive oxygen/nitrogen species, ions, photons, and electric-field effects.	Low bulk temperature and multiple microbial targets.	Oxidative chemistry, dose standardization, liquid-reactor design, toxicology, regulation.	Emerging	Decontamination and hurdle applications after product-specific validation.

Source: author's synthesis based on Makroo, Rastogi and Srivastava (2020), Aganovic et al. (2021), Arshad et al. (2021), Singh et al. (2021), Laroque et al. (2022), Bayati et al. (2024), and Astráin-Redín et al. (2024).

Microbiological Safety: Why Product-Specific Validation Is Critical

One of the most consistent findings across technologies is the strong influence of the food matrix on microbial inactivation. Low pH can increase the sensitivity of some microorganisms to HPP, whereas fat, protein, sugar, or total solids can provide protection; in PEF, conductivity, product temperature, cell type, and electrical parameters jointly influence electroporation and specific energy; in UV-C, even modest differences in absorbance can markedly alter light penetration; and in thermal processing, viscosity and flow behavior affect heat distribution. Parameters validated for apple juice therefore cannot be transferred directly to milk, oat beverages, or protein drinks. Product-specific validation is not a regulatory formality but a scientific requirement arising from matrix-dependent transport, reaction, and microbial-resistance mechanisms (Podolak, Whitman and Black, 2020; Arshad et al., 2020; Pierscianowski et al., 2021; Dimpler, Huppertz and Kulozik, 2020; Cavalcanti et al., 2023).

Spore resistance makes this limitation especially clear. HPP and PEF can provide substantial reductions in vegetative cells, but bacterial spores generally require more aggressive pressure-temperature combinations, thermal treatment, or additional hurdles, particularly in low-acid shelf-stable liquids. A defensible process-development sequence therefore begins with hazard analysis and a defined process target, followed by selection of a technology or combination that can be validated on the intended formulation, package, equipment, and storage regime. This outcome-based language also improves scientific and commercial communication by distinguishing pasteurization, microbial inactivation, and commercial sterility according to evidence rather than marketing terminology (Aganovic et al., 2021; EFSA BIOHAZ Panel et al., 2022; Meijer et al., 2021; Lytras et al., 2024).

Nutritional and Sensory Quality: The Non-Thermal Advantage Is Conditional

The literature supports a relative advantage of several non-thermal technologies in preserving heat-sensitive compounds, color, and aroma when they are compared with overly intensive thermal treatments. That advantage is nevertheless conditional rather than absolute: HPP can alter protein structure and texture, PEF can introduce secondary ohmic heating and electrochemical reactions, UV-C can cause photochemical degradation, and cold plasma can oxidize lipids, pigments, vitamins, and aroma compounds. Apparent increases in phenolics or antioxidant activity after treatment may also result from enhanced release or extractability rather than from the formation of new nutritional value. Technology comparisons should therefore distinguish analytical changes from genuine improvements in nutritional and sensory performance over shelf life (Taha et al., 2022; Gharbi, Marciniak and Doyen, 2022; He et al., 2021; Saremnezhad et al., 2021; Oner et al., 2023; Bayati et al., 2024).

Modern thermal processing can also retain high quality when heat load is minimized and cooling is rapid. Direct steam systems and ohmic heating demonstrate how improved engineering can narrow the quality gap between thermal and non-thermal processing by reducing residence time and temperature gradients. A more useful comparison criterion is therefore the amount of quality retained per unit of verified microbial safety rather than the nominal technology label. This criterion discourages the simplistic assumptions that non-thermal processing is always superior or that thermal processing is necessarily destructive (Eisner, 2021; Rocha et al., 2022; Shao et al., 2021; Grossmann, Hinrichs and Weiss, 2022; Astráin-Redín et al., 2024).

Shelf Life, Food Loss, and Distribution Reach

Shelf-life extension is a principal mechanism linking processing technology to food security. When microbial deterioration is controlled and quality remains stable for longer, the product gains a wider distribution window and greater inventory flexibility, which can reduce the probability that safe food is discarded before reaching consumers. For shelf-stable UHT products, reduced dependence on refrigeration can expand geographic reach and lower exposure to cold-chain failures, whereas HPP and many non-thermal pasteurization applications still rely on chilled distribution and therefore generate a different logistics profile. The food-security value of a shelf-life intervention consequently depends on how the additional time is actually used within the distribution system (Song et al., 2022; Chung et al., 2022).

