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COMPREHENSIVE REVIEW

Emerging technologies in seafood processing: An overview of innovations reshaping the aquatic food industry

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Abstract

Seafood processing has traditionally been challenging due to the rapid spoilage rates and quality degradation of these products. With the rise of food science and technology, novel methods are being developed to overcome these challenges and improve seafood quality, shelf life, and safety. These methods range from high-pressure processing (HPP) to edible coatings, and their exploration and application in seafood processing are of great importance. This review synthesizes the recent advancements in various emerging technologies used in the seafood industry and critically evaluates their efficacy, challenges, and potential benefits. The technologies covered include HPP, ultrasound, pulsed electric field, plasma technologies, pulsed light, low-voltage electrostatic field, ozone, vacuum cooking, purified condensed smoke, microwave heating, and edible coating. Each technology offers unique advantages and presents specific challenges; however, their successful application largely depends on the nature of the seafood product and the desired result. HPP and microwave heating show exceptional promise in terms of quality retention and shelf-life extension. Edible coatings present a multifunctional approach, offering preservation and the potential enhancement of nutritional value. The strength, weakness, opportunity, and threat (SWOT) analysis indicates that, despite the potential of these technologies, cost-effectiveness, scalability, regulatory considerations, and consumer acceptance remain crucial issues. As the seafood industry stands on the cusp of a technological revolution, understanding these nuances becomes imperative for sustainable growth. Future research should focus on technological refinements,

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Abbreviations: AEW, acidic electrolyzed water; APC, aerobic plate count; BAs, biogenic amines; CAP, cold atmospheric plasma; CP, cold plasma; EOs, essential oils; FAO, Food and Agriculture Organization of the United Nations; FDA, Food and Drug Administration; HPP, high-pressure processing; LVEF, low-voltage electrostatic field; LVVFEF, low-voltage variable frequency electric fields; MAIH, microwave-assisted induction heating; MDA, malondialdehyde; O_3-MNBs, ozone micro–nano bubbles; PAHs, polycyclic aromatic hydrocarbons; PAW, plasma-activated water; PBC, psychrotrophic bacteria count; PCS, purified condensed smoke; PEF, pulsed electric field; PF, partial freezing; PFB, plasma-functionalized buffer; PIS, pumpable ice slurry; PL, pulsed light; ROS, reactive oxygen species; SVC, sous-vide cooking; TBARS, thiobarbituric acid reactive substances; TVB-N, total volatile basic nitrogen; UAF, ultrasonic-assisted freezing; UVC-LEDs, ultraviolet light-emitting diodes; WHC, water-holding capacity.

understanding consumer perspectives, and developing regulatory frameworks to facilitate the adoption of these technologies in the seafood industry.

KEYWORDS
fish, food preservation, high pressure processing, nonthermal technology, shelf life

1 INTRODUCTION

The seafood industry is a crucial part of the global economy, providing food, employment, and income to millions of people worldwide. The seafood sector generates over $200 billion in sales annually and employs over 56 million people globally (Food and Agriculture Organization of the United Nations [FAO], 2020). However, the seafood industry faces several challenges that limit its growth potential and threaten its sustainability. One of the key challenges facing the seafood industry is food safety. According to Food and Drug Administration (FDA) seafood testing results, 47% of seafood imports showed high rates of contamination with bacteria and unapproved drugs, highlighting the need for better food safety measures (FDA, 2022). The seafood industry also faces environmental challenges, such as overfishing, habitat destruction, and pollution, which threaten the long-term sustainability of the industry (FAO, 2022).

The state of world fisheries and aquaculture report by FAO published in 2020 reveals that total fisheries and aquaculture production reached a record high of 179 million tonnes in 2018, with aquaculture accounting for 46% of the total production. Capture fisheries production has remained relatively stable over the past decade, with a slight increase to 96.4 million tonnes in 2018 (FAO, 2020). Aquaculture production has continued to grow at a steady pace, driven mainly by the increase in the production of tilapia, carp, and catfish. However, there is growing concern about the sustainability of shrimp and salmon production, due to environmental and social issues. Aquaculture, particularly tilapia, carp, and catfish, has seen steady growth. Yet, sustainability concerns arise for shrimp and salmon due to environmental and societal issues. The FAO notes that over 34% of fish stocks are overfished, emphasizing the need for better fisheries management. Meanwhile, global fish consumption per capita rose to 20.5 kg in 2018, a trend likely to persist given the rising demand for protein-rich foods and seafood's growing popularity (FAO, 2022).

Finally, there is a growing awareness that the seafood industry plays a vital role in achieving the United Nations' 2030 Agenda for Sustainable Development. There is a need for a transformative change in the industry toward sustainable aquaculture production, innovative value chains, and improved fisheries management to ensure social, economic, and environmental sustainability for current and future generations. Ensuring that seafood is fresh, safe, and of high quality is essential for maintaining consumer confidence and protecting public health (Abel et al., 2022; FAO, 2022; Hassan et al., 2023; Willer et al., 2021). The industry has also been affected by challenges arising from the COVID-19 pandemic, including closures of processing plants and disrupted supply chains (FAO, 2020). Although these challenges underscore the pressing need for innovative solutions, the evolution of processing technologies and changing consumption trends offer a promising avenue for the seafood industry's future.

Processing technologies play a crucial role in seafood preservation, serving multiple functions that contribute to the overall quality and safety of the product (Kulawik et al., 2022). They are primarily designed to extend the shelf life of seafood products, a critical aspect in the seafood industry (Gautam & Venugopal, 2021; Pérez-Won et al., 2021). This is achieved by inactivating spoilage microorganisms and enzymes that contribute to the deterioration of the product over time (Bermudez-Aguirre, 2020). Technologies such as high-pressure processing (HPP), cold plasma (CP), and pulsed electric field (PEF) have been shown to be particularly effective in this regard (Bermudez-Aguirre, 2020; Chen et al., 2022; Jakobsen et al., 2022). In addition to extending shelf life, these processing technologies also help maintain the nutritional quality of seafood products. Unlike conventional thermal processing methods, which often result in significant nutrient loss, HPP, CP, and PEF preserve the nutritional integrity of seafood products (Bermudez-Aguirre, 2020; Humaid et al., 2020; Shiekh, Benjakul et al., 2021). This is particularly important given the high nutritional value of seafood, which is a rich source of proteins, omega-3 fatty acids, vitamins, and minerals. Edible coatings are another innovative approach to seafood preservation that have gained significant attention in recent years (Derbew Gedif et al., 2022). These coatings, often derived from biopolymers like chitosan, alginate, and gelatin, serve multiple purposes. They are biodegradable materials that can be consumed along with the food product, offering a sustainable and effective method to extend shelf life. These coatings can be formulated with various natural substances, including proteins, polysaccharides, and lipids, and can be further enhanced with functional additives such as antimicrobials or antioxidants (Hasan et al., 2023; Zhang, Zhao et al., 2022; Ucak et al., 2020).

Food safety is another key aspect addressed by processing technologies. HPP, for instance, has been shown to effectively mitigate pathogenic microorganisms in seafood, significantly reducing the risk of foodborne illnesses (Chen et al., 2022). This is particularly important in the context of raw or minimally processed seafood products, which are often associated with a higher risk of microbial contamination (Abel et al., 2022).

Processing technologies can also enhance the organoleptic properties of seafood products, improving their taste, texture, and overall consumer acceptability. Recent novel emerging technologies have been shown to improve the texture of certain seafood products without affecting their flavor (Lee et al., 2022; Qian, Zhang et al., 2022). Moreover, consumer demand for fresh-like, minimally processed, and additive-free seafood products has increased in recent years. This poses a significant challenge to the seafood industry, as maintaining the safety and quality of such products without the use of traditional preservatives can be difficult (Khouryieh, 2021).

Lastly, emerging processing technologies often exhibit greater energy efficiency compared to traditional methods, contributing to the sustainability of the seafood industry. This is particularly relevant in the context of growing concerns about the environmental impact of food production and processing (Misra et al., 2022).

The aim of this review is to provide a comprehensive and critical analysis of emerging processing technologies in the seafood industry, with a particular focus on HPP, CP, PEF, ozone, edible coatings, and other novel methods. The review will assess the effectiveness of these technologies in terms of extending shelf life, maintaining nutritional quality, ensuring food safety, enhancing organoleptic properties, and promoting sustainability in the seafood industry. Furthermore, the review will identify gaps in current research and propose directions for future studies. By doing so, the review aims to contribute to the advancement of processing technologies in the seafood industry and promote the development of safer, higher quality, and more sustainable seafood products.

2 | METHODS OF REVIEW

This review is conducted as a comprehensive and systematic literature survey, focusing on the most recent advancements in the field of seafood processing technologies. The primary databases used for the literature search include Scopus and Web of Science. The search was limited to peer-reviewed articles published between 2020 and June 2023 to ensure the relevance and recency of the information.

The search strategy involved the use of specific keywords and phrases related to the seafood industry and the processing technologies of interest, including as a main keyword “fish” and “food technology,” but not limited to “processing,” “seafood,” “crustaceans,” “molluscs,” “shellfish,” “emerging technologies,” and “coatings.”

The articles identified through the database search were screened based on their titles, keywords, and abstracts. The full texts of potentially relevant articles were then reviewed for their applicability to the study objectives. The reference lists of the selected articles were also examined to identify additional relevant studies.

The data extracted from the selected articles included the type of seafood product, the processing technology used, the main findings, and the implications for the seafood industry. This information was then summarized and analyzed to provide a comprehensive overview of the current state of emerging processing technologies in the seafood industry and to identify areas for future research.

The writing process involved integrating the synthesized information from the selected studies into a coherent narrative, ensuring that each study’s findings were accurately represented and appropriately cited.

2.1 | Database analysis

The investigation took place in June 2023. The aim was to retrieve and select those papers that investigate the utilization of new seafood emerging technologies, in order to evaluate the research trends based on literature in the Web of Science and Elsevier Scopus databases, over the last 3 years and a half (from 2020 to June 2023). To ensure the quality of the research, only peer-reviewed articles were selected. A total of 1251 documents were found in the databases. From these, 679 documents were original articles, 294 reviews, 143 conference papers, 118 book chapters, and 17 conference reviews. In order to report the latest advances in the field, we excluded the literature review papers, conference reviews, and books and analyzed the remaining 822 documents.

The number of documents for each selected technology published since 2020 in the seafood technology field is reported in Figure 1.

This stacked bar chart represents the number of papers published each year from 2020 to June 2023, categorized by the technology they pertain to. The technologies considered in this analysis include HPP, CP, ultrasound, PEF, pulsed light (PL), low-voltage electrostatic field (LVEF), microwave, ozone, edible coatings, active packaging, and smoking. The total number of selected papers was 107 for these specific technologies. Overall, there seems to be an

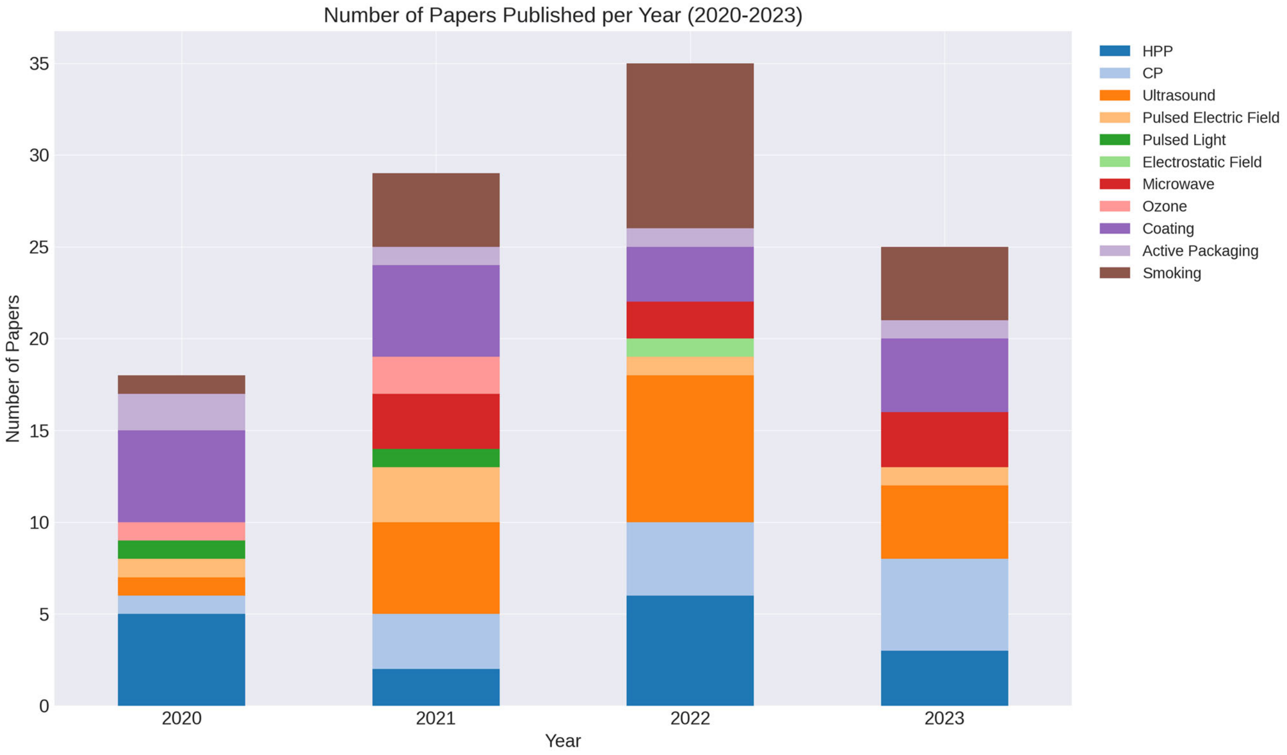


FIGURE 1 Annual publication count by specific technology (2020 to June 2023) applied for seafood products based on Scopus and Web of Science databases.

increasing trend in the number of papers published from 2020 to 2022 across all technologies. In 2023, this trend seems to confirm this increase. HPP and ultrasound have been relatively popular topics for papers throughout the years, with a relatively consistent number of papers published each year. The topic of "smoking" showed a significant increase in papers from 2020 to 2022. CP has seen a steady increase in the number of papers from 2020 to 2023. The topic of "coating" seems to have a consistent number of papers each year, making it a steady area of research.

