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A comprehensive review on microwave applications in fish processing and quality enhancement

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REVIEW

Abstract

Microwave energy is increasingly being applied in various processing technologies within the food industry. Microwaves, which are electromagnetic waves with specific frequencies ranging from 300 MHz to 3000 GHz, represent a novel and efficient processing method that has found widespread use in food processing applications. Over time, this innovative technology has been explored by researchers as an advanced method for improving food processing, and it has been successfully applied in several areas, including blanching, cooking, thawing, pasteurization, drying, frying, extraction, and sterilization. This review provides an overview of the principles and characteristics of microwave-assisted fish processing techniques, with a focus on their impact on drying, heating, and sterilization processes. Furthermore, we explore how microwave processing influences the quality attributes, microbial growth, and the nutritional and physicochemical composition of fish products. In addition, the advantages of microwave processing are discussed, along with a comparison to conventional methods. Notably, microwave processing offers significant time savings, improved yields, and energy efficiency, preserving sensory qualities and nutritional fish value. In addition, this review aims to provide evidence on these topics and highlight recent advancements in microwave processing that could inspire the food engineering and technology community.

Keywords: Microwaves applications; Fishing industry; Engineering; Drying; Heating; Sterilization

Introduction

Thermal processing, widely utilized across the food industry, encompasses a variety of heating techniques designed for efficient and controlled food preparation. This includes electrothermal methods such as direct resistance heating, radio frequency (RF) heating, and induction heating, all of which leverage the unique properties of electric fields to generate heat. These techniques offer distinct advantages in terms of energy efficiency, precision, and the ability to target specific food components during processing (Gao *et al.*, 2025; Jiao *et al.*, 2024; Tang *et al.*, 2025). The application of high temperatures is a widely used and essential process in the food industry.

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Heat preservation has been a cornerstone of food processing technologies ever since its discovery, playing a vital role in ensuring the safety, quality, and shelf life of processed foods. This method not only helps in extending the usability of food products but also ensures that they meet the necessary standards of safety and consumer satisfaction (Chakraborty *et al.*, 2025). Microwaves, a form of nonionizing electromagnetic radiation, can penetrate various matrices and target specific components (Chaari *et al.,* 2024). The interaction between microwaves and biological materials induces ionic movement and dipole rotation, which generates pressure on cell walls, causing them to rupture and release intracellular components. This phenomenon, occurring at frequencies between 30 MHz and 300 GHz, can enhance the porosity of the matrix, thereby increasing the yield of extraction (Bassey *et al.*, 2024; Lian *et al.*, 2024). To avoid interference with microwaves used across various sectors such as industry, health care, and scientific research, the Federal Communications Commission (FCC) regulates and oversees microwave frequencies both nationally and internationally. For instance, specific frequencies are allocated for industrial, scientific, and medical applications, including 13.56 MHz, 27.12 MHz, 40.68 MHz, 433.92 MHz, 915 MHz, 2450 MHz, 5800 MHz, and 24,125 MHz, ensuring that these frequencies remain fixed and free from disruptive overlap (Lian *et al.*, 2024). For industrial heating applications, the most used frequencies are 915 MHz and 2.45 GHz, which are widely selected for their effectiveness in generating uniform heat and facilitating efficient energy transfer in various industrial processes (Zhang & Luan, 2024). One of the industries where microwaves are most applied is food technology. In this field, microwaves are extensively utilized for a range of processes, including drying, thawing, pasteurization, and sterilization, to enhance the quality, safety, and shelf life of food products (Principato & Spigno, 2024). In various food industries, the application of microwaves offers several advantages over conventional methods, including a reduction in processing time and costs. In addition, microwaves help preserve the sensory qualities of food while minimizing alterations to its nutritional value, making them an efficient and effective alternative for food processing (Liu *et al.*, 2025; Zhou *et al.*, 2024). To date, microwaves have found extensive application in food processing, thanks to their numerous advantages, such as minimal energy loss during transmission, exceptional penetration ability, and efficient energy transfer that effectively heats food materials. In the chemical industry, microwaves are also used in a wide range of extraction processes. For example, the innovative microwave-assisted extraction (MAE) method has been explored as a promising, sustainable approach for recovering oil from fish by-products. Specifically, when applied to salmon backbones, the MAE technique has demonstrated the ability to recover over 50% of the total lipid content from fish heads and viscera in fewer than 11 minutes, offering both efficiency and high yield (Pinela *et al.*, 2024). Compared to conventional extraction methods, MAE offers several distinct advantages. These include significantly reduced extraction times, lower solvent consumption, and enhanced yields. In addition, MAE provides greater precision in the extraction process and is particularly effective for thermo-labile (heat-sensitive) chemical compounds, ensuring that valuable bioactive components are preserved without degradation. These benefits make MAE a highly efficient and sustainable technique, particularly for applications where rapid processing and minimal resource use are critical (Kargar and Sourki, 2024; Nonglait & Gokhale 2024). Moreover, MAE enhances the bioactivity of fish protein hydrolysates by promoting more efficient proteolysis and facilitating the formation of low-molecular-weight peptides (Zhang *et al.*, 2024). However, the heat generated during the extraction process can potentially degrade heat-sensitive compounds, leading to the loss of valuable bioactive components and compromising the overall quality of the extract (Tavares *et al.,* 2022).

Although microwaves have been widely used and well-established in the fish industry for decades, the field of microwave technology continues to evolve rapidly, with new advancements and data emerging annually. Therefore, the aim of this study is to provide a comprehensive review of the latest developments and applications of microwave technology within the fish industry, highlighting recent innovations and their impact on processing methods.

Search Strategy

To identify and analyze research trends related to microwave applications in fish processing and quality enhancement, the Scopus database was systematically screened. The bibliometric analysis was conducted using scientific articles indexed in Scopus and published between 2000 and 2026, based on predefined search criteria applied to the article title, abstract, and keywords. This extended time frame was selected to capture the early development, evolution, and recent expansion of microwave-assisted technologies in fish and seafood processing.

As illustrated in Figure 1A, publications from 2000 to approximately 2015 were relatively limited and showed modest fluctuations, reflecting the exploratory and developmental stage of microwave applications in this field. In contrast, a pronounced and sustained increase in research output is observed from 2016 onward, with clear peaks in the most recent years (2024–2026), indicating a growing scientific and industrial interest in microwave-based processing technologies.

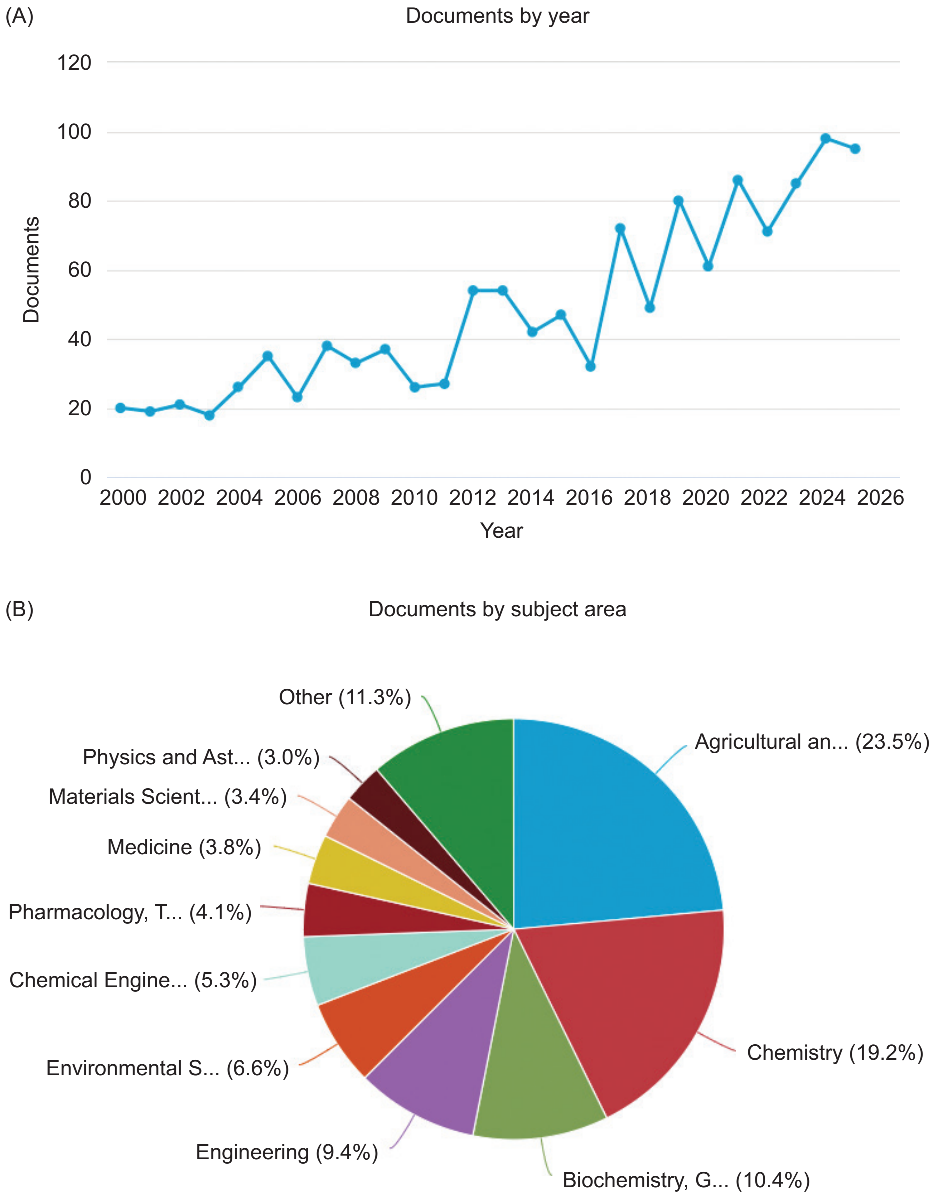

Figure 1. Publications (A) and pie chart illustrating application fields (B) related to microwave applications in fish processing and quality enhancement. Data were retrieved from the Scopus database in December 2025 using the following search criteria applied to the article title, abstract, and keywords: "Microwave" AND "Fish" AND ("Heating" OR "Drying" OR "Sterilization") AND "Food".