Research on food loss and waste shows that no single intervention is effective across the entire supply chain. Loss prevention requires coordinated

improvements in processing, packaging, handling, forecasting, information, inventory management, transport, and commercial decision-making. Sterilization and microbial-inactivation technologies make their clearest contribution where losses are driven by microbiological spoilage or insufficient distribution time, but they cannot by themselves correct overproduction, demand mismatches, physical damage, or market rejection. Claims about food-security contributions should therefore remain proportional to the specific causes of loss that processing can realistically influence (Moraes, Lermen and Echeveste, 2021; Magalhães et al., 2021; Luo et al., 2022; Benyam, Soma and Fraser, 2021).

For Indonesia, this logic supports segmentation of processing and distribution strategies rather than a single national technology prescription. Products intended for regions with limited cold-chain capacity can obtain the greatest logistical benefit from validated shelf-stable processes, while premium products sold through reliable refrigerated channels may justify HPP or PEF when fresh-like quality has commercial value. Technology choice should therefore be aligned with route length, product value, producer capability, infrastructure, target hazards, and consumer needs. A differentiated portfolio is more likely to improve food-system resilience than a uniform requirement that ignores local supply-chain conditions (Gantina et al., 2020; Prasetya et al., 2022).

Consumer Trust and Industrial Competitiveness

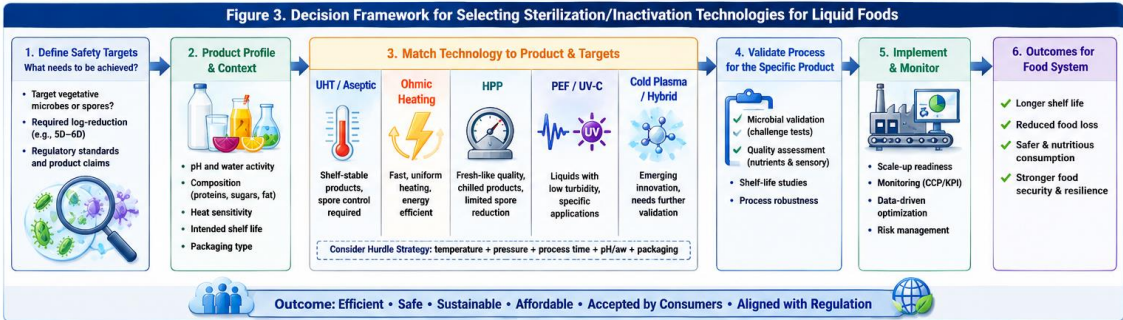
Validated safety and reproducible quality are important foundations of consumer trust, but emerging technologies can create a communication paradox. Consumers often seek products that are fresh, minimally processed, and free from unnecessary preservatives while simultaneously expressing uncertainty about technical terms such as high pressure, pulsed electric field, or plasma. Research on technology acceptance suggests that credible institutions and transparent communication of benefits and risks are more effective than relying on broad claims such as “natural” or “advanced.” Public and industry communication should therefore explain what a process does, what it has been validated to achieve, and what limitations remain, without disguising the degree of processing or overstating safety (Meijer et al., 2021; Song et al., 2020).

In international and domestic trade, reproducible processing, documented validation, and demonstrated shelf-life stability can increase the ability of firms to meet buyer specifications and regulatory requirements. HPP and PEF can support differentiation in higher-value products, whereas UHT/aseptic systems remain highly competitive for long-distance trade in shelf-stable categories. Competitiveness therefore derives from the combination of safety assurance, throughput, total cost, consistent quality, logistical fit, and credible shelf-life evidence rather than from technological novelty alone. A portfolio approach also

allows large manufacturers and micro, small and medium-sized enterprises to select different levels of technological complexity according to their capabilities and market positions (Aganovic et al., 2021; Arshad et al., 2021; Chakka, Sriraksha and Ravishankar, 2021).