Measurements of the quality and quantity of the scientific production were accomplished using the VOSViewer science mapping software tool (Eck & Waltman, 2020). Previously, selected data for VOSViewer-supported file types (Web of Science and Elsevier Scopus) were exported to Microsoft 365 Excel and then elaborated. From the database, 5280 keywords were extrapolated, but for the analysis, the occurrence threshold was set at a minimum of 10 among all of the documents.

A word cloud related to searched keywords is represented by Figure 2. The font size of the given keywords indicates the number of times they appear in literature records. The most numerous occurrences are naturally represented by the main keyword (fish), but also by the terms used most often in the seafood industry, such as "food safety," "shellfish," "fisheries," "seafood," "food supply," and "food storage." As can be observed from Figure 2, the keywords mostly used in the fish topic mainly concern those of shelf life and food safety, followed immediately after by those concerning food processing and technologies.

On the one hand, this indicates that the processing technologies for the seafood sector have not yet been extensively investigated by the scientific community, and on the other hand, this latest trend has been growing in recent years. In fact, in Figure 3, the database keyword occurrence overlay is reported based on the number of times that selected keywords appear in literature from 2020 to June 2023. It appears that more recently, the terms "sustainability," "food security," and other terms related to food quality and safety have gained much more attention in scientific literature in the last few years. Moreover, the cluster related to food microbiology registered an increase during the last years, denoting major efforts from the scientific community to study these research fields. This is an important trend as the seafood sector is a topic that requires more research to increase food safety, sustainability, and the quality of fish products.

3 | EMERGING TECHNOLOGIES FOR SEAFOOD PROCESSING

Based on the database analysis, the emerging technologies found were as follows: HPP; ultrasound; PEF; PL; CP; vacuum cooking; innovative ozone treatments; innovative

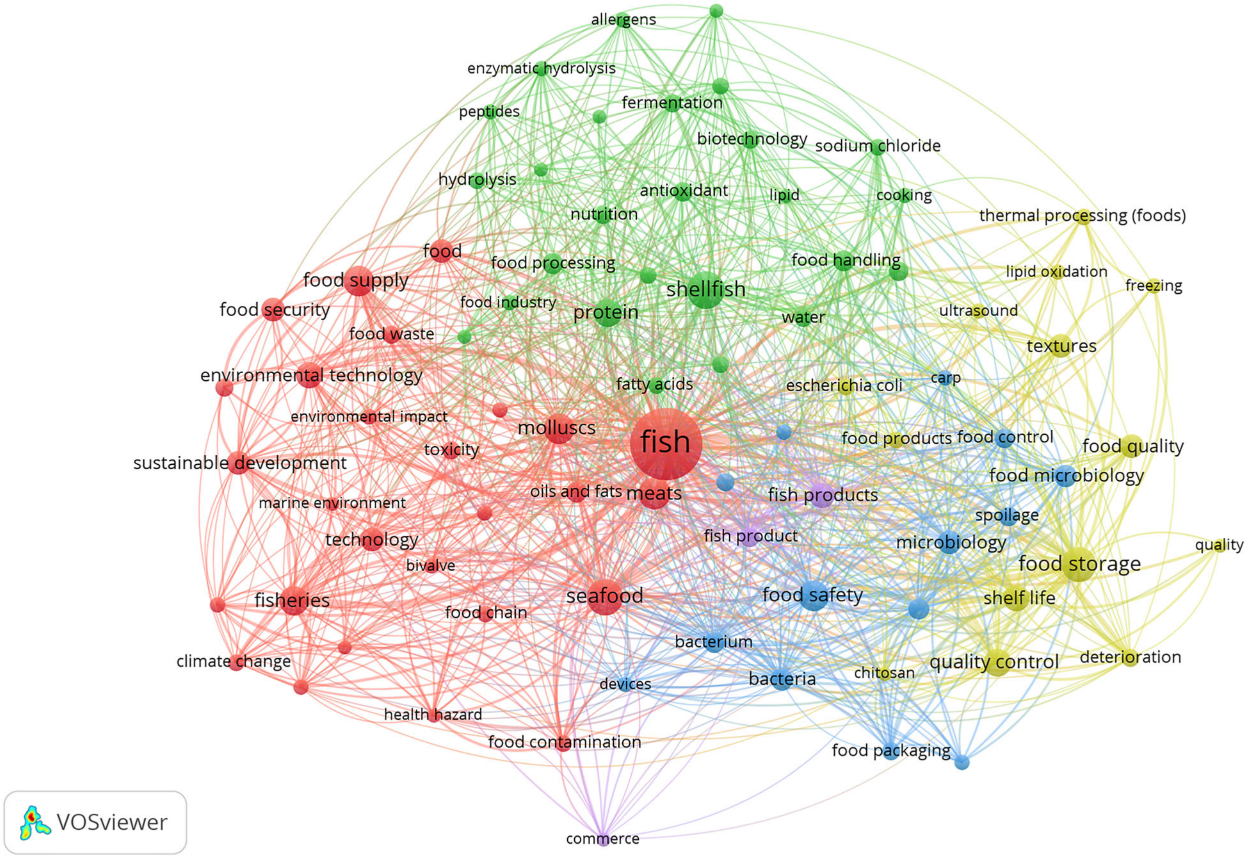


FIGURE 2 Database keywords occurrence network based on the search "seafood technology" from Scopus and Web of Science databases (822 documents results from 2020 to June 2023).

smoking technology; microwave, LVEF, active packaging, and edible coatings. Some of these technologies were used alone or in combination with each other, obtaining different results in terms of quality and microbial safety. In Table 1, the main findings from the most relevant paper regarding the technologies studied are reported. Table 2 instead reports the effects of single-emerging technology on the shelf life of seafood studied.

3.1 | High-pressure processing

HPP is a nonthermal food preservation technology that has gained significant attention in recent years due to its ability to maintain the sensory and nutritional quality of food products while ensuring their safety (Chen et al., 2022; Khouryieh, 2021; Valø et al., 2020).

The mechanism of HPP involves the application of high hydrostatic pressure, typically between 100 and 800 MPa, to the food product for a certain period of time, usually a few minutes (Khouryieh, 2021). This pressure is applied uniformly throughout the product, regardless of its size, shape, or composition, which is a distinct advantage over thermal processing methods.

One of the primary applications of HPP in the seafood industry is its use in microbial inactivation. HPP has been shown to effectively reduce the microbial load in seafood products, including pathogenic bacteria such as *Listeria monocytogenes* and *Vibrio parahaemolyticus*, which are commonly associated with seafood-borne illnesses (Roobab et al., 2022). This contributes to an extended shelf life and improved safety of the product. The application of high pressure disrupts the cellular structures of microorganisms, including bacteria, yeasts, and molds, leading to their inactivation (Khouryieh, 2021; Roobab et al., 2022). Specifically, the high pressure affects the integrity of the microbial cell membrane and inhibits essential enzymatic activities, thereby preventing microbial growth and proliferation (Roobab et al., 2022).

In addition to its antimicrobial effects, HPP can also inactivate enzymes responsible for food spoilage, thereby further extending the shelf life of seafood products (Chen et al., 2022; Kulawik et al., 2022).

Ahmad and Traynor (2022) conducted a study on the effect of HPP and sous-vide cooking (SVC) on the physicochemical, sensorial, and textural properties of fresh white shrimp (*Litopenaeus setiferus*). The study found that the combination of HPP and SVC processing positively affects

TABLE 1 Resume of the main emerging technologies applied in seafood processing from literature data with key findings.

Technology applied	Specie studied	Key findings	References
High-pressure processing with sous vide cooking	Fresh Whiteleg Shrimp (*Litopenaeus setiferus*)	Reduced total bacterial counts while maintaining fresh-like attributes of shrimps treated with HPP	Ahmad and Traynor (2022)
High hydrostatic pressure and vacuum impregnation	Sea bream (*Sparus aurata*)	Reduction of total mesophilic bacteria counts below 4 log CFU/g after 16 days of storage at ≤2°C	Bou et al. (2023)
High hydrostatic pressure for shucking process	Freshwater clam (*Corbicula fluminea*)	Pressurization of 300 MPa for 3 min on clam samples was able to reach 100% shucking, inactivate microbial growth, and retard quality loss	Lin et al. (2022)
High-pressure-assisted vacuum-freeze drying	Pacific white shrimp (*Penaeus vannamei*)	HPP processing at 550 MPa for 10 min increases drying rate and process time	Ling et al. (2020)
High hydrostatic pressure for shucking process	Oysters (*Magallana gigas*)	HPP-treated oysters showed higher shucking yield (17%) than untreated control oysters, with minimal changes in texture and color, regardless of storage time and temperature	Puértolas et al. (2023)
Ultrasonic treatment	*Crassostrea gigas*	Inactivation of *Vibrio parahaemolyticus* on oysters by 3.13 log CFU/g; improvement of texture, color, and muscle fibers during cold storage	Ma et al. (2023)
Ultrasonic-assisted freezing	Sea bass (*Dicentrarchus labrax*)	Muscle tissue of the fish was more uniform and dense in the dual-frequency orthogonal ultrasonic-assisted freezing group, without excessive oxidation of myofibrin	Yu and Xie (2023)
Plasma-activated water	Sea bream (*Sparus aurata*)	Extension of the shelf life of 2.8 days using plasma processing technologies respects standard procedures	Chanioti et al. (2023)
Cold atmospheric plasma	Golden pomfret (*Trachinotus ovatus*)	Improvements in the color parameters, hydration properties, and textural property parameters of muscle proteins	Situ et al. (2023)
Cold atmospheric plasma with helium	Sea bass (*Dicentrarchus labrax*)	He-plasma treatments were found to suppress the growth of psychrophilic bacteria more effectively after 5 days of cold storage	Mol et al. (2023)
Pulsed electric field	Chilean abalone (*Concholepas concholepas*)	Vacuum microwave drying with PEF pretreatment resulted in the most efficient drying times, being 67% lower than freeze drying and significantly reduced energy consumption and greenhouse gas emissions	Pérez-Won et al. (2023)
Functional ice glazing	Cuttlefish (*Sepia officinalis*)	Vitamin C sodium salt and carboxymethylcellulose sodium used as functional ice glazing. The putrescine formaldehyde and free amino acids were substantially inhibited (TVB-N < 7.15 mg/100 g) during cold chain simulation	Wu et al. (2023)
High-voltage electrostatic field	*Larimichthys crocea*	HVEF treatments (10 and 15 kV/m) registered lower muscle fiber damage and better tissue structures, delaying the decrease in springiness and hardness of fish during refrigerated storage	Qian, Pan et al. (2022)
Immersion freezing technology with edible medium	Grass carp (*Ctenopharyngodon idellus*)	The aspect of protein structure, the intrinsic fluorescence intensity, ionic bonding, and hydrogen bonding in the immersion freezing group were significantly higher than in the air-blast freezing group	Yuduan et al. (2022)

(Continues)

TABLE 1 (Continued)