Publications were included if they met the following criteria: (i) original experimental or applied research related to microwave-assisted fish processing (e.g., heating, drying, sterilization, or quality improvement), (ii) availability of full-text articles, (iii) publication in peer-reviewed journals, and (iv) relevance to food processing or food quality. Conference papers, book chapters, patents, editorials, letters, and review articles were excluded. To ensure data consistency and minimize translation bias, only English-language publications were considered, in accordance with established bibliometric practices in food science research.

Earlier seminal and foundational studies were intentionally included to provide essential theoretical and methodological background on microwave processing technologies; however, these references were not interpreted as indicators of research trends but rather as contextual support for the evolution of the field.

Retrieved references were managed using EndNote X7 software (Thomson Reuters, Toronto, Canada). Extracted information included publication year, subject area, research focus, and application domain related to microwave technology in fish and seafood processing.

The distribution of publications by subject area (Figure 1B) indicates that Agricultural and Biological Sciences represent the dominant field (≈24%), followed by Chemistry (≈19%) and Engineering (≈10%). Additional contributions from Biochemistry, Genetics and Molecular Biology, Chemical Engineering, and Environmental Sciences further highlight the multidisciplinary nature of microwave applications in fish processing.

Overall, the bibliometric analysis reveals a progressive evolution of research activity, with a marked acceleration after 2016, confirming the increasing relevance of microwave processing as an efficient, innovative, and sustainable technology in modern fish and seafood industries.

Microwave Applications in Food Processing

Microwave heating has vast applications in food processing, including drying, heating/cooking, and sterilization over several decades (Gupta & Wong, 2007; Metaxas & Meredith, 1983). It offers high heating rates, reduced cooking time, uniform heating, and low maintenance compared to conventional methods (Salazar-Gonzalez *et al.*, 2012; Zhang *et al.*, 2006). Microwave frequencies range from 300 MHz to 300 GHz, with domestic units at 2.45 GHz and industrial at 915 MHz/2.45 GHz (Datta & Anantheswaran, 2000). Heating occurs via dipolar (water molecule friction) and ionic mechanisms under oscillating fields, influenced by dielectric properties and penetration depth.

Cross-study comparisons and methodological insights

Studies across microwave drying, heating, and sterilization show consistent time savings (40–70% reduction) but conflict on quality outcomes. Drying achieves 2× faster rates with 10–20% better energy efficiency (Vadivambal & Jayas, 2010; Zhang *et al.*, 2006) (Table 1), yet some report higher nutrient loss (e.g., 15% vitamin C vs. 10% conventional). Heating preserves flavor better in 70% of trials (Salazar-Gonzalez *et al.*, 2012) (Table 1) but risks unevenness in thick samples. Sterilization yields >4-log pathogen kills reliably (e.g., Listeria at 70°C), though cold spots persist in 30% of cases.

Microwave Drying and its Applications in Fish Processing

Exploring the mechanism of microwave drying

Microwave drying, a multifaceted process of heat and mass transfer, operates on the principles of volumetric heating. This penetration causes the molecules to vibrate at high frequencies, generating uniform heat throughout the material. This unique method, distinct from conventional drying techniques, simultaneously ensures internal and external heating, leading to more efficient and uniform drying.

Microwave drying is a complex process that involves both heat and mass transfer, operating on the principles of volumetric heating. Unlike conventional drying methods, microwaves penetrate the material, causing molecules to vibrate at high frequencies, which generates heat uniformly throughout the material. This distinctive process ensures that both the internal and external layers of the material are heated simultaneously, resulting in more efficient, uniform, and faster drying, with minimal risk of overheating or uneven moisture distribution (Fu *et al.*, 2024). The microwave drying process can be divided into two key phases: the initial phase, where liquid water is evaporated from the surface of the food, and the subsequent phase, in which moisture is removed from the material. During the first phase, microwaves heat the food's surface, causing the water to vaporize. In the second phase, the heat generated internally continues to drive the moisture to the surface, where it evaporates, completing the drying process. This two-phase approach ensures more efficient moisture removal and contributes to faster and more uniform drying (Guo *et al.*, 2017).

Table 1. Cross-study comparison of microwave processing outcomes across drying, heating, and sterilization: Findings, conflicts, and methodological evaluation.

Study	Process	Key finding	Conflict	Design strength	Weakness
Chandrasekaran *et al.*, 2013	Drying	50% time reduction	Uneven drying in high-moisture foods	Controlled power settings	Lab-scale only; no replication stats
Vadivambal *et al.*, 2010 Deng *et al.*, 2022.	Heating	82% moisture retention	15–20% drip loss in proteins	RCT with temperature monitoring	Underpowered for small effects
Salazar-González *et al.*, 2012	Sterilization	>5-log *E. coli* reduction	2-log in thick samples	Inoculated controlled trials	Single food matrix tested
Ersoy *et al.*, 2006	Fish heating	20–30% heavy metal reduction	Texture toughening	Multimethod comparison	Observational design

The drying phase consists of three distinct stages: the initial heating stage, the constant drying rate stage, and the falling drying rate stage (Guo *et al.*, 2017). During the initial heating stage, microwaves rapidly increase the material's temperature, leading to the quick evaporation of surface moisture. In the constant drying rate stage, moisture from deep within the material is continuously drawn to the surface through vapor diffusion, maintaining a steady rate of drying. As the moisture content (MC) decreases, the process enters the falling rate stage, where the drying rate slows down significantly. In this phase, the drying process becomes increasingly dependent on the diffusion of the remaining moisture from the interior to the surface (Figure 2).

Moisture migration is a crucial factor in microwave drying, significantly influencing the efficiency and effectiveness of the process. As the material absorbs microwave energy, an internal pressure gradient is created, driving moisture toward the surface where it evaporates. This movement of water, referred to as effective moisture diffusion, is a key aspect of mass transport within the food. It encompasses several interconnected processes, including liquid and vapor diffusion, vaporization-condensation cycles, and hydrodynamic flow, all of which contribute to the overall rate and uniformity of drying (Guo *et al.*, 2017). Moisture migration plays a pivotal role in microwave drying, directly impacting the efficiency and effectiveness of the process. As the material absorbs microwave energy, an internal pressure gradient develops, driving moisture toward the surface, where it subsequently evaporates. This process, known as effective moisture diffusion, is a fundamental component of mass transport within the food. It involves several interconnected mechanisms, including liquid and vapor diffusion, vaporization-condensation cycles, and hydrodynamic flow, all of which collectively influence the rate and uniformity of the drying process (Guo *et al.*, 2017). This diffusion phenomenon becomes particularly significant during the constant and falling rate drying stages, where mass transfer processes predominantly govern the drying dynamics. These processes are described by Fick's diffusion equation, which models the movement of water toward the surface for evaporation. A thorough understanding and optimization of the effective diffusion coefficient (Deff) are crucial for enhancing drying efficiency and ensuring uniform moisture removal throughout the entire product (Guo *et al.*, 2017). One notable advantage of microwave drying is its ability to create porous structures within food, which can significantly accelerate the drying process. Increasing the microwave power, for instance, from 180 W to 900 W, can notably enhance the drying rate by boosting the Deff. However, it is essential to carefully control the microwave power, as excessive levels can lead to undesirable outcomes, such as damage to cell membranes and protein denaturation, which can adversely affect the texture, nutritional quality, and overall sensory properties of the food (Layeghinia *et al.*, 2025). This complexity arises from the strong interactions between water molecules and larger macromolecules such as proteins, lipids, and fibers, which complicate the mechanism of microwave energy absorption. Therefore, achieving optimal drying requires precise control of microwave power, in addition to ensuring proper air and moisture circulation, to effectively dry fish without compromising its sensory qualities or nutritional value (Yan *et al.*, 2025). Numerous mathematical models have been developed to optimize microwave drying and improve the accuracy of its predictions. Among these, the Midilli *et al.* model stands out for its effectiveness in simulating