A Technology-Selection Framework for the Indonesian Context

Figure 3 presents a practical decision framework derived from the literature synthesis. The sequence deliberately starts with the safety target rather than equipment availability: hazards and process objectives are defined first, followed by simultaneous assessment of product properties, desired quality, packaging, distribution requirements, and operating constraints. UHT/aseptic processing, ohmic heating, HPP, PEF, UV-C, cold plasma, or a hybrid approach is considered only after these requirements have been established. This ordering reduces technology-push behavior, in which equipment is purchased before a suitable application is identified, and instead directs investment toward product-process fit and verifiable performance (Aganovic et al., 2021; Arshad et al., 2020; Singh et al., 2021; Astráin-Redín et al., 2024).



Source: Synthesized by author based on Podolak, Whitman and Black (2020), Aganovic et al. (2021), Makroo, Rastogi and Srivastava (2020), Arshad et al. (2021), Singh et al. (2021), and Laroque et al. (2022).

Figure 3. Decision framework for selecting sterilization/inactivation technologies for liquid foods.

Source: author's synthesis based on Podolak, Whitman and Black (2020), Aganovic et al. (2021), Makroo, Rastogi and Srivastava (2020), Arshad et al. (2021), Singh et al. (2021), and Laroque et al. (2022).

Figure 3 also makes process validation the final decision gate rather than an assumption derived from the literature. Published evidence can narrow the technology options and provide starting parameters, but a commercial decision must be demonstrated on the actual formulation, package, equipment, flow regime, process controls, and intended shelf life. For Indonesian MSMEs, this principle supports shared processing facilities, pilot centers, or technology-service hubs that can distribute equipment and validation costs across multiple producers. Larger firms can justify more complex systems when product volume,

margin, technical staffing, and market access are sufficient to support them (Yadav, 2022; Chakka, Sriraksha and Ravishankar, 2021).

National Implementation Priorities and the Answer to RQ2

The answer to RQ2 is that processing technology contributes most strongly to food security when four conditions are met simultaneously: the process achieves the required safety target, shelf life increases materially, the distribution model captures the value of that additional shelf life, and total cost remains compatible with industrial scale and consumer affordability. On this basis, optimization of UHT/aseptic processing, hygienic design, heat recovery, rapid thermal processes, and aseptic control remains a near-term priority because these platforms are mature and directly relevant to mass-market distribution. HPP can be prioritized for higher-value fresh-like products when cold-chain and economics are favorable, while PEF and UV-C are most defensible as targeted pilots for liquids with suitable electrical or optical properties. Cold plasma is better positioned in the research and pilot portfolio until product chemistry, standardization, reactor scale-up, and validation become more mature (Grossmann, Hinrichs and Weiss, 2022; Aganovic et al., 2021; Arshad et al., 2021; Bayati et al., 2024; Bains et al., 2024).

Public policy should avoid subsidizing technologies simply because they are novel and should instead reward measurable outcomes such as reduced spoilage, longer validated shelf life, lower energy use per unit of safe product, wider distribution reach, improved compliance, or lower system-level emissions. Joint university-industry pilots, shared validation laboratories, databases of local liquid-food properties, operator training, and stronger metrology can reduce the cost and uncertainty of adoption. These initiatives should also be connected to traceability, demand planning, and inventory management so that extended shelf life does not merely create overstock that later becomes waste. Outcome-based support is therefore more defensible than technology-specific promotion (Benyam, Soma and Fraser, 2021; Luo et al., 2022; Arshad et al., 2022; Bains et al., 2024).

From a public-health perspective, the priority must remain consistent safety assurance. Emerging technologies should expand the hazard-control toolkit rather than weaken process-validation standards, and this requires microbiological laboratories, challenge testing, shelf-life studies, hygienic design, process monitoring, and oversight of product claims. Supply-chain disruptions experienced during the COVID-19 period also demonstrated that food safety and resilience cannot be separated from the broader capacity of the food system to continue operating under stress. Technology policy should therefore be

integrated with public-health protection, logistics preparedness, and institutional capability

Table 3. Phased agenda for strengthening liquid-food processing technologies in Indonesia

Horizon	Primary focus	Recommended instruments	Outcome indicators
Short term (1–3 years)	Optimize UHT/aseptic processing, hygienic design, heat recovery, shelf-life validation, and selected ohmic/UV-C pilots.	Process audits, operator training, shared validation facilities, and a database of local liquid-food properties.	Lower rejects and spoilage, stable quality, improved energy efficiency, and stronger process compliance.
Medium term (3–7 years)	Industrial-scale HPP/PEF pilots, validated hybrid processes, and shared processing hubs.	Industry–university matching funds, outcome-based incentives, and standardized validation methods.	Validated new products, reduced losses, wider market reach, and lower processing cost per unit.
Long term (>7 years)	AI/sensor integration for process control, validated cold-plasma/hybrid systems, life-cycle assessment, and circular processing.	Regulatory science, life-cycle evidence for environmental claims, and national or regional technology-competence centers.	Safety-by-design, lower system footprint, stronger exports, and greater supply-chain resilience.