Technology applied	Specie studied	Key findings	References
Microwave-assisted induction heating	Barramundi (*Lates calcarifer*)	Reductions in the aerobic plate count, psychrotrophic bacteria count, hydrogen sulfide-producing bacteria, and coliform count, along with lower contents of total volatile basic nitrogen in treated samples	Tsai et al. (2022)
Shucking method with high-pressure processing	Asian hard clam (*Meretrix lusoria*)	Significant reduction of moisture content, aerobic plate count, psychrotrophic bacteria count, and coliform counts with HPP shucked clams were significantly lower than conventional frozen shucking method	Lee et al. (2022)
Cold atmospheric plasma	Bolti fish (*Tilapia nilotica*)	Extension of tilapia fish shelf life up to 10 days, respect to the 4 days of control specimen	Mohamed et al. (2021)
High-intensity ultrasound	Threadfin bream (*Nemipterus* spp.)	Improvement of textural properties and color of the surimi gels at 0.5% NaCl, concomitant to an increase in ultrasonic intensity. Ultrasound technology can be applied to improve surimi gel	Tang and Yongsawatdigul (2021)
Atmospheric pressure plasma jet	Salmon (*Salmo salar*)	Treatment with N_2 plasma for 12 min reduced the NoV viral load from an initial inoculum of 2.7×10^4 copies/g to 2.17×10^4 copies/g. Air-based or O_2-based plasma treatments for 9–12 min were even more effective, reducing the viral load to undetectable levels (below 100 copies/g). TBARS values in the sashimi, remained within acceptable levels for salmon sashimi	Huang et al. (2021)
Ultraviolet light-emitting diodes	Tuna (*Thunnus albacares*)	UVC-LED treatments at a dose of 4000 mJ/cm^2 lead to a reduction of 1.31-, 1.86-, and 1.77-log in *Salmonella typhimurium*, *Listeria monocytogenes*, and *Escherichia coli* O157:H7, respectively	Fan et al. (2021)
Cold smoking	Sea bass (*Dicentrarchus labrax*)	Cold smoking was effective in maintaining the total volatile basic nitrogen below the threshold for spoilage and preventing lipid peroxidation	Messina et al. (2021)
Low-temperature vacuum cooking	Russian sturgeon (*Acipenser gueldenstaedti*)	Sous-vide cooking improved the food quality of sturgeon fillets by reducing pH and increasing redness, chewiness, and hardness values	Shen et al. (2020)
Pulsed electric field and cold plasma	Pacific white shrimp (*Penaeus vannamei*)	Samples treated with PEF and chamuang leaf extract showed the lowest melanosis score compared to untreated control over 18 days of storage at 4°C	Shiekh, Zhou et al. (2021)
Pulsed light	Yellow croaker (*Pseudosciaena crocea*)	PL treatment led to a sterilization efficiency of 86.27% ± 4.32% and extension of shelf life of 3 days	Zhang, Zhou et al. (2022)
Gaseous ozone	Salmon (*Salmo salar*)	Ozonation treatment with the dose of 1 and 3 mg/m^3 for 10 min significantly reduced the microbial load compared to control. Reduced content of TVB-N TBARS	Qian, Zhang et al. (2022)
Ozone water rinsing	Grass carps (*Ctenopharyngodon idellus*)	Improved surimi gel's ability to retain water by promoting the cross-linking of myofibrillar proteins and forming a more hydrophilic gel network	Liu et al. (2021)
Ozone with slurry ice	Yellow croaker (*Pseudosciaena crocea*)	Ozone slurry ice showed a significant inhibition of microbial growth and slow down the increase of TBARS, TVB-N, *K* value and BAs	Zhao et al. (2022)

(Continues)

TABLE 1 (Continued)

Technology applied	Specie studied	Key findings	References
Atomized purified condensed smoke	Salmon (*Salmo salar*)	PCS-processing inhibits bacterial growth, enhancing the shelf life of smoked salmon. Condensed smoke–processed salmon was firmer, darker, and slightly less reddish and yellowish compared to those smoked traditionally	Valø et al. (2020)

Abbreviations: BA, biogenic amine; HPP, high-pressure processing; PCS, purified condensed smoke; PEF, pulsed electric field; PL, pulsed light; TBARS, thiobarbituric acid reactive substances; TVB-N, total volatile basic nitrogen; UVC-LEDs, ultraviolet light-emitting diodes.

the sensory and texture of fresh whiteleg shrimp. The study concludes that the combination of HPP and SVC technology can satisfactorily obtain microbiologically safe shrimp that is preferable from an organoleptic perspective, representing a meaningful contribution to the food industry when seeking to increase shelf life while maintaining sensorial quality and consumer acceptability (Ahmad & Traynor, 2022).

Cartagena et al. (2021) studied the use of HPP before freezing albacore steaks to reduce weight loss during thawing and cooking. They found that HPP at 200 MPa for 2 min minimized weight loss and color changes, making it a potential compromise treatment for preserving fish quality and reducing consumer rejection due to color alterations.

The HPP technology has also been used as an alternative method for the shucking of bivalve. In particular, Puértolas et al. (2023) showed that HPP can improve oyster shucking yield (up to 25%) immediately after the treatment and increase the microbiological and sensory shelf life of oysters stored at 0–4°C.

The study by Lee et al. (2022) provides valuable insights into the use of HPP as an alternative to conventional frozen shucking methods for the preparation of soy sauce-marinated Asian hard clams. The study found that HPP can effectively delay the growth of aerobic plate count (APC), psychrotrophic bacteria count, and coliform, as well as the drop of pH of marinated clams compared to frozen marinated clams. Furthermore, it was found that soy sauce marinade also has a synergistic bactericidal effect on HPP-treated clams. The study concluded that HPP at 300 MPa or greater pressures for 3 min was effective to shuck and pasteurize marinated clam simultaneously, as well as to extend the shelf life during storage at 4°C.

Ye et al. (2021) found that HPP at 300 MPa for 20 min at 25°C maintained the quality of the Chinese crab meat during superchilled storage at −4°C for up to 3 weeks. Superchilling refers to a technology where there is a temperature between refrigeration and freezing storage methods; the food temperature is usually controlled at 1–2°C below freezing point. After this combined treatment, the meat's brightness and color started to diminish, whereas its texture in terms of hardness, gumminess, and chewiness stayed consistent. Sensory and microbial evaluations suggested that HPP-shucked crab meat could be preserved in an acceptable manner within 3 weeks, although a negative influence on drip loss was observed. The study concluded that the shelf life of the crab meat was 3 weeks, and that HPP shucking combined with superchilling could effectively preserve the crab meat. This is a remarkable result considering that the crab meat shelf life in refrigerated conditions is of 3–5 days.

Humaid et al. (2020) conducted a study on the effects of HPP and sous vide on the shelf life of high-value lobster tails. They found that HPP at 350 MPa for 10 min or SVC at 65°C maintained lower microbial counts, total volatile base nitrogen, and biogenic amine (BA) levels in raw lobster tails during 28 days of refrigerated storage. This resulted in an extended shelf life of the lobster tails. However, HPP pretreatment did not contribute to additional shelf-life extension for sous-vide-cooked products. The study also found that considerable histamine content was observed in raw lobsters that reached the hazard limit after 14 days, warranting further studies on histamine-forming bacteria in vacuum-packed lobsters.

In the context of seafood preservation, HPP has been shown to be particularly effective. For instance, Khouryieh (2021) found that HPP was the most commonly used nonthermal food processing technology in the United States, with more than 35% of respondents in their survey indicating its use. The study also found that the main factor for choosing HPP was its ability to maintain better nutrient and sensory properties compared to other technologies (Humaid et al., 2020; Roobab et al., 2022). In fact, as HPP is a nonthermal process, it does not cause significant changes in the sensory attributes and quality of the food, unlike traditional thermal processing methods (Ahmad & Traynor, 2022; Roobab et al., 2022). Moreover, HPP has been shown to maintain the nutritional quality of seafood products. Essential nutrients, such as proteins, omega-3 fatty acids, and vitamins, are well preserved during HPP, making it a desirable method for the processing of nutritionally rich seafood products (Humaid et al., 2020; Lee et al., 2022).

Despite its advantages, there are some challenges associated with the use of HPP. One of the main limitations is the high investment cost associated with the technology, which can be a barrier for its implementation, particularly for small and medium enterprises (Khouryieh, 2021). However, the benefits of HPP in terms of product quality

TABLE 2 Effects on shelf life of emerging technologies applied on seafood processing.

Technology used	Shelf-life results	References
High-pressure	Control: 7 days Treated samples 28 days	Humaid et al. (2020)
	No significant extension of shelf life	Puértolas et al. (2023)
	Control: 21 days Treated samples: 28 days	Chen et al. (2022)
	Control: 9 days Treated samples: from 12 to 15 days	Lee et al. (2022)
	Control: 6 days Treated samples: from 9 to 12 days	Lin et al. (2022)
	Control: 5 days Treated samples: 9 days	Giannoglou et al. (2021)
Ultrasound	Control: 3 days Treated samples: 6 days	Esua et al. (2022)
	Control: 3 days Treated samples: 5 days	Ma et al. (2023)
Pulsed electric field	Control: 9 days Treated samples: 18 days	Shiekh, Zhou et al. (2021)
	Control: 12 days Treated samples: 18 days	Shiekh, Benjakul et al. (2021)
	No significant extension of shelf life	Shiekh and Benjakul (2020)
	Control: 15 days Treated samples: 25 days	Pérez-Won et al. (2021)
	Control: 5 days Treated samples: 6 days	Giannoglou et al. (2021)
Plasma	Control: 5 days Treated samples: 20 days	Chaijan et al. (2021)
	No significant extension of shelf life	Mol et al. (2023)
	Control: 4 days Treated samples: 10 days	Mohamed et al. (2021)
	Control: 4.7 days Treated samples: 7.5 days	Chanioti et al. (2023)
	Control: 9 days Treated samples: 21 days	Olatunde et al. (2020)
	Control: 6 days Treated samples: 18 days	Shiekh, Benjakul et al. (2021)
	Control: 5 days Treated samples: 7–8 days	Giannoglou et al. (2021)
Pulsed light	Control: 6 days Treated samples: 8–10 days	Zhang, Zhou et al. (2022)
Low-voltage electrostatic field	Control: 12 days Treated samples: 18 days	Zhang et al. (2023)
Ozone treatment	Control: 12 days Treated samples: 20 days	Zhang et al. (2023)
	Control: 12 days Treated samples: 18 days	Zhao et al. (2022)
	Control: 8 days Treated samples: 10 days	Nghia et al. (2022)
	Control: 5 days Treated samples: 6 days	Giannoglou et al. (2021)

(Continues)

TABLE 2 (Continued)

Technology used	Shelf-life results	References
Edible coatings	Control: 6 days Treated samples: 9 days	Hua et al. (2022)
	Control: 10 days Treated samples: 15 days	Xiong et al. (2021)
	Control: 4 days Treated samples: 12 days	Agdar GhareAghaji et al. (2021)
	Control: 15 days Treated samples	Chaijan et al. (2022)

and safety, as well as its potential to extend shelf life, make it a promising technology for the future of seafood preservation.

3.2 | Ultrasound

Ultrasound is an emerging nonthermal food processing technology that has gained significant attention in recent years due to its potential to improve food safety and quality while maintaining the nutritional and sensory attributes of the product (Ma et al., 2023; Sireesha et al., 2022).

Ultrasound technology utilizes high-frequency sound waves (typically in the range of 20 kHz to 1 MHz) to induce mechanical effects in the food matrix, such as cavitation, which can disrupt microbial cells and enzymes, leading to their inactivation (Ma et al., 2023; Sireesha et al., 2022). The intensity and frequency of the ultrasound waves, as well as the duration of the treatment, can be adjusted to optimize the inactivation of specific microorganisms and enzymes, providing a high degree of control over the process (Hasan et al., 2023; Ma et al., 2023).

Hasan et al. (2023) studied the use of ultrasound for decontaminating cockle shells, a key step in seafood processing. They found the optimal settings for ultrasonic cleaning to be between 0.35 and 0.41 W/cm^2 at 37 kHz for 15 min. The study also suggested that combining ultrasound with other solvents could improve decontamination efficacy. This research contributes to understanding how ultrasound can improve seafood processing by effectively decontaminating shells (Hasan et al., 2023).

Ultrasonication has been shown to improve the physiochemical properties such as texture and color while also increasing the water-holding capacity (WHC). Additionally, it has been shown to increase omega-3 fatty acid content while reducing lipid oxidation (Sireesha et al., 2022). Ultrasonication has also been shown to be effective in microbial inactivation, reducing the number of bacteria and viruses in seafood products (Ma et al., 2023). The study by Ma et al. (2023) investigated the use of ultrasound technology to inactivate *Vibrio parahaemolyticus*, a foodborne pathogen, in raw oysters. The study found that after treating the oysters with 7.5 W/mL ultrasound for 12.5 min, the pathogen was reduced by 3.13 log CFU/g. The ultrasound treatment also delayed microbial growth and quality loss in the oysters during cold storage, maintaining their color, texture, and flavor better than traditional heat treatment (Ma et al., 2023).

Esua et al. (2021) conducted a study on the decontamination of grass carp using thermoultrasound-assisted plasma functionalized buffer (PFB). The study used the Box–Behnken design to evaluate the process variables, including PFB generating voltage, ultrasound treatment time, and temperature. The results showed significant reductions in the populations of *Shewanella putrefaciens* and *Salmonella typhimurium* under optimized conditions, exhibiting promising potential for fish decontamination that could be used as an alternative to conventional water washing.

Esua et al. (2022) conducted another study on the effects of a treatment combining ultrasound with plasma-functionalized liquids on the quality of vacuum-packaged silver pomfret. The treatment led to conformational modifications in myofibrillar proteins, improvements in nutritional value and biomedical index of fatty acids and lipids, reduced pH, increased *K* value, thiobarbituric acid reactive substances (TBARS), and total volatile basic nitrogen (TVB-N) at values of 12.05%, 0.576 mg MDA/kg, and 9.15 mg N/100 g, respectively, and 1.99 log reductions in spoilage microorganisms. In that case, the combination with vacuum packaging ensured optimal quality enhancement effects, such as stability of myofibril fragmentation, inhibition of physicochemical quality degradation, and microbial growth control. Recently, the ultrasonic technology has been applied to assist in the freezing process of fish.