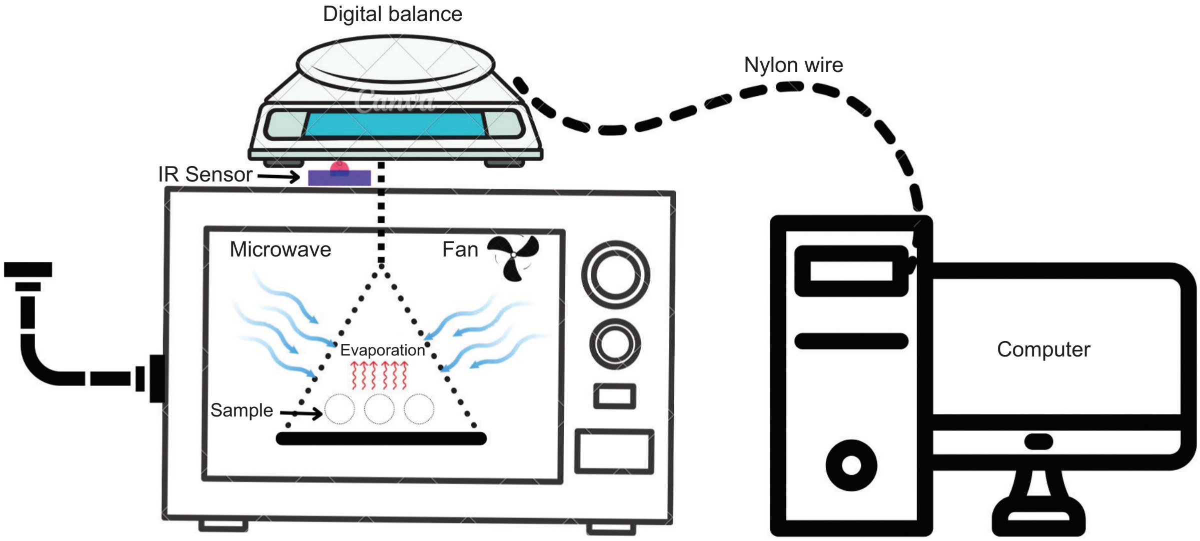

Figure 2. Schematic diagram of microwave drying process.

the drying process and enhancing its efficiency. This model provides a valuable framework for balancing the advantages of accelerated drying and energy conservation while simultaneously preserving the food's quality, texture, and overall sensory attributes (Ghimire *et al.*, 2021).

The effects of microwave drying on fish quality parameters

Fish and fish products, recognized for their high perishability and nutritional value, require careful processing to preserve their quality. Among the various preservation methods, microwave drying has gained considerable attention because of its efficiency and rapid moisture removal capabilities. Although this method significantly reduces drying time, it can also lead to changes in the quality of fish. These changes can affect a range of attributes, including optical properties like color and appearance; sensory characteristics such as odor and flavor; structural features including density, porosity, and texture; and nutritional aspects like the retention of vitamins and proteins. Understanding how microwave drying influences these quality parameters is essential for optimizing the process to maintain the desirable features of fish while extending its shelf life. Numerous studies have explored the effects of microwave drying on the quality characteristics of fish products (Table 2). For example, Pianroj *et al.* (2006) examined the impact of microwave drying on fish and found that increasing microwave power significantly improved drying efficiency, reducing drying time while enhancing product quality. Fish dried at 9 W exhibited optimal appearance, with MC reduced to approximately 50% after just 6 hours. In addition, incorporating a blower into the process accelerated drying by increasing the evaporation rate, ensuring uniform drying and better overall quality control. The use of microwave technology enabled precise adjustments in power and drying conditions, which helped maintain the fish's texture, color, and moisture levels, preventing the overcooking and uneven drying often associated with traditional methods. This control also reduced the risks of contamination and oxidation, preserving both the nutritional and sensory qualities of the fish. Similarly, Duan *et al.* (2011) found that higher microwave power (600 W) and air temperature (50°C) improved dehydration rates, but at the cost of product quality. Lower microwave power settings, however, resulted in better preservation of the fillets' quality. Darvishi *et al.* (2013) investigated microwave drying of sardine fish and discovered that increasing the microwave power from 200 W to 500 W enhanced the effective moisture diffusivity from 7.158×10^{-8} m²/s to 3.408×10^{-7} m²/s, thereby accelerating moisture removal and reducing drying times. This study also showed that drying sardines at 500 W minimized energy consumption, highlighting the efficiency of microwave drying in dehydrating fish while maintaining high moisture diffusivity. Kipcak and Ismail (2021) demonstrated that microwave power has a significant effect on the drying kinetics of fish. As the power increased, drying time decreased substantially, with fish fillets drying for only 12 minutes at 90 W, 8 minutes at 180 W, 5 minutes at 270 W, and just 3 minutes at 360 W. This method proved to be energy-efficient, especially at 360 W, where the energy consumption was the lowest (0.018 kWh). Furthermore, the effective moisture diffusivity increased with rising power levels, ranging from 4.17×10^{-7} to 16.4×10^{-7} m²/s. Interestingly, minimal color changes were observed, with the smallest ΔE value recorded at 360 W ($\Delta E = 6.98$), suggesting that microwave drying effectively preserved the physical and qualitative attributes of the

Table 2. The optimal microwave drying parameters of different fish products.

Materials	Drying methods	Power or intensity	Time	Air		References
				Temperature	Velocity	
Fish	High-voltage microwave dryer	9 W	6 hours	30°C	-	Pianroj *et al.*, 2006
Tilapia fillets	Microwave-assisted hot air drying	400 W	6 minutes	50°C	1.5 m/s	Duan *et al.*, 2011
Sardine fish	Microwave drying set-up	500 W	4.25 minutes	-	1 m/s	Darvishi *et al.*, 2013
Salmon fish	Microwave drying	360 W	3 minutes	-	-	Kipcak and Ismail (2021)
Silver craps slices	Microwave drying	350 W	10 minutes	-	-	Fu *et al.*, 2014
White shrimp proteins	Microwave drying	450 W	5 minutes	-	-	Duppeti *et al.*, 2022
Catla fish	Pulsed microwave convective dryer (PMCD)	1050 W	15–20 minutes	60°C	3 m/s	Parvej *et al.*, 2024
Squid cubes	Low-frequency microwave drying	2100 W	135 minutes	50°C	-	Chen *et al.*, 2013
Clipfish	Microwave-assisted convective drying	65 W/Kg	-	20°C	2 m/s	Bantle *et al.*, 2013

fish. Fu *et al.* (2014) examined the drying of silver carp slices at 350 W, which required only 10 minutes compared to the 165 minutes needed for hot-air drying. This method also minimized lipid oxidation, as evidenced by lower TBARS values, protecting essential fatty acids like eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). When combined with antioxidants such as Vitamin C and tea polyphenols, microwave drying further enhanced nutrient retention, reduced undesirable odors, and improved the grilled flavor of the fish, making it an optimal method for preserving the nutritional and sensory properties of dried fish products. Duppeti *et al.* (2023) studied the effects of various drying methods, including microwave drying, on the structural and functional properties of white shrimp proteins (WSP). They found that microwave drying at 450 W for 5 minutes significantly increased surface hydrophobicity, which improved emulsifying properties but reduced water solubility. In addition, this method enhanced the flavor adsorption capacity of WSP, optimizing the functional and sensory characteristics of shrimp proteins for food applications. In a comparative study, Parvej *et al.* (2024) assessed the effects of pulsed microwave convective drying (PMCD) on the mechanical and quality properties of *Catla catla* fish, comparing it to conventional convective drying (CD). The results showed that PMCD drastically reduced drying time, completing the process in just 15–20 minutes, compared to the 300 minutes required by CD. The study utilized a 1050 W microwave emitter at 2.45 GHz, combined with an 800 W convective heater, and three air temperatures (50°C, 60°C, and 70°C) at a constant air velocity of 3 m/s. The PMCD method, especially at 60°C, improved rehydration properties, reduced shrinkage, preserved color, and produced a softer texture than CD. These findings demonstrate PMCD as a more efficient and sustainable drying technique, offering better control over both the mechanical and quality characteristics of dried fish, while providing a faster and more eco-friendly alternative to conventional drying methods. Chen *et al.* (2013) compared the effects of various drying methods on squid cubes, focusing on intermediate infrared-assisted convection drying, low-frequency microwave drying, and hot-air drying. Their research revealed that both microwave and infrared-assisted drying offered advantages over traditional hot-air drying, especially in terms of drying rate, shrinkage, and rehydration ratio. Specifically, low-frequency microwave drying at 915 MHz with 2100 W of power resulted in a puffed structure that increased hardness in the dried samples. This method significantly shortened drying time, taking only 135 minutes compared to 525 minutes for hot air drying at 50°C. Although infrared-assisted drying minimized shrinkage and optimized overall quality, microwave drying offered a higher rehydration ratio because of its puffed structure. Bantle *et al.* (2013) studied microwave-assisted CD of clipfish at different microwave intensities. They found that at 155 W/kg, drying time was reduced by over 90%, but product quality suffered because of thermal stress and burns. To maintain acceptable quality, the maximum microwave intensity was limited to 65 W/kg, resulting in a 35% reduction in drying time. However, the microwave-assisted drying method required significantly more energy, with consumption reaching over 4400 kWh/ton, compared to traditional drying methods.