Source: author’s synthesis based on Chung et al. (2022), Arshad et al. (2022), Benyam, Soma and Fraser (2021), Bayati et al. (2024), and Bains et al. (2024).

Research Agenda: Evidence Gaps That Need to Be Addressed

The first research priority is standardized reporting of process conditions. HPP studies should report pressure, time, temperature, compression history, and relevant matrix properties; PEF studies should report field strength, pulse shape, specific energy, conductivity, treatment temperature, and residence-time information; UV-C studies should report delivered fluence, absorbance, reactor geometry, and residence-time distribution; and cold-plasma studies should define source configuration, gas composition, power, distance, treatment time, reactive species, and an operationally meaningful dose. Without such reporting, cross-study comparison and translation to industrial scale remain uncertain. Recent reviews of PEF and electrical processing reinforce that incomplete reporting is a direct barrier to reproducibility, safety validation, and industrial adoption (Arshad et al., 2020; Pierscianowski et al., 2021; Laroque et al., 2022; Cavalcanti et al., 2023; Lytras et al., 2024; Zheng et al., 2024).

The second priority is to build evidence for liquid-food matrices that are strategically important in Indonesia, including dairy and protein beverages, coconut-based products, tropical fruit juices, herbal drinks, and beverages made

from legumes and cereals. These matrices differ in pH, fat, protein, pigments, particles, viscosity, optical properties, and conductivity, all of which can alter technology performance. Future studies should integrate microbiological challenge testing with quality kinetics, sensory acceptance, packaging interactions, and shelf-life modeling under realistic distribution conditions. Such product-specific work would provide a more reliable basis for regulation and investment than extrapolation from model solutions or unrelated commodities (Taha et al., 2022; Oner et al., 2023; Zargarchi et al., 2024; Brito and Silva, 2024).

The third priority is economic and environmental evaluation using consistent functional units. Comparisons should account for electricity or thermal energy, water, refrigeration, packaging, yield, equipment utilization, waste, and the delivered shelf life per liter of safe product reaching the consumer, rather than focusing only on the energy consumed during the treatment step. A technology that appears energy intensive inside the plant can still reduce the overall system footprint if it substantially decreases cold-chain demand or food loss, while a low-energy process can perform poorly if it creates short shelf life or high rejection rates. Techno-economic analysis and life-cycle assessment should therefore be integrated early in pilot studies rather than added only after microbiological proof of concept (Chung et al., 2022; Chakka, Sriraksha and Ravishankar, 2021; Moraes, Lermen and Echeveste, 2021; Bains et al., 2024).

The fourth priority is stronger regulatory and consumer science for emerging processes. Research should investigate reaction products, sublethal injury, potential microbial regrowth, chemical stability, packaging interactions, and changes during storage while also testing communication strategies that improve consumer understanding without creating a misleading halo in which “non-thermal” is equated with “natural” or automatically “safe.” This requirement is particularly important for cold plasma because reactive species can generate both desirable antimicrobial effects and unwanted chemical transformations. Integrating regulatory science with consumer research can therefore reduce commercialization risks while improving the credibility of innovation (Warne et al., 2021; Bayati et al., 2024; Meijer et al., 2021).

Final Synthesis of the Research Questions

With respect to RQ1, no single technology simultaneously optimizes all safety, quality, economic, and operational objectives. UHT/aseptic processing remains the benchmark for commercial sterility and ambient shelf stability; ohmic heating provides rapid volumetric heating when electrical and engineering conditions are appropriate; HPP is particularly strong for fresh-like quality but often requires temperature or additional hurdles for spore control; PEF is highly promising for pumpable liquids and vegetative cells but is

constrained by spore resistance and product electrical properties; UV-C is effective only when optical transmission is adequate; and cold plasma offers novel mechanisms but still requires stronger standardization, chemical-safety evidence, and scale-up. The most defensible technology decision is therefore based on the safety target and product-process fit rather than on novelty or a generic thermal/non-thermal hierarchy (Dumpler, Huppertz and Kulozik, 2020; Aganovic et al., 2021; Arshad et al., 2021; Singh et al., 2021; Bayati et al., 2024; Astráin-Redín et al., 2024; Brito and Silva, 2024).