Ultrasonic-assisted freezing is a new green and safe freezing technology that relies on the cavitation effect produced by ultrasonic to act on aquatic products. The study of Yu and Xie (2023) evaluated the impact of orthogonal ultrasonic waves on the quality of frozen sea bass. The study found that, compared to single-frequency ultrasound, multifrequency ultrasound could better reduce the size of ice crystals, reduce the damage to fish cells, and better maintain the quality of the fish. These results suggest

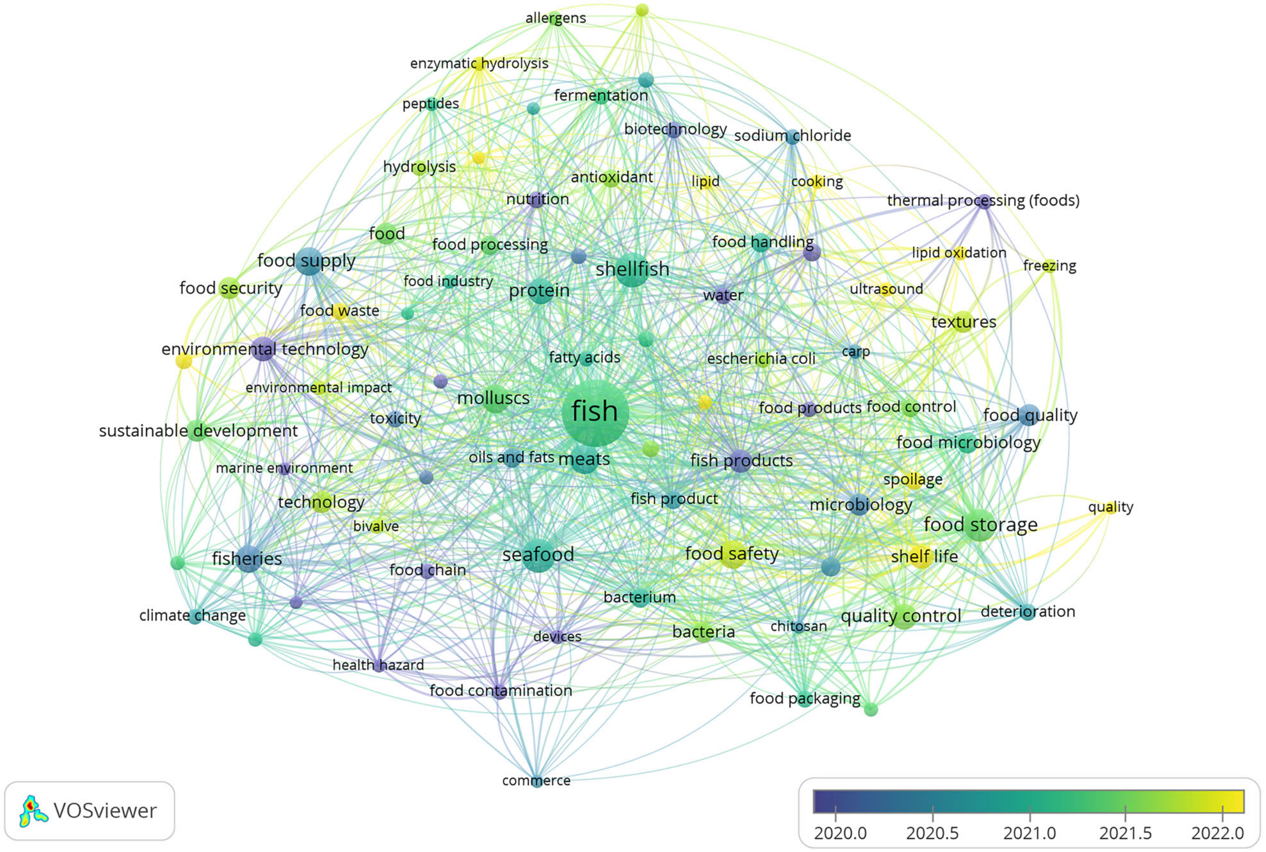


FIGURE 3 Database keywords occurrence overlay based on the search "seafood technology" from Scopus database (822 document results). The keywords are colored differently by the time of their appearance in literature records (2020 to June 2023).

that orthogonal ultrasonic freezing technology could provide a method for the food freezing industry to improve the quality of aquatic products and innovate this food sector (Yu & Xie, 2023).

However, the application of ultrasound in the seafood industry is not without challenges. The effectiveness of ultrasound can vary depending on the type of seafood product and its initial microbial load, and there are concerns about potential negative effects on the sensory quality of the product, such as changes in texture and color (Khouryieh, 2021). Regarding the limitation of ultrasound, the effectiveness of microbial inactivation can be influenced by the type of microorganism, the properties of the food matrix, and the ultrasound parameters used (Ma et al., 2023). Additionally, high-intensity ultrasound can cause changes in the texture and color of seafood products, which may affect their sensory quality (Tang & Yongsawatdigul, 2021).

3.3 | Pulsed electric field

PEF technology is a recent technology that employs short bursts of high-voltage electric fields (typically in the range of 20–80 kV/cm) to permeabilize the cell membranes of microorganisms, leading to their inactivation (Abel et al., 2022; Khouryieh, 2021; Pérez-Won et al., 2021). Similar to ultrasound, the intensity and duration of the electric field, as well as the number of pulses, can be adjusted to optimize the inactivation of specific microorganisms. In fact, PEF treatment has been shown to effectively inactivate *L. monocytogenes* in vacuum-packed cold-smoked salmon, leading to an extended shelf life (Aymerich et al., 2019). Moreover, Perez-Won et al. (2021) conducted an interesting study on the effects of PEF, CO_2, and HPP on the physicochemical properties and microbiological shelf life of coho salmon under pre- and post-rigor conditions during refrigerated storage (Pérez-Won et al., 2021). The combined treatments of PEF, CO_2, and HP were found to reduce color changes more effectively in pre-rigor than in post-rigor salmon.

PEF technology offers promising opportunities for the seafood industry. In fact, PEF can enhance the extraction of bioactive compounds from seafood byproducts, adding value to these often underutilized resources (Franco et al., 2020). However, despite the promising applications of PEF, there are several limitations that need to be addressed. For instance, one of the main limitations is the high cost of the technology, which can be a barrier to its widespread adoption in the seafood industry (Khouryieh, 2021). Moreover, PEF treatment can lead to lipid oxidation, resulting in undesirable off-flavors in seafood products (Shiekh, Benjakul et al., 2021).

Nonetheless, PEF offers several potential benefits for the seafood industry. This technology can effectively inactivate spoilage and pathogenic microorganisms, leading to an extended shelf life and improved safety of seafood products (Pérez-Won et al., 2021; Shiekh, Benjakul et al., 2021). Further research is needed to overcome the challenges associated with their application and to fully realize their potential in the seafood industry.

3.4 | Recent innovations of plasma technologies

Cold plasma (CP) is an emerging technology that is increasingly being recognized for its potential uses in the food industry. This process involves energizing a gas (either single or combined) with a high-intensity electric field, or energy beyond its ionization potential, which then transitions the gas into an ionized state, commonly referred to as plasma. During this transformation, a broad spectrum of species are generated, including both positive and negative ions, radicals, neutrally and excitedly charged molecules, electrons, and quantities of electromagnetic radiation, such as visible light and ultraviolet (UV) (Abel et al., 2022; Mol et al., 2023; Situ et al., 2023). As an advanced nonthermal technique, CP technology has made significant strides in a short time, with a myriad of applications ranging from microbial disinfection and cancer treatment to wound healing (Olatunde et al., 2020, 2021).

Cold atmospheric plasma (CAP), also known as nonthermal plasma, is a novel technology that has been gaining attention for its potential applications in the seafood industry (most of all microbial decontamination). This technology involves the ionization of gases (i.e., air, oxygen, nitrogen, helium, and argon) at atmospheric pressure, creating a mixture of charged particles, reactive species, UV radiation, and heat (Mol et al., 2023; Shiekh, Benjakul et al., 2021). To elucidate, both "cold plasma (CP)" and "cold atmospheric plasma (CAP)" refer to plasma technologies that function at near-ambient temperatures. The distinction lies in the emphasis that CAP is generated at atmospheric pressure. For the purpose of this review and to avoid redundancy, we will use the term "cold plasma" to encompass both concepts, focusing on its applications in seafood processing.

The mechanism of CAP is primarily based on the generation of reactive species, including reactive oxygen species and reactive nitrogen species. These reactive species can cause oxidative damage to the cell membranes of microorganisms, leading to cell death. This makes CAP a promising technology for microbial decontamination of seafood products (Khouryieh, 2021; Shiekh, Benjakul et al., 2021).

One of the main advantages of CAP is that it operates at near-ambient temperatures, making it a nonthermal processing method. This means that it can effectively inactivate microorganisms without causing the detrimental changes to the sensory and nutritional properties of seafood that can occur with traditional thermal processing methods. Furthermore, CAP can be applied to the surface of products, making it suitable for the treatment of delicate seafood products that may be damaged by other processing methods (Situ et al., 2023).

In terms of its application in the seafood industry, CP has been found to effectively reduce the microbial load on various types of seafood, including fish and shellfish. For example, a study by Olatunde et al. (2020) found that CP treatment significantly reduced the microbial count on Asian sea bass slices, extending the shelf life up to 18 days (respect to the 6 days of control without CP).

Many different plasma instruments have been developed, and one of these involves the application of plasma to water. Water can be transformed into plasma-activated water (PAW) by applying a plasma source, which generates various interactions between the plasma in gas form and liquid water. These interactions result in modifications to the physiochemical attributes of the water (Chanioti et al., 2023; Esua et al., 2021).

Chanioti et al. (2023) investigated the effectiveness of PAW as a decontamination agent for sea bream fillets. In this study, PAW was found to be effective in controlling microbial degradation in sea bream fillets, while maintaining the quality of the fillets. This treatment resulted in an extended shelf life of over 60% compared to untreated products, offering potential benefits for the storage and transportation of fish fillets.

However, there are also some challenges associated with the application of plasma technologies in the seafood industry. The effectiveness of CAP and PAW treatments can be influenced by several factors, including the type and concentration of the gas used, the treatment time, and the characteristics of the product itself. Furthermore, the technology is still relatively new, and more research is needed to fully understand its potential and limitations, including its impact on different types of seafood, its long-term effects on product quality and safety, and its economic feasibility for large-scale implementation in the seafood industry (Khouryieh, 2021). Nonetheless, the implementation of this technology has been constrained due to a multitude of biochemical processes taking place in marine food sources, most notably lipid and protein oxidation.

These oxidative reactions are driven by the reactive species produced by the CP, thereby curbing the broader adoption of this technique.

3.5 | Pulsed light

PL is an innovative nonthermal technology that has been gaining attention in the food industry, including seafood, for its potential in microbial inactivation. This technology employs high-intensity, short-duration pulses of broad-spectrum light, typically in the UV range, to inactivate microorganisms (John & Ramaswamy, 2018; Mandal et al., 2020; Zhang, Zhou et al., 2022).

The mechanism of microbial inactivation by PL is primarily attributed to the absorption of UV light by the DNA of the microorganisms, leading to the formation of pyrimidine dimers. These dimers cause disruptions in the DNA structure, preventing replication and ultimately leading to cell death. This makes PL a powerful tool for surface decontamination, as it can significantly reduce the microbial load on the surface of seafood products (Zhang, Zhou et al., 2022).

One of the key advantages of PL technology is that it is a nonthermal process, meaning it does not involve the application of heat. This is particularly beneficial for seafood products, as it allows for effective microbial inactivation without causing changes to the sensory attributes of the product, such as texture and flavor, which can occur with thermal processing methods (Mandal et al., 2020).

However, it is important to note that the effectiveness of PL treatment can be influenced by several factors, including the intensity and duration of the light pulses, the distance between the light source and the product, and the characteristics of the product itself, such as its shape, color, and transparency. Therefore, the application of PL technology in the seafood industry requires careful optimization to ensure effective microbial inactivation while maintaining product quality (Khouryieh, 2021).

In the study of Zhang, Zhou et al. (2022), PL treatments of varying intensities (100, 200, 300, 400, and 500 J/pulse) were administered for 30 pulses on yellow croaker fillets. The study showed that a 300 J/pulse PL treatment led to an initial sterilization efficiency of 86.27% ± 4.32%. Additionally, this treatment slowed the increase of TVB-N and TBARS during storage compared to the control group.

Another study instead investigated the use of UV light-emitting diodes (UVC-LEDs) for decontaminating raw tuna fillets (Fan et al., 2021). UVC-LEDs are emerging as a safer alternative to traditional mercury-vapor-based UV lamps for food product and packaging decontamination. The study from Fan et al. (2021) reported that UVC-LED radiation at doses up to 4000 mJ/cm^2 shows promise in significantly reducing microbial contamination while maintaining the physicochemical properties of the raw tuna fillets, barring an increase in lipid oxidation.

PL technology represents a promising alternative to traditional preservation methods in the seafood industry. However, further research is needed to fully understand its potential and limitations, and to develop guidelines for its optimal application in different seafood products. In particular, the PL technology is well studied for the meat industry, but there is a scientific gap regarding the application of PL treatments to different types of seafood products (crustaceans, shellfish, etc.). Moreover, future research should explore the use of UVC-LEDs in combination with other preservation methods for better efficiency and maintenance of the nutritional and sensory qualities of food products.

3.6 | Low-voltage electrostatic field and magnetic field

LVEF technology is a nonthermal preservation method that leverages the effects of an electric field on the physiological and biochemical reactions related to charged particles in food (Wang et al., 2023; Zhang et al., 2023).