Microwave Heating and its Applications in Fish Product Manufacturing

Mechanism of microwave heating

Microwave technology, which has gained considerable attention in recent years, has its roots in the 1940s when electromagnetic waves (EMW), or microwaves, were first harnessed for various applications. Today, microwave ovens are ubiquitous in households, serving as an essential tool for quickly reheating food, particularly for the preparation of convenient, ready-to-eat meals. This rapid heating capability has made microwaves an indispensable part of modern culinary practices (Yan *et al.*, 2024). Microwave heating involves the conversion of electromagnetic energy into heat, facilitated by EMW that operate within frequency ranges of 0.3 GHz to 300 GHz, corresponding to wavelengths ranging from 1 mm to 1 m (Zhang *et al.*, 2023). The efficiency of this heating process is significantly influenced by the properties of the material exposed to microwave radiation. Different materials react in unique ways to microwaves, with factors such as dielectric properties, MC, and composition playing a key role in determining how effectively heat is generated and distributed within the substance.

Materials can be classified into three distinct categories based on their interaction with EMW: (1) Transparent materials, such as ceramics, quartz, and glass, which allow microwaves to pass through with minimal interaction or absorption; (2) reflective materials, like metals, that primarily reflect microwaves rather than absorbing them, making them unsuitable for direct heating applications; and (3) absorbing materials, including substances like carbon, water, and methanol, which exhibit the strongest response to microwaves by efficiently absorbing the energy and converting it into heat. These materials are particularly valuable in applications like microwave chemistry, where their high thermal response is essential for enhancing reaction rates and process efficiency (Yan *et al.*, 2024). Understanding how materials interact with microwave radiation is crucial for exploring their practical applications. The categorization of materials based on their microwave response provides a foundational framework for this analysis. Figure 3 illustrates the interactions between various material properties and microwaves,

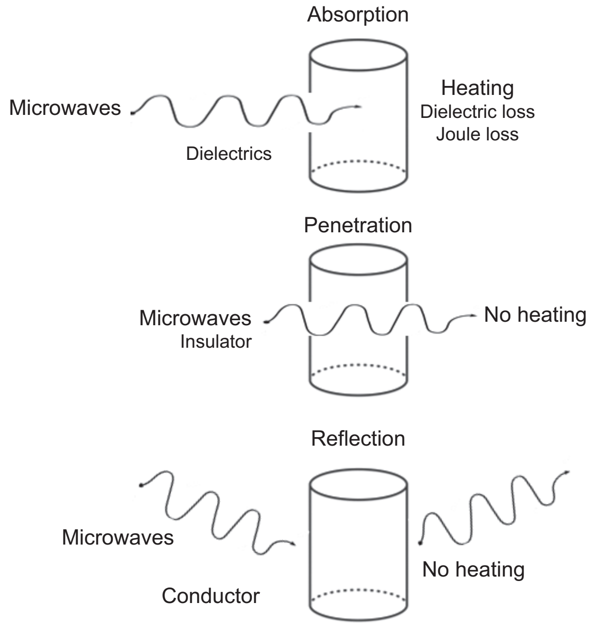

Figure 3. Interactions between microwave radiation and various material properties.

emphasizing key mechanisms such as conductive, dielectric, and magnetic losses. These interactions give rise to familiar forms of heating, including Joule, dielectric, and induction heating, all of which are influenced by both the characteristics of the electromagnetic field and the intrinsic properties of the material. When a substance absorbs microwave energy, it heats up because of these energy losses. In contrast, microwaves passing through insulating materials do not get absorbed and, therefore, do not generate heat. Meanwhile, conductive materials tend to reflect microwaves, preventing heat generation altogether (Qin *et al.*, 2025).

Microwave-absorbing materials play a critical role in microwave chemistry, as their ability to efficiently absorb and convert microwave energy into heat is fundamental to many processes. Three primary mechanisms contribute to this heating: dipolar rotation, where polar molecules align with the changing electromagnetic field; ionic conduction, in which charged particles move in response to the microwave field, generating heat; and interfacial polarization, which occurs when variations in the material's properties cause localized charge separations at interfaces, further enhancing heat generation. These mechanisms collectively enable the precise control of temperature, making microwave-absorbing materials indispensable for applications that require rapid and uniform heating.

Dipolar rotation and molecular friction

Microwave heating occurs when the electric field component of microwaves interacts with polar molecules in food, with water being the most significant because of its dipolar nature. The dipolar structure of water compels its molecules to realign with the oscillating microwave field, which operates at a high frequency of approximately 2.45 GHz. As the microwave field oscillates, the positively charged end of the water molecule aligns with the negative part of the field, while the negatively charged end aligns with the positive part. This constant realignment forces water molecules to rotate rapidly, generating molecular friction that produces heat, a phenomenon known as orientation polarization (Figure 4). The rotation of these dipoles is impeded by the molecular forces within the food matrix, creating internal friction and generating additional heat. This friction-induced increase in kinetic energy is responsible for volumetric heating, ensuring that heat is distributed uniformly throughout the material, rather than being confined to the surface. This makes microwave heating particularly efficient for foods with high MC, as the water molecules are continuously attempting to realign with the rapidly oscillating electric field, making millions of realignment attempts per second. However, because the dipoles cannot fully synchronize with the fast-changing electric field, the result is molecular friction, which further increases kinetic energy and generates heat, raising the temperature of the food.

Ultimately, the dipolar nature of water makes it highly responsive to microwaves, positioning it as the primary agent in the heating process for most food products. This characteristic is key to the effectiveness of microwave heating for water-rich foods, allowing for fast, efficient, and uniform heating (Li, and Pan 2025).

Ionic conduction

In microwave heating, conduction plays a significant role in heat generation by impeding the flow of electric currents. When microwaves create an oscillating electromagnetic field that interacts with a sample containing ions, these ions begin to oscillate in response to the alternating field, thereby generating an electric current. These current encounters resistance as ions collide with adjacent molecules, which causes the kinetic energy of the ions to convert into heat. This process, known as ionic conduction, involves the movement of charged particles under the influence of the oscillating electric field. As ions move and collide with neighboring molecules, friction is generated, which leads to the production of heat. The intensity of this heat generation is directly influenced by the number of ions present and their ability to move freely within the material, making ionic conduction an important mechanism for heat transfer in materials with high ion content (Nayak *et al.*, 2016). In the conduction mechanism, dissolved ions oscillate in response to the

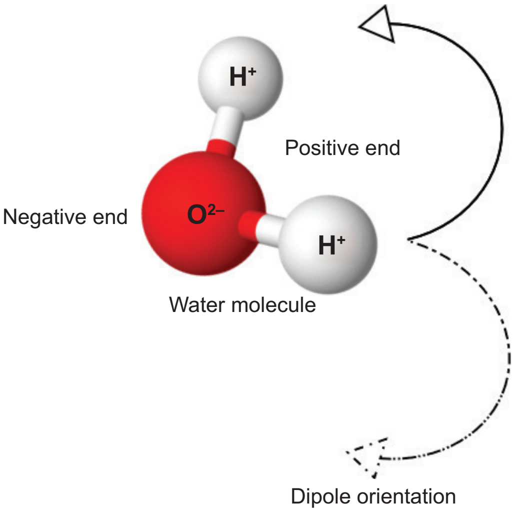

Figure 4. **Modeling of dipole orientation.**

microwave's electric field, resulting in frequent collisions with surrounding molecules. These collisions generate friction, which enhances internal heating within the material. Compared to dipolar polarization, conduction is generally more efficient at producing heat, primarily because the energy required for the transport of ions through a polar medium is relatively high. The greater the polarity of the solvent, the more effectively it absorbs microwave energy, leading to more substantial temperature increases. This heightened energy absorption results in more efficient heating, making highly polar solvents ideal candidates for microwave heating applications (Tsatsop *et al.*, 2025). In spite of its advantages, this method has some limitations. High-conductivity materials, such as metals, are generally unsuitable for microwave heating because they reflect a significant portion of the microwave energy, leading to poor energy absorption and reduced efficiency. On the other hand, materials with lower conductivity, such as water-based or ionic substances, allow for the movement and interaction of ions within the material when subjected to an oscillating electric field. This ion motion creates internal friction, which generates heat, enhancing the overall heating process. As a result, ionic conduction becomes a key mechanism in achieving efficient and uniform microwave heating, especially in materials where ionic activity is more pronounced. This makes it an essential factor for effectively heating food and other materials with moderate conductivity (Nayak *et al.*, 2016).