With respect to RQ2, processing technologies contribute to food security through a measurable chain of effects: improved microbial control reduces spoilage risk, longer shelf life increases distribution and inventory flexibility, lower spoilage can reduce food loss, and more stable supply can improve access and availability. This chain is nevertheless moderated by cost, cold-chain capacity, technical skills, regulation, market structure, packaging, and the ability of firms to maintain validated process conditions. For Indonesia, a phased portfolio strategy is therefore more rational than selecting a single flagship technology: mature platforms should be optimized for high-volume products, HPP, PEF, and UV-C should be deployed where matrix and market conditions create a clear advantage, and cold-plasma or hybrid processes should remain on validation-oriented pilot pathways until the evidence base is stronger. This strategy links process innovation to actual supply-chain constraints and therefore offers a more credible route to food-system resilience (Gantina et al., 2020; Moraes, Lermen and Echeveste, 2021; Luo et al., 2022; Arshad et al., 2022).

CONCLUSION

This review demonstrates that sterilization and microbial inactivation of liquid foods should be treated as a food-system decision rather than merely as a choice of processing equipment. Microbiological safety is the primary requirement, but the strategic value of a technology also depends on quality retention, shelf life, energy and water use, packaging, throughput, total cost, distribution requirements, and the capacity to maintain validated operating conditions. The distinction between commercial sterility and non-thermal pasteurization or microbial inactivation is therefore fundamental to accurate scientific communication and responsible product claims. A technology that performs strongly on one dimension cannot be assumed to deliver equivalent benefits across all matrices and supply chains.

For RQ1, the synthesis confirms that the principal technologies are complementary rather than universally substitutable. UHT/aseptic processing remains the most established option for shelf-stable low-acid products and for safety targets in which spore resistance is central, while ohmic heating offers

opportunities to reduce over-processing through rapid volumetric heating. HPP and PEF can provide substantial advantages in fresh-like quality and vegetative-cell inactivation when the matrix is appropriate, but neither should be considered a universal replacement for commercial sterilization. UV-C remains strongly dependent on optical transmission, and cold plasma requires further progress in dose standardization, chemical characterization, safety assessment, and scale-up before broad liquid-food deployment can be justified.

For RQ2, the contribution of processing technologies to food security occurs primarily through longer safe shelf life, lower spoilage, improved distribution stability, and wider market reach. These benefits materialize only when the selected process is compatible with product characteristics and with the logistics model that will use the resulting shelf-life gain. In Indonesia, mass-market products intended for areas with limited cold-chain capacity will continue to benefit from robust shelf-stable platforms, whereas HPP, PEF, and UV-C are more likely to create value in selected higher-value or technically compatible product categories. A portfolio strategy is therefore more realistic than the assumption that one technology can address all liquid-food challenges across the country.

The main policy and industrial implication is that investment should prioritize validation capability as much as equipment acquisition. Shared challenge-testing facilities, shelf-life laboratories, product characterization, hygienic design, operator training, metrology, and digital traceability can improve process reliability while reducing the risks of technology adoption. Public incentives should be tied to measurable outcomes such as reduced spoilage, verified shelf-life extension, lower system-level energy use, wider safe distribution, and stronger compliance rather than to the purchase of specific technologies. This outcome-oriented approach can also improve access for MSMEs by supporting shared facilities and technical services.

Future research should prioritize standardized process reporting, studies on strategically important Indonesian liquid-food matrices, pilot- and industrial-scale techno-economic and life-cycle assessments, and stronger regulatory and consumer science for emerging technologies. Longitudinal shelf-life studies that combine microbial safety, sensory quality, nutrient stability, packaging interactions, energy, distribution conditions, and cost would provide a substantially stronger evidence base for both industry and policy decisions. Research should also examine hybrid processes only when their added complexity is justified by demonstrable gains in safety, quality, or system performance. With this agenda, sterilization and microbial-inactivation technologies can develop from isolated processing innovations into strategic

capabilities for a safer, more resilient, efficient, and sustainable Indonesian food system.

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