In the context of seafood preservation, LVEF has been shown to promote ice crystal miniaturization, which can reduce damage to the tissue structure of the product. Additionally, LVEF stimulation can promote the relaxation of muscle fibers, accelerate the maturation of meat after the rigidity stage, improve color, sensory characteristics, and reduce juiciness loss (Yang et al., 2023). The LVEF appears to even out electric field force within the food, leading to strong vibrations that might improve preservation processes. In addition, it was discovered that the combined approach inhibited the growth of two dominant spoilage bacteria, *Bacillus subtilis* and *Pseudomonas* (Wang et al., 2023).

The LVEF technology has been combined with the partial freezing (PF) technique. PF is a low-temperature preservation technology that has the potential to extend the shelf life of food products. This technique involves controlling the storage temperature at 1–2°C below the initial freezing point of the organism's muscle tissues. In this state, aquatic products can be preserved nearly at −3°C, which inhibits microbial growth and the freeze-induced denaturation of proteins (Zhang et al., 2023). PF preservation can also maintain the original flavor and freshness of aquatic products, extending their shelf life by 1.5–4 times compared to chilled storage. This makes PF an attractive alternative to traditional preservation methods such as frozen storage and conventional chilling (Khouryieh, 2021).

In the study of Zhang et al. (2023), the effect of PF combined with LVEF treatment on the quality enhancement of large yellow croakers was explored. The results highlighted the importance of LVEF-PF treatment in maintaining the quality of large yellow croaker during storage, effectively avoiding the rapid oxidative degradation of protein, microbial growth, and nucleotide degradation metabolism of large yellow croaker during storage.

Another study investigated the effects of low-voltage variable frequency electric fields (LVVFEF) and compound preservatives on the preservation of steamed mussels stored at ice temperature (Wang et al., 2023). The study revealed that the combined effect of LVVFEF and compound preservatives was the most effective at maintaining the quality of the mussels and delaying protein deterioration, when compared to using compound preservatives or LVVFEF alone.

This technology is particularly effective in the preservation of aquatic products due to its ability to induce changes in water, protein, and enzymes in the food (Zhang et al., 2023). Nonetheless, this technology has been extensively studied for fruit and meat products, but actually, the applications of LVEF to seafood are very limited to a few species. Further studies on a wider range of seafood and in combination with other hurdle technologies are required prior to its industrial utilization.

Moreover, there are some limitations to the application of LVEF, such as high energy consumption and security concerns.

Despite these challenges, LVEF has been found to be effective in extending the shelf life of food products during chilled storage (Wang et al., 2023; Yang et al., 2023).

Another interesting emerging technology for assisting freezing is the application of magnetic freezing. Magnetic field–assisted freezing is an innovative approach to the freezing process that aims to optimize the quality of frozen food. By applying a magnetic field during freezing, smaller and more uniformly distributed ice crystals can be achieved, which is beneficial for preserving the food's quality (Kaur & Kumar, 2020). A recent study by Zhou et al. (2023) focused on the evaluation of the MIF effects on golden pompano (*Trachinotus ovatus*) muscle using different magnetic field intensities (0, 20, 40, 60, and 80 mT). Compared to refrigerator freezing and immersion freezing without a magnetic field, the use of MIF extended the freezing time. The study concluded that using a magnetic field intensity of 20 mT during immersion freezing can effectively enhance the quality of frozen golden pompano muscle (Zhou et al., 2023). MF technology is advantageous because it does not necessitate complex machinery. The process is straightforward, cost-effective, and environmentally friendly.

MF technology offers a promising avenue for improving the quality of frozen foods, but its application in preserving aquatic products remains under-researched.

3.7 | Innovative ozone treatments

Ozone is a form of oxygen well known for its disinfecting properties. It has been used for water treatment in Europe and for various commercial purposes, such as disinfecting bottled water, swimming pools, and preventing fouling in wastewater treatments. Ozone is capable of destroying 99.9% of pesticides and microorganisms often found in food products due to its strong oxidizing capacity, second only to fluorine. As such, it can effectively eliminate contaminants that are susceptible to oxidation (Gonçalves, 2019). With minimal concentrations and short exposure times, ozone can effectively eliminate harmful microorganisms, bacterial spores, and viruses, establishing it as a potent antimicrobial and disinfectant. Additionally, it is recognized as one of the most powerful agents for water treatment (Pinnaduwa et al., 2020).

Given these benefits, ozone is seen as a potential candidate for use in the food processing industry to ensure high-quality food products. In 2001, the US FDA granted ozone the status of "Generally recognized as safe" (GRAS), permitting its use in food applications and allowing direct contact with food products, including fish, meat, and poultry (Pinnaduwa et al., 2020). Its recent use in a wide range of foods, including seafood, is due to the fact that it leaves no residue or taste in the treated food product.

Due to its pro-oxidant properties, ozone rapidly destroys a wide variety of microorganisms present in food systems, including bacteria, yeast, fungi, parasites, and viruses. It is particularly effective against Gram-negative microorganisms like *Escherichia coli* and coliform, as well as viruses and parasitic cysts (Qian, Zhang et al., 2022). The destructive capability of ozone extends to its metabolites, which can eliminate unwanted microorganisms by affecting their metabolic enzymes, nucleic acids, and other cellular components. Ozone also oxidizes pesticides, herbicides, natural organic compounds, and detergents in the food system.

Ozone treatment can reduce the microflora in fish and fish fillets by dipping and washing them in ozonized water. Studies have shown that such treatment does not negatively impact the quality of food products. In fact, ozonized water was found to reduce the total bacteria content in salmon, leading to the conclusion that ozone gas is a potent disinfectant. In the study of Qian, Zhang et al. (2022), the effect of gaseous ozone on salmon quality was examined at different doses and exposure times. The authors found that ozone treatment significantly reduced microbial growth and slowed the deterioration of sensory qualities.

Ozonized water treatment is also effective in shrimp processing. It reduces spoilage microorganisms in the product, with increased effectiveness at higher ozone concentrations and longer contact times. The treatment method does not induce lipid oxidation in the shrimp immediately after treatment (Nghia et al., 2022).

Ozone has also been applied to improve the technological properties of seafood. The study conducted by C. Liu et al. (2021) examined the effect of ozone water rinsing on the WHC, gel microstructure, capillary pressure, and protein–water interactions of grass carp surimi gel. The gels treated with 5 and 7 mg/L ozone water showed notably enhanced gel strength, and a homogenous microstructure with smaller pore sizes was formed (Liu et al., 2021).

Ozone application in freezing chambers and warehouses is becoming more popular among food processors. It aims to extend the product's shelf life by eliminating bacteria from the food system, thereby reducing the bacteriological index in storage systems (Pinnaduwa et al., 2020). When applied to freezing chambers or storage, the ozone concentration should be maintained at 2–3 ppm. Intermittent ozonization is seen as an effective method of applying ozone to the freezing chambers, as it helps extend the shelf life of the products while reducing weight losses during storage.

A recent innovation of ozone treatments is the combination with slurry ice (Lan et al., 2022; Zhao et al., 2022). Slurry ice, a homogeneous two-phase aqueous secondary refrigerant composed of tiny ice particles and a carried liquid, can significantly address these issues. The physical and engineering properties of slurry ice, such as tiny and smooth ice particles, excellent refrigeration and flow properties, and high heat exchange rate, allow it to reduce surface abrasion damage, slow down chemical and enzymatic reactions, enable faster cooling, and wash surfaces. However, slurry ice treatment alone cannot effectively prolong the shelf life of aquatic products. Therefore, slurry ice should be combined with different types of preservatives to achieve optimal results. Studies have been conducted on slurry ice combined with ozone, showing that this treatment has a comprehensive and effective preservation effect (Lan et al., 2022; Zhao et al., 2022). In fact, the study of Zhao et al. (2022) demonstrated that the combination of slurry ice and ozone could more efficiently retard the water migration and maintain the quality of fish. The ozonated slurry ice showed a significant reduction in water migration and loss and successfully reduced the decrease of texture properties and color difference. In this context, the study of Zhang et al. (2023) proposed a novel strategy for accelerating the production of pumpable ice slurry (PIS) using ozone micro–nano bubbles (O_3-MNBs). The addition of O_3-MNBs to a sodium alginate (SA) solution used for producing PIS resulted in quicker production by promoting ice nucleation and eliminating supercooling. When used for the preservation of small yellow croakers, PIS containing O_3-MNBs was more effective than traditional flake ice or conventional PIS due to the strong bacteriostatic ability of ozone. However, the study also found that the injection of O_3-MNBs increased the fat oxidation of the fish sample (Zhang et al., 2023). Therefore, further research is required to develop more types of PIS combined with antimicrobial compounds.

However, other papers have confirmed that ozone itself does not negatively affect the quality parameters of seafood products. In fact, ozone has been shown to suppress several mechanisms that facilitate lipid hydrolysis and oxidation (Gonçalves, 2019; Pinnaduwa et al., 2020). These benefits represent some of the improvements for seafood products that can be achieved through ozone treatment. In order to improve the results achieved through ozone treatments and understand their impact on the texture of various food items, it is crucial to carry out comprehensive studies on metabolic and proteomic aspects. It is also important to acknowledge that the effectiveness of this emerging technology can be influenced by a multitude of factors.

3.8 | Vacuum cooking technology in seafood processing

The SVC process involves vacuum sealing the seafood in heat-stable plastic pouches, which can be seasoned or flavored before being sealed. The pouches are then cooked/pasteurized under precisely controlled conditions and cooled for later consumption (Abel et al., 2022).

Sous-vide technology provides many benefits for seafood preparation and storage, such as extending shelf life, inhibiting off-flavors, preventing evaporative loss of flavor and moisture, and reducing bacterial growth (Humaid et al., 2020). Sous-vide-cooked seafood does not lose its moisture, flavor, and nutritional components, maintaining their quality for a longer time. Furthermore, the vacuum packaging reduces the risk of post-process contamination, and its inhibitive effects on aerobic microbial growth allow for longer storage stability for polyunsaturated fatty acids, especially ω-3 fatty acids (Coşansu et al., 2022).

The SVC technology has been recently used to cook rainbow trout (Öztürk et al., 2021), whiteleg shrimp (Ahmad & Traynor, 2022), lobsters (Humaid et al., 2020), Mediterranean mussels (Russo et al., 2023), and Asian green mussels (Palamae et al., 2023). The research of Palamae et al. (2023) examined the use of acidic electrolyzed water depuration in combination with SVC to ensure the safety and quality of Asian green mussels (*Perna viridis*), a common seafood that can pose health risks due to pathogenic bacteria and rapidly deteriorates within 1–2 days. The study found that an SVC at 100°C for 1 min was effective at reducing harmful bacteria, particularly *Vibrio* species, while preserving the quality, color, texture, and chemical composition of the mussels (Palamae et al., 2023).

Besides the shelf-life extension and quality maintenance, sous-vide technology improves sensory and textural acceptance of seafood products. It allows controlled cooking to different degrees without burning, simplifies food preparation with selected portions, reduces the spread of cooking odors, and potentially prevents the formation of certain heat-induced contaminants (Russo et al., 2023). This convenience allows seafood to be served in places where traditional preparation may be impossible, such as on airplanes or at large events.

Despite its many benefits, sous-vide technology is not without potential drawbacks. The most notable is the risk of anaerobic spore-forming bacterial growth, particularly *Clostridium botulinum*, in vacuum-sealed products (Palamae et al., 2023). The spoilage cannot be noticed until the package is opened, posing a risk to food safety. However, a high cooking temperatures required for extended shelf life can reduce the seafood product's sensory acceptability. Future work could explore the combination of sous vide with other techniques to mitigate these risks and further enhance the benefits of this method.

3.9 | Purified condensed smoke

Atomized purified condensed smoke (PCS) is a novel technology used in food smoking processes. It is created by condensing smoke and then purifying it to remove undesirable and potentially harmful compounds (Valø et al., 2020). In detail, the process involves the following steps: Initially, smoke is generated, typically by burning wood chips or similar materials, which are then condensed, usually through a cooling process. The condensed smoke is then purified. This step is crucial because it removes potentially harmful substances, such as polycyclic aromatic hydrocarbons (PAHs), ash, and soot. These compounds are naturally produced in the smoke but are undesirable in the finished product due to their potential health risks; finally, the purified, condensed smoke is atomized or converted into a fine mist. This process often involves the use of compressed air in a closed chamber. The atomized smoke can then be applied to the food product in an even and controlled manner.

Recently, a study from Valø et al. (2020) investigated the use of PCS in the smoking process of lightly salted salmon, and how it affects product quality. The study found that PCS processing inhibits bacterial growth, including APC and lactic acid bacteria, which potentially enhances the shelf life of cold-smoked salmon. The PCS-processed salmon was found to be firmer, darker, and slightly less reddish and yellowish compared to traditionally smoked salmon (Valø et al., 2020). The atomization of PCS for smoking salmon could provide a healthier alternative to traditional methods, potentially extend the shelf life of the product, and produce a firmer texture.

Another study was able to produce a promising PCS-processed cold-smoked salmon prototype that was similar in sensory quality and consumer acceptance to conventionally smoked salmon (Waldenstrøm et al., 2021). This was achieved by combining sensory perception results with physicochemical measurements. The study suggests that with further testing and adjustments, it would be possible to produce a healthier version of smoked salmon using PCS that retains similar sensory qualities and consumer acceptance as traditionally smoked salmon (Waldenstrøm et al., 2021). This could potentially be offered to a global market, contributing to healthier food options.