Interfacial polarization

Interfacial polarization is a mechanism that combines both conduction and dipolar polarization effects, making it particularly effective in systems where a conductive material is dispersed within a nonconductive medium. For example, when metal particles are dispersed in a material like sulfur, an efficient microwave-absorbing system can be created. While metals typically reflect most microwave energy, their combination with a nonconductive material like sulfur enhances microwave absorption. This effect is most pronounced when the metal is in powdered form, as the increased surface area of the powder allows for more efficient microwave absorption compared to solid metal surfaces. The powdered metal absorbs the microwave radiation and heats up through a process like dipolar polarization. Meanwhile, the surrounding nonconductive medium acts as a "solvent" for the metal particles, restricting ion movement in a manner similar to how polar solvent restrict molecular interactions. Under the influence of an oscillating electric field, these restrictions create a phase lag in the movement of ions, which leads to random ion motion and results in the generation of heat within the system (Monzavi & Chaouki, 2024).

Variables influencing microwave heating

Several factors influence microwave heating, impacting its efficiency and effectiveness. These factors are outlined below:

- Frequency: The penetration depth of microwaves is influenced by their frequency, with commonly used frequencies of 915 MHz and 2450 MHz corresponding to wavelengths of 0.328 m and 0.122 m, respectively. In general, a longer wavelength or a lower frequency results in greater penetration depth. The relationship between polarization and dielectric properties is also frequency-dependent: as frequency increases, the dielectric constantly decreases or remains stable. Once the frequency exceeds a certain threshold, dipole motion ceases, causing shifts in the electric field that reduce the dielectric constant and energy absorption because of phase lag. Ionic conductivity plays a significant role at lower frequencies (<200 MHz), while at higher frequencies, such as 915 MHz and 1800 MHz, ionic conductivity and the dipole rotation of free water molecules interact synergistically. Although lower frequencies produce less dielectric loss in aqueous solutions, higher frequencies result in increased dielectric losses because of the presence of free ions in the solution (Ahmed & Ramaswamy, 2020).
- Temperature: As the temperature of the product increases, water within the food begins to evaporate, causing a shift in its electricity. This change in the dielectric characteristics directly impacts the heat generation within the food during microwave heating, as the temperature of the product is closely linked to its MC. The interplay between temperature and moisture

levels influences the dielectric properties of the food, which in turn affects the efficiency and uniformity of the heating process. This dynamic relationship is crucial in determining how effectively the microwaves interact with the food, influencing the overall heating behavior and the quality of the final product (Pratap-Singh, 2024).

- Moisture content: In general, higher MC enhances microwave absorption because of the increased dielectric loss factor, but it also reduces the penetration depth of microwaves, leading to more efficient heating within the surface layers of the food. As MC decreases, microwave penetration depth increases, but the specific heat capacity of the food also declines, potentially hindering uniform heating throughout the product. In addition, the nature of the water present—whether free or bound—significantly influences the dielectric properties. Free water typically has a greater impact on dielectric behavior compared to bound water. In most cases, higher MC raises both the dielectric constant and the loss factor, which improves microwave energy absorption. However, there are instances where the loss factor may decrease with increased MC at specific frequency ranges. For instance, in apples, the dielectric constant increases as the temperature rises when MC is below 70%, but decreases when moisture exceeds 70%, particularly within the frequency range of 915–1800 MHz. This demonstrates the complex relationship between MC, temperature, and dielectric properties, which varies depending on the specific material and frequency used (Pratap-Singh, 2024).
- Density: Food materials with high porosity generally exhibit lower dielectric properties because the air filling the pores has an exceptionally low dielectric constant of 1 and a loss factor of 0. When bread, for example, is baked in a microwave oven, the reduction in MC and the formation of pores further diminish its dielectric properties. As moisture evaporates and air fills the pores, the overall dielectric constant and loss factor decrease, which in turn reduces the efficiency of microwave energy absorption. Interestingly, the influence of porosity on the dielectric properties often outweighs the effect of MC, as the presence of air significantly alters how microwaves interact with the material. This highlights the importance of considering both MC and porosity in optimizing microwave heating processes, as these factors collectively influence the material's response to electromagnetic radiation (Prakash *et al.*, 2025).
- Spatial arrangement and positioning of food: The dimensions and shape of a product significantly influence its penetration depth, heating rate, and overall heating uniformity. Regularly shaped products, such as cubes and discs, tend to heat more evenly because their uniform thickness allows for a more consistent distribution of microwave energy. In contrast, irregular shapes, such as cylinders, spheres, and prisms, often experience larger temperature gradients, with the most significant differences observed between the core and surface. Among these shapes, prisms tend to show the smallest temperature disparity. In addition, food particles with larger surface areas generally exhibit smaller temperature differences between the core and the outer layers, as more surface areas allow for faster heat transfer. Another important factor is the position of the food within the microwave oven. Items placed on the outer edge of the turntable typically heat more quickly than those in the center, because of the uneven distribution of microwave energy, which leads to temperature variations within the oven. These factors, surface area, and positioning—must be carefully considered to optimize heating efficiency and ensure more consistent results (Verma *et al.*, 2024).
- Heat properties: The thermal characteristics of food, particularly thermal conductivity and specific heat capacity, play a crucial role in determining the efficiency and uniformity of microwave heating. Among these, thermal conductivity is the most influential property for achieving consistent heating. Foods with higher thermal conductivity allow heat to distribute more evenly throughout the material, leading to faster and more uniform heating. This characteristic is especially important in ensuring that heat is not concentrated on the surface while the core remains underheated, thereby enhancing both the speed and consistency of the microwave drying or cooking process (Prakash *et al.*, 2025).

Microwave versus conventional heating: A comparative analysis

Microwave and conventional heating technologies differ fundamentally in their heat transfer mechanisms, efficiency, operational characteristics, and environmental impact. Microwave heating is based on the direct interaction of EMW with polar molecules and ionic species within the material, leading to volumetric heat generation throughout the product. This mechanism enables rapid internal heating without dependence on surface heat conduction, resulting in significantly reduced processing times and high heating rates (Chandrasekaran *et al.*, 2013; Laguerre *et al.*, 2020).

In contrast, conventional heating relies on external heat sources and transfers thermal energy to the product through conduction, convection, and radiation. Heat is progressively transferred from the surface toward the core of the material, often leading to slower heating rates and prolonged processing times, as well as energy losses associated with heating reactor walls and surrounding media (Datta *et al.*, 2001).

In spite of its high efficiency, microwave heating is frequently associated with challenges related to heating uniformity. Variations in dielectric properties, MC, and composition within the food matrix can result in selective energy absorption and localized overheating. Consequently, precise temperature control and advanced monitoring techniques, such as fiber-optic thermometry, are often required to ensure process stability and product safety (Chandrasekaran *et al.*, 2013; Vadivambal & Jayas, 2010). Conversely, conventional heating generally provides more predictable and controllable temperature profiles, with gradual temperature gradients developing from the surface inward, although at the expense of longer processing durations.

From an equipment and operational standpoint, microwave systems are typically more compact, lightweight, and flexible, facilitating easier integration into industrial processing lines. Conventional heating equipment, on the other hand, is often bulkier and less adaptable because of the need for heat-transfer media, insulation, and large heating surfaces (Laguerre *et al.*, 2020).

Environmental considerations further distinguish the two technologies. Microwave heating uses electrical energy and does not require direct fossil fuel combustion, allowing more efficient energy utilization and reduced on-site emissions. However, its overall environmental impact remains dependent on the energy source used for electricity generation. In contrast, conventional heating commonly relies on direct fuel combustion, contributing to higher greenhouse gas emissions and greater environmental burden (Awuah *et al.*, 2007).

Overall, this integrated comparison highlights the trade-offs between microwave and conventional heating technologies in food processing, emphasizing the balance between processing efficiency, heating uniformity, equipment design, and environmental sustainability.

Effect of heating on nutritional and physicochemical composition of fish

Fish are renowned for their rich nutritional profile, making them a valuable source of high-quality nutrients. They typically comprise 70–84% water, 15–24% protein, and 0.1–25% fat, which include essential polyunsaturated fatty acids (PUFAs) such as EPA and DHA. Both are crucial for growth and cardiovascular health and must be obtained through diet as they cannot be synthesized by the body. In addition, fish contains 1–2% minerals and important micronutrients, including calcium, phosphorus, and vitamins A, D, B, and C (Sahana *et al.*, 2024). The biochemical composition of fish varies significantly across species, influenced by a range of factors including feeding habits, gender, and seasonal changes. This unique nutritional profile makes fish an invaluable addition to a balanced diet, providing a diverse array of essential nutrients. Understanding and analyzing their composition is crucial for accurately assessing their energy content and overall nutritional value, guiding both dietary recommendations and food industry practices. The biochemical composition of fish plays a critical role in its processing, as it directly impacts both the quality and technological properties of the final product. Variations in components such as lipids, proteins, and MC can affect texture, flavor, and shelf life, making an in-depth understanding of these factors essential for optimizing processing techniques (Aman Hassan *et al.*, 2024). Different processing methods, particularly microwave heating, can significantly alter the chemical, physical, and nutritional properties of fish, impacting digestibility because of protein degradation and a reduction in PUFAs (Sahana *et al.*, 2024). Microwave heating specifically affects the chemical composition, leading to changes in cooking losses, antioxidant activity, and variations in bioactive and anti-nutritional compounds, including trypsin inhibitors, hemagglutinin activity, tannins, saponins, and phytic acid (Dudu, and Georgescu 2024). In addition to these biochemical changes, sensory attributes such as texture and color can be notably affected. Color changes, for example, may result from the degradation of pigments, oxidation of ascorbic acid, and both enzymatic and nonenzymatic browning reactions (Ling *et al.*, 2015). Furthermore, protein denaturation plays a key role in these color changes: denatured proteins scatter light, leading to a decrease in lightness, while thermal denaturation of myoglobin and other proteins causes a reduction in redness. Consequently, higher microwave power can reduce processing time, thereby minimizing the extent of protein denaturation and preserving the color and nutritional quality of the fish (Guo *et al.*, 2017). Recognizing the crucial role of microwave heating in fish processing, numerous researchers are exploring its effects on the nutritional and functional components of fish. A study investigated how different cooking methods, namely, boiling, steaming, microwaving, grilling, pan-frying, and deep-frying, impact lipid oxidation and the fatty acid profile in grass carp fillets. Microwaved fish experienced significant moisture loss than raw and wet-processed fish, leading to increased concentrations of fat and protein in the microwaved, grilled, and fried samples. Fried fish contained the most polar lipids of any cooking method, whereas microwaved and grilled samples had twice as much as the others. All cooking processes resulted in a reduction in free fatty acids (FFA), most likely because of lipase inactivation and the loss of volatile FFA. Importantly, microwaving had no significant effect on the n-3/n-6 fatty acid ratio (0.97) compared to raw fillets (0.95) while frying resulted in a decrease in this ratio because of the absorption of oil (Verma *et al.*, 2024).

In addition to these findings, (Cheng *et al.*, 2024) conducted a study demonstrating that fish is highly heat-sensitive compared to meat, especially in cold-water species that exhibit specific protein denaturation at mild heating temperatures. For example, collagen in the muscles of cod and salmon begins to denature at temperatures between 30 and 40°C, resulting in flaking and substantial textural changes. The principal nutritional group in fish muscle is protein, whereas heat processing below 100°C does not modify the amino acid composition. It may affect the functional qualities of the proteins, perhaps enhancing digestibility (Cheng *et al.*, 2024). Meanwhile, it has been demonstrated that microwave heating affects the fatty acid content of minced fish, causing variations in the levels of certain fatty acids, probably because of water loss. Heating fresh minced common carp and mackerel initially reduces peroxide and acid values; however, after 24 minutes, the peroxide value remains unchanged while a slight increase in acid value is noted in carp after 20 minutes. In addition, the levels of conjugated dienes in carp lipids show a slight increase, while those in mackerel rise fourfold. Both species contain key fatty acids, including palmitic, stearic, oleic, linoleic, linolenic, EPA, and DHA. However, mackerel possesses significantly higher amounts of n-3 PUFAs, especially DHA and EPA (Huang *et al.*, 2025). To further explore the effects of microwave heating on fatty acid composition, a comparative study on African catfish was conducted. After microwaving, the protein and ash contents of the fish fillets increased, while moisture decreased from 76.8% to 72.7%. Likewise, there was a notable increase in mineral content between raw and microwaved fish. Specifically, sodium (Na) rose from 308 ±0.3 mg in raw fish to 375±4.3 mg in microwaved fish; potassium (K) increased from 1817±132.4 mg to 2373±48.11 mg; and calcium (Ca) grew from 40.1±0.08 mg to 164±3.95 mg. Conversely, fat-soluble vitamins, including vitamins A and E, are often less heat-labile than water-soluble vitamins. Nevertheless, they can be destroyed at elevated temperatures in the presence of oxygen. As a result, the vitamin A content decreased from 18.1±0.05 mg in raw fish to 16.3±0.58 mg in microwaved fish, while vitamin E increased from 0.34±0.01 mg to 0.52±0.01 mg after microwaving. For vitamins B_1, B_2, and B_6, there was a slight drop in content after heating, with losses not over 0.03 mg (Dangal *et al.*, 2024). Another study on the proximate composition and mineral content of rainbow trout, both raw and microwaved, showed an approximate 10% decrease in moisture, accompanied by increases of 10%, 0.2%, and 1% in protein, ash, and fat content, respectively, after microwave heating. Furthermore, there was an observed increase in the levels of (Na), (K), and phosphorus (P) following the heating process, while (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn) levels decreased. Notably, copper (Cu) remained unchanged after microwave heating (Dangal *et al.*, 2024). The lipid profile of fish was observed to change significantly, with notable differences among various fish types compared to raw samples. It was concluded that EPA + DHA (%) levels decreased after microwaving compared to raw samples: from 5.8 to 2.2 in tuna, 16.0 to 11.8 for salmon, 28.3 to 16.9 for mackerel, and 13.4 to 5.2 in sardine. In addition to changes in the lipid profile, there was also an alteration in the mineral profile, particularly for Mg, Zn, and Fe, which showed a reduction after microwave heating in tuna, salmon, mackerel, and sardine (Dangal *et al.*, 2024).

Microwave Sterilization and its Applications in Fish Processing

Mechanism of microwave sterilization

The primary objective of sterilization is to improve food safety and significantly prolong the shelf life of perishable products. Fish is highly vulnerable to spoilage because of its high MC, which facilitates the rapid breakdown of proteins and lipids. While traditional heat-based sterilization methods are effective in microbial control, they often lead to the loss of essential nutrients, deterioration of texture, and the development of undesirable changes in flavor and aroma. These changes can compromise both the sensory and nutritional quality of the fish, highlighting the need for more advanced and gentler processing techniques to preserve its integrity (Abd El-Hay, 2022). Microwave sterilization offers a modern and efficient solution for ensuring microbial safety in fish, while better preserving its overall quality. This technique utilizes microwave energy to rapidly and evenly heat fish tissue, effectively inactivating harmful pathogens and preventing spoilage. Compared to traditional heat methods, microwave sterilization minimizes nutrient loss and helps maintain the fish's texture, flavor, and nutritional value, making it a promising alternative for processing perishable seafood (Rabiepour *et al.*, 2024). Microwave heating, as an alternative to traditional thermal methods such as hot water or hot air, has been extensively studied for its ability to improve safety, extend the shelf life, and preserve the sensory and nutritional quality of fish products (Rabiepour *et al.*, 2024). While the primary preservation effect of microwave heating stems from the rapid rise in temperature (thermal effects), other mechanisms may contribute to its efficacy. These include: (i) Electroporation: involves the application of an electric field to microbial cells, which induces the formation of pores in their membranes, leading to cell rupture and the leakage of intracellular contents. Another mechanism is (ii) selective heating, where microbial cells are subjected to localized temperatures higher than those of the surrounding medium, resulting in rapid and more efficient cell death. In addition, (iii) electromagnetic interactions with cellular components, such as DNA and proteins, can enhance the sterilization effect by directly damaging essential cellular structures, further compromising microbial viability (Guo *et al.*, 2017).

Impact of microwave sterilization on microbial inactivation

The effectiveness of microwave sterilization can vary significantly between different manufacturers and processing designs. The FDA's recognition of dielectric sterilization as a dependable method highlights its suitability for the food industry, particularly in the United States, as it accurately determines and validates the necessary lethality of heat treatments for ensuring microbiological safety. When creating a new thermal process to achieve sufficient sterility for shelf-stable foods, it is crucial to identify cold spots within packaged products (FDA). In the United States, foodborne infections are estimated to cause 48 million illnesses, 128,000 hospital admissions, and 3000 fatalities per year, not including cases that go unreported (Chiller, 2019). Some of the primary pathogens of concern include *Shigella*, *Staphylococcus aureus*, *Salmonella*, *Campylobacter*, *Escherichia coli*, *Listeria monocytogenes*, and various strains of *Enterococci* (Newell & Burnard, 2010). Microwave sterilization effectively eliminates these pathogens by generating heat, which varies based on the type of food medium, the frequency of microwave use, and the temperature achieved in different areas of the food.