Overall, the use of PCS is seen as a healthier and more environmentally friendly alternative to traditional smoke-processing methods. It provides better control over the smoking process and an even distribution of smoke flavor. It is used in the processing of various foods, including meats and fish, to give them the characteristic smoked flavor (Waldenstrøm et al., 2022).

The European Union endorses the application of PCS, recognizing it as a healthier alternative to conventional smoke-processing methods. Its usage is now commonplace in the meat industry. Nevertheless, there is limited knowledge about the feasibility and effects of PCS-processing in the seafood sector. In the future, more research is needed to explore the potential of PCS in seafood processing. Different PCS types and atomization methods could be evaluated to determine the optimal conditions for producing high-quality PCS-processed seafood products. It could also be beneficial to assess consumer perceptions and acceptance of PCS-processed seafood to ensure market feasibility.

3.10 | Microwave heating advances in seafood industry

Microwave heating uses electromagnetic waves, typically at a frequency of 2.45 GHz, to penetrate the material and generate heat through the excitation of molecules, particularly polar molecules like water. The heat is generated from within the material itself rather than being conducted from an external source, which can lead to more uniform and faster heating than conventional methods (Lee et al., 2021; Pankyamma et al., 2021).

The microwave technology has been applied over the years as an alternative method of heating and, recently, also as a new technique for shucking (shell opening) of shellfish (Marinopoulou & Petridis, 2022).

The study of Marinopoulou and Petridis (2022) explored the effects of different heat treatment methods on the cooking loss and shucking of fresh mussels (*Mytilus galloprovincialis*). These methods included moist-heat and dry-heat processes, such as boiling, steaming, baking, and microwaving. The study found that microwave heating was the most efficient method for shell opening and had optimal results for reducing cooking loss. The authors suggest that microwave heat treatment could be a valuable method for industrial mussel processing, as it offers higher quality end products compared to other methods. However, further research should be conducted to evaluate the effects of continuous microwave processing on the physical, mechanical, and sensory characteristics of heat-treated mussel meat on an industrial scale (Marinopoulou & Petridis, 2022).

Microwave-assisted induction heating (MAIH) is an emerging hybrid heating technique that combines the features of both microwave heating and induction heating. Induction heating generates heat in a material by exposing it to an alternating magnetic field. This process induces electric currents (known as eddy currents) within the material, leading to resistance and thus heat generation. This method is highly efficient and also provides rapid and uniform heating (Lee et al., 2021). In MAIH, the combination of these two methods is used to create a unique heating process. The microwaves penetrate the material and start the heating process from within, whereas the induction heating can further increase the temperature and ensure uniformity. This dual system allows for rapid and efficient heating, making it useful for applications such as cooking, sterilization, or other thermal treatments in the food industry.

The study of Lee et al. (2021) explored the use of MAIH, to heat-prepackaged raw hard clams (*Meretrix lusoria*), and examined the effects on microbial and physiochemical qualities of the clams (Lee et al., 2021). Upon heating the clam meat samples, it was observed that bacterial count and TVB-N levels decreased as heating time increased. Meanwhile, the shucking ratio, area shrinkage, and texture characteristics increased. Heating with MAIH for at least 110 s at 130°C or 130 s at 90°C resulted in well-cooked samples with complete shucking, and no detectable microbial count.

Therefore, the optimal heating conditions for prepackaged hard clams using an MAIH machine were identified as 130°C for 110 s or 90°C for 130 s. The research concluded that MAIH, as an emerging thermal technique, has potential for developing short-time in-package pasteurization processes in the food industry due to its fast heating rate and the ability to heat and pasteurize after packaging, which eliminates the post-pollution issue (Lee et al., 2021).

Tsai et al. (2022) found that MAIH treatment at either 90°C for 110 s or 70°C for 130 s resulted in completely cooked, contaminant-free barramundi with good appearance, color, and texture (hardness and chewiness). These results suggests that the MAIH method could serve as a viable future alternative for thermal processing in the manufacturing of ready-to-eat seafood, due to its advantages of simultaneous heating and pasteurization after packaging.

The microwave technology has also been used as an enhancer for drying procedures of fish. Pankyamma et al. (2021) evaluated the effects of different drying methods on marinated boneless tuna chunks. The authors studied microwave vacuum drying at different powers (600, 650, and 700 W) and compared it to sun drying and hot air drying. Microwave vacuum drying resulted in a smoother morphology of the dried tuna chunks, with better microbial stability. However, the study pointed out that microwave treatment led to higher protein denaturation and significantly increased lipid oxidation.

These findings indicate that microwave vacuum drying can enhance the end product quality of dried fish by providing rapid dehydration and could be a useful tool for fish processing entrepreneurs. However, the increase in lipid oxidation with higher microwave power needs to be considered and studied.

3.11 | Edible coating

An edible coating refers to a thin layer of edible material that is applied to the surface of food products. It serves as a protective barrier between the food and its surrounding environment, providing various benefits, such as extended shelf life, preserved quality, and enhanced visual appeal. Edible coatings are typically made from natural or food-grade synthetic materials, which are safe for consumption (Zhang & Rhim, 2022).

Edible coating can be used as a preservation technology to extend the shelf life of fish products by slowing down the deterioration process, preventing moisture loss, gas exchange, and the growth of microorganisms (Dehghani et al., 2018). It can help maintain the freshness, texture, and flavor of the food, making it more appealing to consumers.

Edible coatings can also act as a carrier for adding functional ingredients, such as antimicrobial agents, antioxidants, vitamins, and flavorings, which further enhance the quality and nutritional value of the food (Umaraw et al., 2020). Widely used and tested active components are essential oils (EOs), extracts of herbs and spices, probiotics, and so on. In general, EOs extend food stability during storage, inhibiting the growth of spoilage or pathogenic microorganisms and protecting against oxidation (Hassoun & Emir Çoban, 2017).

Biopolymer or the active compound can also be obtained by the valorization of industrial food processing byproducts as a promising strategy for producing sustainable coatings (Lionetto & Esposito Corcione, 2021).

Carvacrol (isopropyl phenol) is a hydrophobic compound that accumulates in the microbial cell membrane and induces conformational changes in its membrane, ultimately causing cell death. Monoterpenes such as thymol and menthol cause the perturbation of lipid fraction in microbial cell membrane and alter its permeability, resulting into leakage of cellular contents (Paulino et al., 2022). Similarly, oregano EO modifies microbial membrane permeability, leading to phosphates, protons, and potassium leakage. These active agents also improve barrier properties of films due to interaction between film and polyphenols.

One of the most used biopolymers is chitosan. Chitosan is a functional biomaterial used for food preservation, primarily due to its natural origin and excellent biological properties. It exhibits antimicrobial activities against spoilage microorganisms and foodborne pathogens, which make it particularly useful in food preservation (Rezaeifar et al., 2020). It also shows a strong antioxidant activity, protecting against lipid oxidation in foods.

Chitosan coating enriched with EO (clove oil, citronella oil, lemon verbena EO) or active compounds (nisin, carvacrol, and gallic acid) was successfully applied on salmon fillets (Hai et al., 2022; Yuan et al., 2022), grey mullet (*Mucil cephalus*) steaks (Aref et al., 2022), Atlantic horse mackerel (*Trachurus trachurus*) fillets (Zarandona et al., 2021), rainbow trout (Rezaeifar et al., 2020), and mori (*Cirrhinus mrigala*) (Nawaz et al., 2020).

The presence of nanoparticles of chitosan has been shown to improve the antimicrobial or antioxidant effect of the active coating (Aref et al., 2022; Zarandona et al., 2021). The maximum extension of shelf life was registered for the grey mullet steaks coated with chitosan, chitosan nanoparticles, and clove oil. Results showed that the active coating was able to prolong the shelf life of the fish product to 24 days at refrigeration temperature, by preserving the chemical, microbiological, and sensory characteristics of the fresh fish steaks. The samples that contained a combination of 2% nanochitosan and clove oil had the lowest pooled mean TVB-N value (16.66 mg/100 g), TMA pooled mean (0.76 mg/100 g), peroxide value (1.29 meq/kg) after 21 days (Aref et al., 2022).

Another interesting outcome was reported for the use of composite coating based on chitosan- and pepsin-soluble collagens extracted from blue shark (*Prionace glauca*) skin that were applied to fresh red porgy (*Pagrus major*) fillets, preserving most of the deterioration indices during storage life (Liu et al., 2020).

A relevant study that supports the use of coatings and films in the preservation of fish was carried out with a coating derived from nanoemulsified clove EOs and fish gelatin that could control the *Pseudomonas*-causing spoilage in tilapia (*Oreochromis niloticus*) fillets by reducing the surviving bacteria populations (0.78–1.80 log CFU/g reductions) and inhibited the proteolysis and oxidation during cold storage. However, the levels of metabolites (e.g., amino acids and osmoprotectants) were upregulated after 3 h and then back to normal concentration after 24 h, which indicated a defense system was built in bacterial cells to tolerate nanoemulsified clove EOs (Hai et al., 2022). Moreover, gelatin films enriched with propolis extract (2%, 8%, and 16%) had great inhibitory effects on the microbial growth and delayed the lipid oxidation and sensory deterioration in rainbow trout fillets during 15 days of refrigerated storage (4 ± 1°C) (Ucak et al., 2020).

Another interesting study evaluated the application of coating protective layers of *Zanthoxylum* EOs combined with superchilling ice-glazing (−1°C) on salmon sashimi fillets (He et al., 2020). This study found that *Zanthoxylum* EOs used as ice glazing layers can keep the postmortem quality of sashimi fillets.

A composite coating based on chitosan and gelatin extracted from salmon fish bones was incorporated with gallic acid and/or clove oil as bioactive ingredients for the preservation of fresh salmon fillet at cold storage (4°C for 15 days). Results showed that a shelf-life extension of 5 days was possible thanks to the combination of gallic acid and clove oil. Furcellaran coatings enriched with a gelatin extract obtained from carp skins enriched with dry herbs (thyme or rosemary) proved effective in inhibiting the formation of BAs, and slowing down the microbial deterioration of carp fillets (reduction by 0.53 and 0.29 log CFU/g). The evaluated herb coatings changed the characteristic taste of fish. Interestingly, the coatings emphasized the natural saltiness of fish meat (Derbew Gedif et al., 2022; Tkaczewska et al., 2023).

To resume the main findings related to the utilization of edible coatings, Table 3 reports and summarizes the main papers found in the literature.

Edible coatings have shown promise in enhancing the shelf life and sensory attributes of seafood products. These coatings can act as barriers to moisture, oxygen, and lipid oxidation and can also be fortified with antimicrobial agents or antioxidants. However, there are limitations to consider. In fact, not all edible coatings may be suitable for all types of seafood. The choice of coating material must be compatible with the specific seafood product to ensure effective protection and preservation. Moreover, the economic feasibility of implementing edible coatings

TABLE 3 Resume of emerging coatings and active packaging applied on seafood products.

Biopolymer	Active compound	Fish species	Key findings	References
Furcellaran-gelatine	Thyme and rosemary water extract (5%)	Carp fillet (*Cyprinus carpio*)	The coatings with added rosemary proved effective in inhibiting the formation of biogenic amines, and slowing down the microbial deterioration of carp fillets (reduction by 0.53 and 0.29 log CFU/g). Interestingly, the coatings emphasized the natural saltiness of fish meat	Tkaczewska et al. (2023)
Furcellaran-gelatine	Thyme and rosemary water extract (5%)	Carp fillet (*Cyprinus carpio*)	The active coating was effective in inhibiting lipid oxidation but impacted the color of the carp fillets, which became slightly darker	Derbew Gedif et al. (2022)
Chitosan or chitosan nanoparticle	Clove oil (1.5%)	Grey mullet (*Mugil cephalus*) steaks	A combination of nanochitosan and clove oil treatment prolonged the shelf life of mullet steaks to 24 days at refrigeration temperature, by preserving the chemical, microbiological, and sensory characteristics of the fresh fish steaks	Aref et al. (2022)
Dietary fiber	Tea polyphenol	Fish floss	The nanoemulsion-based edible film effectively enhanced the flavor and taste of fish floss, controlled the release of tea polyphenol antioxidant, and reduced the water activity during the storage, thereby extending the shelf life	Zhang, Zhao et al. (2022)
Gelatine from salmon fish bone + chitosan	Gallic acid or clove oil	Salmon fillet	The combination of gelatine, chitosan, gallic acid, and clove oil had the best performance on salmon fillet preservation and prolonged the shelf life for at least 5 days	Xiong et al. (2021)
Sodium alginate	Postbiotics + probiotic bacteria cells	Salmon fillets	The fortified coating significantly inhibited the proliferation of psychrophilic bacteria, *Pseudomonas* spp., *Enterobacteriaceae*, as well as the spiked *Listeria monocytogenes* on the salmon fillets during a refrigeration storage of 9 days	Hua et al. (2022)
Liposome + xanthan gum (1:3 v/v)	Nano-encapsulated *Litsea cubeba* essential oil (5 mg/mL)	Salmon (*Salmo salar*)	Coating performed the best preservative properties; the coating treatment delayed the oxidation of salmon and controlled the growth of *Vibrio parahaemolyticus*	Cui et al. (2022)
Fish gelatin	Nanoemulsified clove essential oils	Tilapia (*Oreochromis niloticus*) fillets	The coating delayed the deterioration of tilapia fillets because it significantly reduced the surviving bacteria populations (0.78–1.80 log CFU/g reductions) and inhibited the proteolysis and oxidation during cold storage	Hai et al. (2022)
Chitosan	Nisin + carvacrol	Salmon fillets	The coating significantly increased the shelf life of fish fillets, demonstrating optimal potency in preserving fish fillets	Yuan et al. (2022)