Microwave radiation, including water-assisted microwave heating and microwave sterilization, can effectively control harmful microorganisms in food products. Table 3 illustrates the inactivation of pathogens during the microwave sterilization process. This method can significantly lower the microbial colony count in foods. Furthermore, enhancing microwave power and sterilization temperature or prolonging the sterilization duration can increase the efficacy of microwave sterilization (Sharma *et al.*, 2025). In a recent study, Ulusoy *et al.* (2019) investigated microwave heating's effectiveness in reducing pathogens in whiting and salmon. For writing, *E. coli* was reduced to below detectable levels at 50°C and 70°C. *Staphylococcus aureus* decreased to 4.38 log CFU/g at 50°C and below 1.00 log CFU/g at 70°C, while *Listeria monocytogenes* fell to 3.79 log CFU/g at 50°C and below detectable limits at 70°C. In salmon, *E. coli* was initially at 5.91 ±0.26 log CFU/g and also reached below detectable levels after heating at both temperatures. *Listeria monocytogenes* decreased from 5.48 ± 0.15 log CFU/g to 5.34 ± 0.16 log CFU/g at 50°C, and was below detectable levels at 70°C. These findings highlight the potential of microwave technology as an effective method for enhancing food safety by significantly reducing pathogenic loads in fish, thereby extending their shelf life and ensuring the safety of ready-to-eat fish products. Moreover, after microwave radiation process, Bauza-Kaszewska *et al.* (2014) found that salmon and cod fish meals pre-inoculated with *Salmonella enteritidis*, *Enterococcus* spp., and *Clostridium* spores were sterilized. Fish samples were sterilized using microwave power levels ranging from 0 to 700 W for 2.5 minutes. During this process, *E. coli* exhibited the highest sensitivity to microwave treatment, while Enterococci proved to be the most resistant among the vegetative bacteria. In contrast, *Clostridium* spores demonstrated a slower rate of elimination.

The intensity of microwave radiation plays a crucial role in determining the extent of microbial inactivation. Studies have shown that microorganisms are effectively destroyed at specific radiation dosages, indicating that varying microwave power levels induce different biological responses. Furthermore, the temperature increase during the treatment process may be linked to a distinct electromagnetic threshold effect, which enhances sterilization efficiency. Research has also explored how temperature affects the complete inactivation of microorganisms during microwaving. Zeng *et al.* (2025) found that when chicken drumettes, inoculated with *Listeria monocytogenes* at 1.6 × 10^6 CFU/mL, were exposed to microwave radiation, increasing the surface temperature above 74°C within 60 seconds fully eliminated surface contamination. A significant correlation was observed between bacterial reduction and sample temperature ($p < 0.001$, $r = 0.879$). Complete inhibition of *E. coli* (3.2×10^7 CFU/cm^2) on fresh beef slices was also observed by Jamshidi *et al.* (2010) after 30 seconds of microwave treatment, with surface temperatures above 70°C. There was a significant correlation ($p < 0.0001$, $r = 0.973$) between sample temperature and bacterial decrease.

In addition, to achieve optimal performance, it is essential to select the appropriate microwave frequency for each product, as the dielectric properties of fish products vary based on their composition. The choice of packaging material also plays a critical role, as it must be carefully selected to enhance heat generation and ensure uniform penetration throughout the product, maximizing the effectiveness of the microwave treatment.

Impacts of microwave sterilization on quality attribute of fish products

Bioactive compounds, antioxidant activity, enzyme activity, texture, and color are among the primary food quality parameters studied in relation to the effects of microwave sterilization. Thermal treatments applied during seafood processing significantly influence its biochemical composition, which in turn affects both its nutritional value and technological properties. Published research indicates

Table 3. Microbial inactivation in fish samples by microwave (MW) treatment (standardized to $\log_{10}$ CFU/g).

Fish sample	Inoculated pathogens	Inoculation dose	The load after MW	Treatment conditions	References
Whiting	*Escherichia coli*	5.81 ± 0.23 log CFU/g	<2.00 log CFU/g at 50°C and 70°C	• Internal temp: 50–70°C; • Time: 2.2–5.2 minutes; • Power: 360 W	Ulusoy *et al.*, 2019
	Staphylococcus aureus	7.16 ± 0.15 log CFU/g	4.38 ±0.11 log CFU/g at 50°C and <1.00 log CFU/g at 70°C		
	Listeria monocytogenes	5.58 ± 0.05 log CFU/g	3.79 ±0.53 log CFU/g at 50°C and <2.00 log CFU/g at 70°C		
Salmon	*Escherichia coli*	5.91 ± 0.26 log CFU/g	<2.00 log cfu/cm^2 at 50°C and 70°C		
	Staphylococcus aureus	7.03 ± 0.03 log CFU/g	5.97 ±0.02 log CFU/g at 50°C and <1.00 log CFU/g at 70°C		
	Listeria monocytogenes	5.48 ± 0.15 log CFU/g	5.34 ±0.16 log CFU/g at 50°C and <1.00 log cfu/cm^2 at 70°C		
Cod	*Salmonella Enteritidis*	7.30 log CFU/g for the control sample	1.40 log $\text{CFU/cm}^2$for 38.58 $\text{kJ}\times\text{g}^{-1}$ microwave dose	• Dose: 38.58 kJ/g (~700 W, 2.5 minutes); • Freq: 2.45 GHz; NR temp	Bauza-Kaszewska *et al.*, 2014
	E. coli	7.30 log CFU/g for the control sample	Not detected for 38.58 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
	Enterococcus spp	6.40 log CFU/g for the control sample	3.40 log CFU/g for 38.58 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
	Clostridium sporogenes spores	6.70 log CFU/g for the control sample	2.67 log $\text{CFU/cm}^2$for 924 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
Salmon	*Salmonella Enteritidis*	7.18 log CFU/g for the control sample	2.40 log $\text{CFU/cm}^2$for 38.58 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
	E. coli	6.18 log CFU/cm^2 for the control sample	Not detected for 38.58 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
	Enterococcus spp	6.65 log CFU/g for the control sample	4.40 log CFU/g for 38.58 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
	Clostridium sporogenes spores	6.77 log CFU/g for the control sample	3.05 log CFU/g for 924 $\text{kJ}\times\text{g}^{-1}$ microwave dose		
Whiting	*Salmonella Enteritidis*	6.37±0.06 log CFU/g	4.55±0.68 log CFU/g at 50°C and <1.00 log CFU/g at 70°C	• Internal temp: 50–70°C; • Time/power: NR	Alakavuk *et al.*, 2021
Salmon	*Salmonella Enteritidis*	7.23 ± 0.73 log CFU/g	4.84±0.30 log cfu/g at 50°C and <1.00 at 70°C		
Bolti fish fillets	*Aeromonas hydrophila*	5.81 log CFU/g for the control sample	Not Detected after 1 and 2 hours of microwave cooking	• Time: 1–3 minutes cooking; • NR power/temp	Mohamad *et al.*, 2016
Barramundi	*Vibrio parahaemolyticus*	<2.0 log CFU/g for raw sample	<2.0 log CFU/g at 90°C and for 120s <2.0 log CFU/g at 70°C and for 120s	• Internal temp: 70–90°C; • Time: 120 seconds	Tsai *et al.*, 2022
	Coliform	2.57 ± 0.25 log CFU/g for raw sample	<1.0 log CFU/g at 90°C and for 120s <1.0 log CFU/g at 70°C and for 120s		
	E. coli	<1.0 log CFU/g for raw sample	<1.0 log CFU/g at 90°C and for 120s <1.0 log CFU/g at 70°C and for 120s		
	S. aureus	<2.0 log CFU/g for raw sample	<2.0 log CFU/g at 70°C and for 120s <2.0 log CFU/g at 90°C and for 120s		
	Salmonella spp.	2.09 ± 0.12 log CFU/g for raw sample	<2.0 log CFU/g at 70°C and for 120s <2.0 log CFU/g at 90°C and for 120s		
	L. monocytogenes	<2.0 log CFU/g for raw sample	<2.0 log CFU/g at 70°C and for 120s <2.0 log CFU/g at 90°C and for 120s		

NR = Not reported.

Table 4. The impact of heat sterilization on organoleptic quality in food.