(Continues)

TABLE 3 (Continued)

Biopolymer	Active compound	Fish species	Key findings	References
Chitosan	Citronella oil (CNO) + tween 80 (TW)	Salmon fillets	The total number of bacteria of the uncoated salmon sample was 6.42 log CFU/g at day 10, whereas the value of OF-treated group was 4.78 log CFU/g. The thiobarbituric acid (TBA) and TVB-N contents of the OF-treated samples were only 38.4% and 48.6% of the values of the control sample, respectively	Yin et al. (2022)
Rice starch	Mon-pu (*Glochidion wallichianum*) leaf extract (MPE)	Mackerel (*Auxis thazard*) slices	A biopreservative coating made of RS and MPE, especially at 0.5%, can be employed to extend the shelf life of refrigerated mackerel slices up to 9 days	Chumsri et al. (2022)
Salep gum	Orange peel essential oil	Fish fillets	The shelf life of fillets can be increased to at least 12 days by coating them with the salep containing 0.5% orange peel essential oil	Agdar GhareAghaji et al. (2021)
Chitosan	Gallic acid + chitosan nanoparticles	Atlantic horse mackerel (*Trachurus trachurus*) fillets	All chitosan-containing coatings decreased microorganisms' growth in more than 2 log cycles up to late storage stages; those with chitosan nanoparticles resulted to be more effective. Additionally, horse mackerel fillets coated by solutions with chitosan nanoparticles showed the lowest TBARS values, maybe owing to a more sustained release of gallic acid	Zarandona et al. (2021)
Alginate-/protein-based coating	Antimicrobial agents	Sturgeon fillets	Composite coatings can be used as a multifunctional coating material for the freshness preservation of sturgeon fillets to improve quality and extend shelf life	Tan et al. (2022)
Chia mucilage coating	Goji berry extract	Filleted trout	A high shelf life was determined by the coatings formulated with 1% goji berry extract and 2% goji berry extract. Chia mucilage coating may be an alternative to other coatings in the coating of meat and meat products	Emir Çoban and Ergür (2021)
Whey protein isolate (PWA)	Crude ginger extract coating (WC)	Asian sea bass steaks	Conjunction of plasma-activated soaking water and WC was an effective hurdle technique for reducing off-flavor development, drip loss, and extending the shelf life of ready-to-cook Asian sea bass steaks	Chaijan et al. (2022)
Chitosan	Lemon verbena essential oil and extract	Rainbow trout vacuum packed	Chitosan with lemon verbena essential oil and extract effectively preserve vacuum-packed rainbow trout, reducing bacterial counts and maintaining meat quality. This natural preservative combination could potentially replace chemical preservatives in seafood preservation	Rezaeifar et al. (2020)

(Continues)

TABLE 3 (Continued)

Biopolymer	Active compound	Fish species	Key findings	References
Chitosan	Rosemary (*Rosmarinus officinalis*) extract	Mori (*Cirrhinus mrigala*)	The study found that applying a coating of chitosan and rosemary extract improves the shelf life and quality of refrigerated mori fish	Nawaz et al. (2020)
Pectin	Plant essential oil	Yellow croacker (*Pseudosciaena crocea*)	The shelf life of yellow croacker could increase from 20 to 27 days and 24 days, respectively, which indicated that the combination of pectin-plant essential oil coating with vacuum packaging is a promising method for the preservation of fish	Lan, Lang et al. (2022)
Alginate	*Carum copticum* essential oil (CEO)	Fish burger	The study demonstrated that solid lipid nanoparticles with CEO enhanced fish burger shelf life at 4°C, reducing lipid oxidation, microbial growth, and total volatile basic nitrogen production more effectively than free CEO	Hashemi et al. (2023)
Gelatin films	Propolis extract (PE)	Rainbow trout (*Oncorhynchus mykiss*) fillets	Gelatin films enriched with PE had great inhibitory effects on the microbial growth in rainbow trout fillets. The addition of PE enhanced the effectiveness of gelatin films and delayed the lipid oxidation and sensory and microbial deterioration in trout fillets coated with these films	Ucak et al. (2020)

Abbreviations: TBARS, thiobarbituric acid reactive substances; TVB-N, total volatile basic nitrogen.

on a large scale remains a concern. Some coatings, especially those fortified with additional agents, might be cost-prohibitive for widespread commercial use.

4 | COMPARATIVE ANALYSIS OF THE EMERGING TECHNOLOGIES

Despite the high nutritional value of seafood, seafood-borne infections and seafood poisoning can reduce progress in the seafood and processed meat industries. Emerging technologies in seafood processing present a range of benefits and challenges.

A critical aspect of integrating these technologies within the seafood industry pertains to their scalability and adaptability in different regions with varying access to infrastructure and resources. Thermal treatments, for instance, might be more widely adopted due to their relative simplicity and accessibility, but their energy intensity can be a limiting factor in regions with constrained power supplies.

On the other hand, nonthermal technologies, although potentially energy-saving and beneficial for quality preservation, may require substantial initial investment and advanced technical expertise for operation and maintenance. Furthermore, the complexity of these systems can lead to operational challenges in smaller scale facilities or in regions with less developed technological infrastructure.

HPP effectively inactivates microorganisms and enzymes, thereby extending the shelf life of seafood products without compromising their sensory and nutritional properties. However, the high cost of HPP equipment and potential texture changes in some seafood products are limitations to consider (Ferri et al., 2023; Khouryieh, 2021).

PEF also operates on a nonthermal basis, applying short pulses of high voltage to increase the permeability of cell membranes, effectively inactivating bacteria and extending product shelf life. Despite its effectiveness, the technology's application to solid foods, including some seafood types, is currently limited due to technical challenges (Pérez-Won et al., 2023; Shiekh & Benjakul, 2020).

Ultrasound and PEF technologies have shown promise in improving the quality and safety of seafood products by enhancing mass transfer processes and inactivating microorganisms. However, their large-scale application can be challenging due to high energy consumption and potential alterations in sensory attributes (Khouryieh, 2021). Compared to other preservation methods such as thermal processing, ultrasound is a nonthermal method that does not require high temperatures or chemicals. This makes it a more cost-effective and environmentally friendly option for seafood processing (Yu & Xie, 2023). Furthermore, as ultrasound and PEF are among the emerging nonthermal technologies, they can maintain the nutritional and sensory qualities of seafood products better than traditional thermal processing methods (Khouryieh, 2021). However, many authors note that further research is needed to fully understand the potential drawbacks and limitations of using ultrasonication in seafood processing. For example, the effect of ultrasonication on sensory properties such as taste and odor needs to be examined further (Sireesha et al., 2022).

Nonthermal methods like ozone treatment have much potential for the seafood business, owing to the growing global demand for high-quality, minimally processed foods. However, as ozone is a strong oxidizing agent, it effectively inactivates microorganisms in seafood products but can also lead to oxidative changes, affecting sensory and nutritional properties (Qian, Zhang et al., 2022; Zhang et al., 2023; Zhao et al., 2022).

CP technology has shown promise as an antimicrobial treatment, acting rapidly to inactivate bacteria, yeasts, molds, and viruses. It also has the potential for surface sterilization, thus limiting cross-contamination. However, the technology is still in its infancy, and there is a need for more research on its impact on sensory attributes and nutritional properties of seafood.

PL and CP can inactivate surface microorganisms, extending product shelf life. However, their limited penetration depth and potential sensory property changes are drawbacks (Olatunde et al., 2021; Shiekh, Zhou et al., 2021). In fact, we noted that although they offer rapid disinfection, their penetration depth is limited, with reduced efficacy on thicker seafood products or those with irregular shapes.

LVEF technologies have shown potential for preserving seafood product quality. LVEF promotes ice crystal miniaturization, reducing tissue damage, whereas PF inhibits microbial growth and protein denaturation. However, high energy consumption and security concerns are potential LVEF limitations, whereas PF's specific temperature requirements may pose challenges in certain storage environments (Khouryieh, 2021; Zhang et al., 2023). Moreover, LVEF effects on the quality characteristics of food need to be studied in-depth.

PCS, instead, is an innovative production technology widely used in smoked meat products, but its application in seafood is limited. PCS is purified, appearing healthier without unhealthy substances, such as PAHs, ash, and tar. It gives better control and a more even distribution of the smoke flavor after being applied. However, the product quality and industrial usage of PCS on seafood need further exploration (Valø et al., 2020). Moreover, excessive usage can lead to undesirable changes in taste and the formation of potentially harmful compounds.

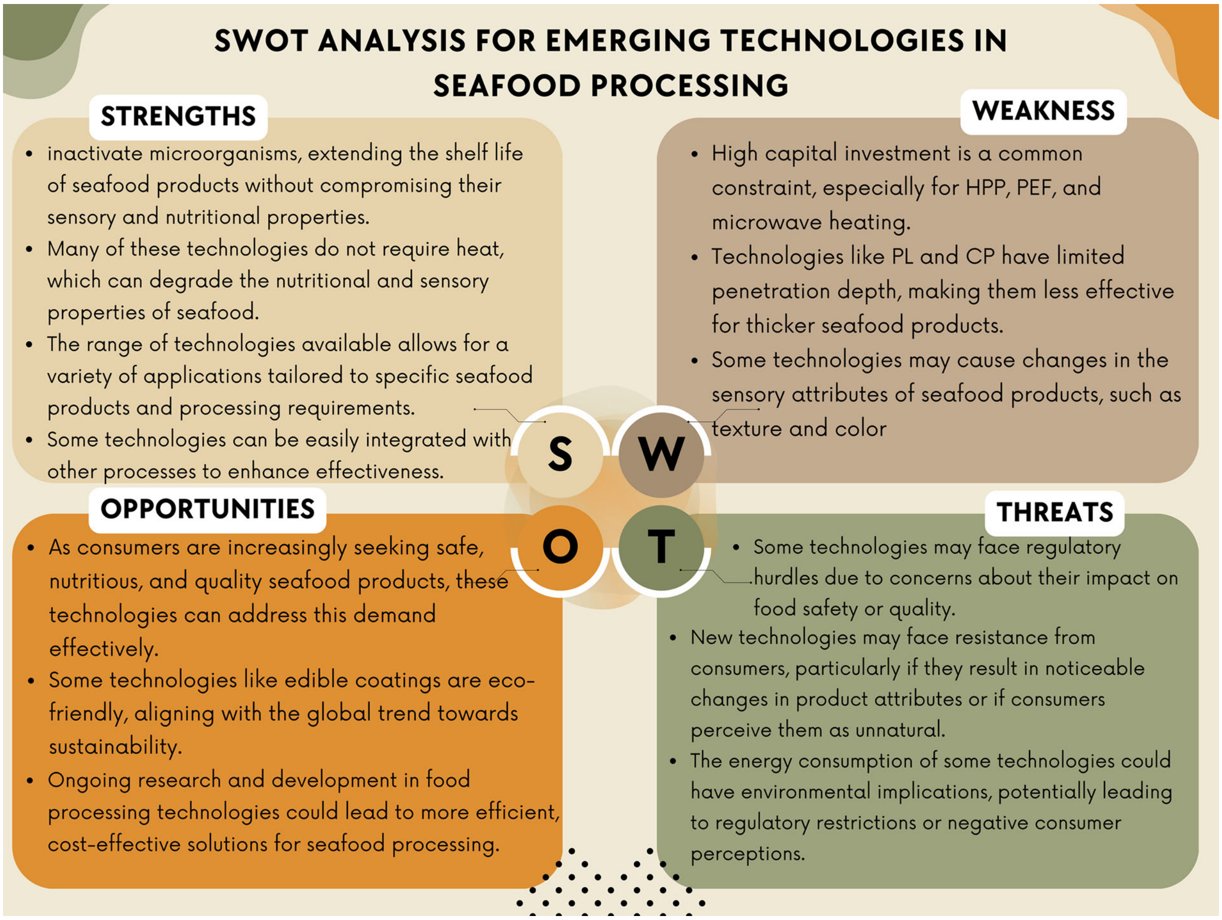
Packaging technologies present opportunities for wide-scale implementation due to their dual benefits of shelf-life enhancement and environmental sustainability. However, the development and adoption of these technologies would need to consider the trade-off among cost, performance, and sustainability. Active packaging technologies might offer superior food preservation but can add to the overall cost of the product. Similarly, biodegradable packaging, while environmentally preferable, might not provide the same level of protection as conventional packaging materials and could come with higher costs. Edible coatings could potentially bridge the gap between food preservation and sensory quality, by serving as a barrier to moisture, oxygen, and microorganisms, while possibly enhancing the product's taste and texture. However, more research is needed to fully understand the impact of these coatings on the sensory experience of consumers and their acceptability.

Based on these data, we can state that a technology can be judged "advanced" when its nature is a combination of novelty, efficiency, effectiveness, and capable to bring values to users or industries compared to existing solutions. The advanced nature of technology is gauged by its innovation, introducing novel solutions distinct from existing ones. It is marked by heightened efficiency, superior performance, and often a complex design. Adaptability to various conditions, seamless integration with other systems, and a focus on sustainability further characterize advanced technologies. Enhanced user experiences, robust safety and security measures, scalability, continuous research and development, and rapid market acceptance are also indicative of its advanced status.

Each technology shows promise for improving seafood processing, but further research is needed to address their limitations, identify optimal conditions, and explore possible synergistic effects with other technologies. Understanding their relative strengths and weaknesses will help processors choose the most suitable technology for a particular application.

4.1 | SWOT analysis

In order to provide a more holistic and nuanced understanding of the emerging technologies in seafood processing, we included a SWOT analysis in this literature review (Figure 4). This can be beneficial for researchers, industry professionals, and policy makers who are interested in the development and application of these technologies. Insights from this analysis reveal that the emerging technologies present many strengths over traditional methods, particularly in preserving quality and ensuring safety. In



SWOT ANALYSIS FOR EMERGING TECHNOLOGIES IN SEAFOOD PROCESSING

STRENGTHS

- inactivate microorganisms, extending the shelf life of seafood products without compromising their sensory and nutritional properties.
- Many of these technologies do not require heat, which can degrade the nutritional and sensory properties of seafood.
- The range of technologies available allows for a variety of applications tailored to specific seafood products and processing requirements.
- Some technologies can be easily integrated with other processes to enhance effectiveness.

WEAKNESS

- High capital investment is a common constraint, especially for HPP, PEF, and microwave heating.
- Technologies like PL and CP have limited penetration depth, making them less effective for thicker seafood products.
- Some technologies may cause changes in the sensory attributes of seafood products, such as texture and color

OPPORTUNITIES

- As consumers are increasingly seeking safe, nutritious, and quality seafood products, these technologies can address this demand effectively.
- Some technologies like edible coatings are eco-friendly, aligning with the global trend towards sustainability.
- Ongoing research and development in food processing technologies could lead to more efficient, cost-effective solutions for seafood processing.

THREATS

- Some technologies may face regulatory hurdles due to concerns about their impact on food safety or quality.
- New technologies may face resistance from consumers, particularly if they result in noticeable changes in product attributes or if consumers perceive them as unnatural.
- The energy consumption of some technologies could have environmental implications, potentially leading to regulatory restrictions or negative consumer perceptions.

FIGURE 4 Strength, weakness, opportunity, and threat (SWOT) analysis of emerging technologies in seafood processing. The figure illustrates the strengths, weaknesses, opportunities, and threats associated with the application of emerging technologies in the seafood industry.

fact, these emerging technologies offer a range of advantages over traditional methods, including improved shelf life, better retention of nutritional and sensory qualities, enhanced food safety, and greater energy efficiency. These advancements are crucial for meeting the growing consumer demand for high-quality, safe, and sustainable seafood products. Moreover, emerging technologies can enhance the taste, texture, and overall consumer acceptability of seafood products, unlike traditional processing (e.g., canning or standard freezing).

SWOT analysis is an approach used in strategic planning that focuses on identifying the strengths, weaknesses, opportunities, and threats of a particular field or topic. In the context of this literature review, a SWOT analysis is particularly useful for providing a thorough insight into the new technologies evolving in the sector of seafood processing. In terms of strengths, these technologies offer a plethora of benefits that traditional methods fail to provide, most notably in preserving the quality and ensuring the safety of seafood products. The ability of these technologies to maintain the nutritional and organoleptic properties of seafood addresses a major challenge faced by the industry. Additionally, the technologies' efficacy in extending shelf life and ensuring microbial safety is commendable. Technologies like HPP, ultrasound, PEF, plasma, PL, and LVEF are particularly effective in eliminating harmful microorganisms. Additionally, some of these technologies stand out for their energy efficiency and their integration capabilities. In fact, the integration capabilities exhibited by some technologies, such as combining vacuum cooking with PCS, or integrating microwave heating with induction heating, increase their strengths and make them more interesting for potential producers. The utilization of these technologies also opens up new opportunities for innovative product development and market differentiation.

However, these technologies also have weaknesses that cannot be overlooked. In fact, despite their advantages, these technologies also present certain flaws. The high investment required for equipment and energy can deter smaller businesses. Furthermore, for some emerging technologies like plasma and LVEF, the understanding of their impact on seafood quality and their potential applications is still incomplete, necessitating further research. Additionally, some technologies may lead to changes in sensory attributes, such as texture, flavor, and color, which could affect consumer acceptance (Khouryieh, 2021).

Opportunities are abundant in the landscape of emerging technologies in seafood processing. With a growing demand for safe, nutritious, and high-quality seafood products, these technologies offer excellent solutions. Certain technologies such as edible coatings exhibit strong sustainability credentials, aligning well with global trends toward environmentally friendly food production. Moreover, there is also vast potential for the creation of new processing techniques through combination strategies, known as hurdle technology. PCS and other nonthermal technologies can lead to healthier products, free from harmful substances like PAHs, ash, and tar. This can help companies differentiate their products in the market, offering consumers high-quality, safe, and innovative seafood products. Regulatory backing, such as that seen with the European Union's support for PCS, may further ease the integration of these technologies in the industry (European Commission, 2020).

However, potential threats need to be considered. Regulatory issues might surface, especially concerning food safety and health claims. Consumers might not automatically accept products made with these new methods, especially if significant changes in quality are perceptible. Technical difficulties tied to large-scale usage may demand significant capital and training, and traditional preservation techniques, which might provide more cost-effective alternatives, could hinder the uptake of these innovative technologies.

4.2 | Future perspectives

The future of seafood processing technologies seems to be heading toward the development and application of innovative, nonthermal, and environmentally friendly methods that can ensure the safety and quality of seafood products while extending their shelf life. The advancements in nonthermal technologies are reshaping the seafood industry, offering significant improvements in product shelf life, taste, and nutritional value.

As the demand for high-quality, safe, and convenient seafood products continues to grow, these emerging technologies are expected to play a crucial role in meeting these needs. They provide an alternative to conventional heat treatments that minimize loss and maintain sensory properties (an advantage that is particularly valuable for the seafood industry).

However, for these technologies to fully realize their potential, further research and development are necessary. Extensive studies should explore the optimal operative conditions for these techniques, their impact on different types of seafood species, and how they affect sensory attributes. Additionally, investigations on the synergistic effects of combining different emerging technologies would be beneficial for the advancements of seafood processing.

Given the increasing environmental concerns, the industry should also focus on the sustainability of these technologies. Energy-efficient and water-saving techniques will likely gain popularity, further driving innovation in this sector.

Furthermore, successfully implementing of these techniques in terms of safety, quality assurance, and sustainability will be crucial, in building trust with consumers.

Lastly, economic feasibility will play a significant role in the widespread adoption of these technologies. Although it is true that certain technologies require investments, it is important to weigh the long-term advantages they bring in terms of improved product quality, enhanced safety measures, and extended shelf life (Khouryieh, 2021).

To summarize all the indications for seafood producers extrapolated from this literature review, a five-point timeline for a possible implementation of emerging technologies in seafood industry has been reported in Figure 5. Moreover, a decision matrix has been elaborated to aid decision-makers of seafood industry to select appropriate technologies for different contexts (Supplementary materials).

First, a thorough understanding of the technology allows for an accurate assessment of its capabilities and limitations. This is crucial for determining whether the technology can meet the specific needs of the seafood processing operation. For example, some technologies might be effective for certain types of seafood but not others, or they might require specific conditions to operate effectively. Understanding the technology and its potential impacts on product quality and safety is not just a preliminary step in the adoption of new technology in seafood processing, but a continuous requirement that underpins the entire operation. It is a dynamic process that requires ongoing learning and adaptation as the technology and the regulatory landscape evolve.

However, a feasibility study is required for each technology studied, as it is a crucial step in the adoption of emerging technologies in the seafood industry. In fact, it serves to assess the practicality and economic viability of implementing these technologies in a real-world setting.

Future directions in seafood processing technology should focus on enhancing the efficiency and cost-effectiveness of these techniques, exploring potential

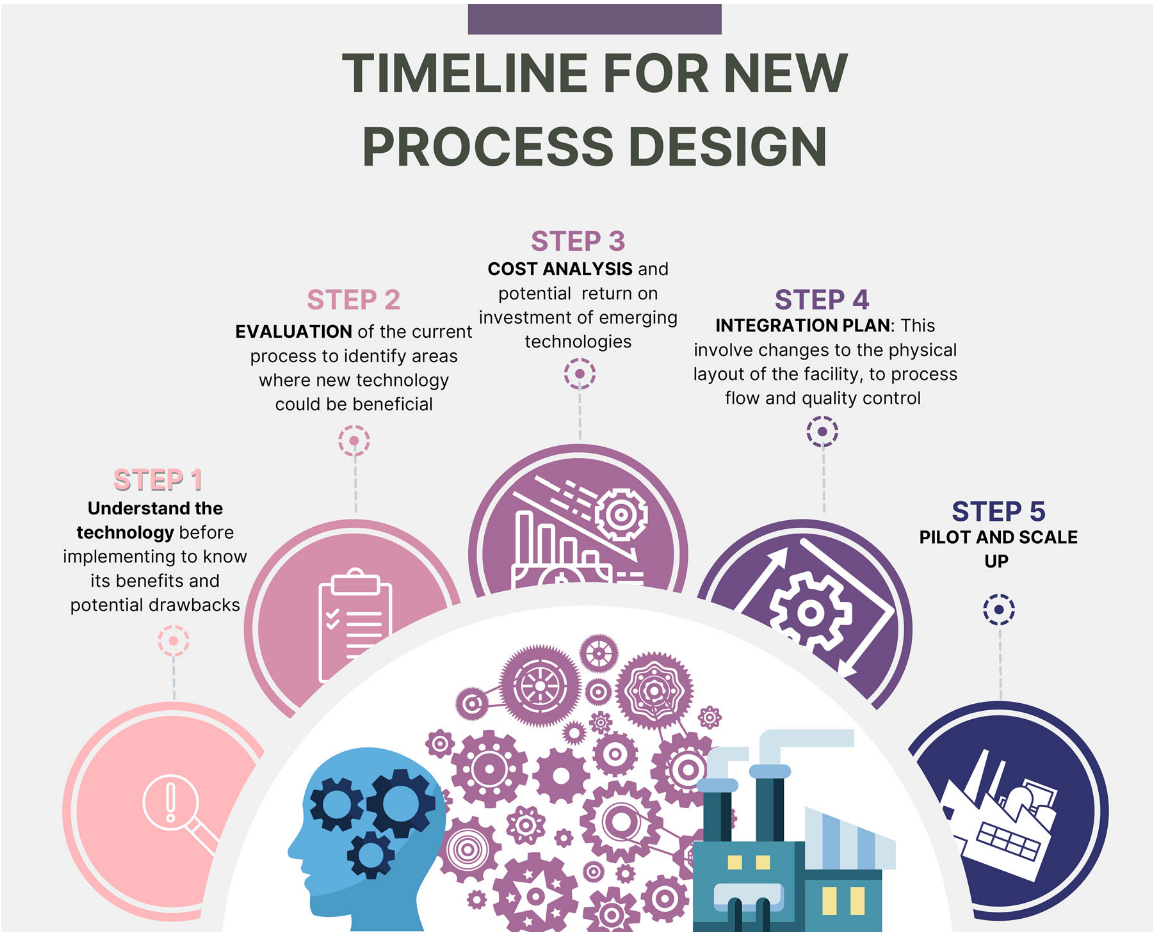


FIGURE 5 Roadmap for implementation of emerging technologies in seafood processing.

synergies between them, and conducting in-depth investigations into their impacts on different seafood species and products. Consumer education and clear communication about these technologies' benefits are also critical to gaining market acceptance.

5 | CONCLUSIONS

The seafood industry is of significant economic importance globally, and yet it faces numerous challenges, such as food safety, environmental sustainability, and pressures from consumer demands for fresh and minimally processed products. The future of seafood processing lies in leveraging these emerging technologies to deliver high-quality, safe, sustainable, and consumer-acceptable products. However, this will require a multifaceted approach, combining rigorous scientific research, effective regulations, consumer education, and thoughtful economic planning.

In conclusion, although each technology demonstrates distinct advantages, their comparative analysis reveals that no single approach is superior in all contexts. Each technology's efficacy is contingent on specific application conditions and seafood product types, requiring careful optimization to ensure the best outcome. Furthermore, each comes with its own set of challenges, such as high initial investment costs, regulatory constraints, and the necessity of consumer acceptance. The choice of technology would depend on the specific requirements of the seafood product, the available resources, and the desired quality attributes.

Although we are witnessing promising advancements in the field of seafood processing technologies, it is vital to remember that achieving the desired balance among product safety, quality, sustainability, and consumer acceptability is a complex task that requires a multifaceted approach. Therefore, it is recommended that future research focuses on overcoming these obstacles, with an emphasis on strategies for efficient upscaling and investigating consumer perceptions. Research should also address the potential synergistic effects of combining these technologies, aiming to maximize their benefits while minimizing any possible drawbacks.

AUTHOR CONTRIBUTIONS

Giovanni Luca Russo: Conceptualization; writing—original draft; software; visualization; methodology; data curation; formal analysis; investigation. **Antonio L. Langellotti**: Conceptualization; investigation; writing—review and editing; visualization; validation; supervision; resources. **Elena Torrieri**: Investigation; writing—review and editing; validation; supervision; resources; data curation. **Paolo Masi**: Writing—review and editing; validation; visualization; funding acquisition; project administration; resources.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

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SUPPORTING INFORMATION

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