Food component	The effect because of thermal sterilization	References
Pink salmon	Decreased color qualities associated with lightness, redness, and yellowness, alongside heightened cooking losses, shrinkage, and muscle toughening, as a function of exposure duration at 121°C.	Kong *et al.*, 2007
Rainbow trout fillet	Compared to frying and boiling, microwave was the most effective since it resulted in more protein, mineral content, and an increase in the n3/n6 ratio.	Asghari *et al.,* 2013
Cape snoek	No discernible change in the amounts of ALA, DHA, and EPA. Significant rise in the monounsaturated fatty acid.	Marimuthu *et al.*, 2012
Orange spotted grouper	The total amount of omega-3 fatty acids, vitamins, and minerals remained the same, but the microwaved samples had a higher atherogenicity index.	Momenzadeh *et al.*, 2016
Mussel	Less beneficial omega-6 fatty acids were present at lower quantities after microwave cooking. But the amount of EPA and DHA was reduced during boiling, grilling, and baking.	Biandolino *et al.*, 2021

that the most notable changes in seafood resulting from microwave cooking are linked to alterations in fatty acid composition, lipid oxidation, and protein denaturation. In contrast, the levels of vitamins and minerals are relatively unaffected by the process. Table 4 presents the nutritional quality changes linked to heating fish and fish products in a microwave. For example, pink salmon exposed to higher temperatures showed a decline in color quality specifically in lightness, redness, and yellowness along with increased cooking losses, shrinkage, and muscle toughening as exposure time at 121°C increased (Kong *et al.*, 2007). The impact of microwave cooking on the fatty acid composition of fish has been widely studied. Asghari *et al.* (2013) investigated the fatty acid profile of rainbow trout subjected to various cooking methods. Their findings revealed that microwave cooking had a protective effect on the total fat and PUFA content, maintaining an optimal ω6/ω3 ratio. The study conducted by Fu *et al.* (2015) revealed that microwave-dried silver carp slices had less lipid oxidation than their hot air-dried equivalents. Surprisingly, a rise in vacuum did not prevent lipid oxidation; instead, it reduced the TBARS value as power intensity increased. On the other hand, compared to hot-air dried mackerel, Viji *et al.* (2019) found that microwave vacuum–dried mackerel had a greater degree of lipid oxidation. Moreover, the primary cause of alterations in protein caused by microwaves is an unexpected rise in temperature and the resulting production of free radicals. According to Yan *et al.* (2020), microwave heating greatly accelerated the creation of covalent bonds in surimi as well as their cross linking. Also, when MH was used instead of traditional heating, the β-sheet content increased by up to 26.85%. Dong *et al.* (2021) investigated the secondary structure of protein in shrimp that was impacted by microwave processing. The findings indicate that the degree of shrimp allergen, tropomyosin, decreased with treatment duration and temperature. The scientists explain the alterations by pointing out that following processing, proteins' secondary structures changed, resulting in an increase in β-helical sheets. In addition, the stability of vitamins and minerals during microwave sterilization is a topic that has received little research. Fish muscles generally lose some of its vitamins and minerals when it is sterilized by microwave. According to Asghari *et al.* (2013), after 12 minutes of microwave at 400 W, the amount of macro (Mg, Na, Ca, P, and K) and micro (Fe and Zn) minerals increased considerably. Momenzadeh *et al.* (2017) found that cooking orange spotted grouper in the microwave greatly improved its vitamin D and A content compared to raw fish; however, it decreased its vitamin B1 and B3 content. The authors claim that after microwaving, the macro-minerals such as Mg, Ca, and Na exhibited a reduction, while the K and P contents revealed a decline. According to Golgolipour *et al.* (2019), the level of vitamin D was found to be lower when microwave exposure of grass carp increased the concentrations of vitamins A and B3. In addition, samples prepared in a microwave showed the greatest concentrations of Ca, K, Mn, Mg, Zn, and Na, whereas the amount of P was lower than those prepared in other techniques.

Industrial and Regulatory Implications

FDA/EFSA

Safety Validation Requirements: Microwave processing of fish products intended for human consumption must comply with FDA's Hazard Analysis and Critical Control Point (HACCP) framework and the Seafood Processing Regulation. Unlike conventional cooking, microwave thermal processing presents unique validation challenges because of nonuniform heating patterns—a critical concern for safety that requires explicit control (Ulusoy *et al.*, 2019).

According to FDA guidance on heat process validation, processors must establish and validate a six-log reduction (99.9999% kill) of the target pathogen, typically nonproteolytic *Clostridium botulinum* for vacuum-packaged refrigerated fish products or *Listeria monocytogenes* for aerobic packaging.

This validation requires three key studies:

- Heat Penetration Study: Temperature must be continuously monitored at the slowest-heating point (cold spot) of the product throughout the process using calibrated thermocouples. For microwave processing, this requires mapping temperature distribution across the entire batch to account for microwave standing waves and reflections (Alakavuk *et al.*, 2021).
- Temperature Distribution Study: Sensors placed throughout the heating vessel (microwave chamber) must verify uniform heat distribution. Microwave-specific concerns include identifying "cold spots" at geometric centers and edges where penetration depth limitations create heat shadows (Alakavuk *et al.*, 2021).
- Critical Limits: For fish products, FDA-recommended thermal processes include ≥145°F (62.8°C) for 30 minutes for hot-processed fish, though equivalent microwave parameters for equivalent lethality must be scientifically validated via inoculated pack studies if deviating from FDA guidance (Bauza-Kaszewska *et al.*, 2014).

EFSA guidance (EU applicability)

The European Food Safety Authority's Regulation on food hygiene and Regulation on animal-origin foods similarly require validation of thermal processes for fish. Under EFSA's framework, microwave processing must be documented as a recognized control measure with supporting lethality data; our results align with EFSA's acceptance of thermal treatments achieving ≥60°C for 1 minute for parasite inactivation, and our data demonstrating 70°C efficacy support EU market approval (El-Demerdash *et al.*, 2023).

Energy efficiency and sustainability considerations

Industrial adoption of microwave processing offers significant energy advantages over conventional retorting. Microwave heating achieves 50–88% electrical-to-heat efficiency (depending on magnetron vs. solid-state power sources), compared to ~30–40% for steam retorts (Bauza-Kaszewska *et al.*, 2014). For the fish industry, this translates to:

- Specific energy consumption: Microwave processing typically requires 5–15 MJ/kg of product, vs. 20–40 MJ/kg for conventional water bath heating (Bauza-Kaszewska *et al.*, 2014).
- CO_2 reduction: At large scale (e.g., 1000 metric tons/year of packaged fish), microwave processing could reduce annual energy consumption by 50–60%, equivalent to ~150–200 metric tons CO_2 saved annually (Bauza-Kaszewska *et al.*, 2014).
- Operational cost: Lower energy inputs reduce processing costs by ~15–25% compared to conventional methods, improving competitiveness for packaged ready-to-eat fish products (Hassan *et al.*, 2023).

Validation in packaged fish products

For ready-to-eat packaged fish (e.g., fillets, surimi analogs), microwave processing validation must account for:

- Package material impact: Polyester trays and vacuum films must withstand microwave exposure (≤100°C) and seal integrity must be verified post-process.
- Product variability: Thickness, MC, and fat composition affect heat penetration; worst-case scenarios (largest fillets, 20% higher initial moisture) must be studied.
- Storage shelf-life correlation: Post-microwave storage at ≤4°C (FDA recommendation for refrigerated products) requires validation that F-values achieved correlate to known shelf-life targets (e.g., 6–18 months for pasteurized crabmeat) (Guzik *et al.*, 2022).

Research Gaps and Priorities

Fish and fish products serve as healthier alternatives to terrestrial proteins, providing easily digestible proteins with all essential amino acids, high omega-3 PUFAs (EPA/DHA), rich minerals, and low caloric density (Tacon *et al.*, 2020). Global production reached 179 million tonnes in 2018, with 156 million tonnes for human consumption (20.5 kg per capita), contributing 17.1% to global protein supply (FAO, 2020). Rising health awareness and declining red meat demand because of carcinogenic risks (Sobral *et al.*, 2020) drive increased fish processing needs.

Microwave (300 MHz–300 GHz) and RF heating offer volumetric, rapid processing advantages over conventional methods, retaining nutrients and improving appearance in tempering/thawing (Yang *et al.*, 2019), cooking (Asghari *et al.*, 2013), drying (Darvishi *et al.*, 2013), and canning. Examples include RF-thawed Pacific Saury with brighter color/softer bones (Uemura *et al.*, 2017), RF-cooked salmon with superior vitamin B retention (Fiore *et al.*, 2013), and preserved ω-3s in Skipjack Tuna (Stephen *et al.*, 2010). Fish's high moisture (64–92%) suits dielectric heating, but dielectric properties—dependent on composition (70–80% moisture, 20–30% protein, and 2–12% fat), species, temperature, and frequency—require optimization (Yang *et al.*, 2017). In spite of these advantages, several critical research gaps persist in microwave/RF fish processing, as summarized in Table 5.

Table 5. Identified research gaps in microwave/RF processing of fish products, with recommended actions.

Research gap	Description	Recommended actions	References
Variability of dielectric properties between species	Sparse systematic data across saltwater/freshwater species/body parts; e.g., differences because of fat/moisture.	Multispecies databases at processing temperatures/frequencies.	Li *et al.*, 2019; Yang *et al.*, 2019
Industrial scale-up challenges	Lab successes face hot spots, uniformity, and equipment/cost barriers in surimi/fish products.	Pilot-scale hybrid systems and techno-economic analysis.	Jiao *et al.*,2024; Viji *et al.*, 2022
Packaging compatibility	Untested interactions (migration/deformation) with films/plastics during RF heating.	Material compatibility protocols.	Zhao *et al.*, 2000; United States Patent, Patent (2001)
Regulatory aspects	Inconsistent standards for RF pasteurization/safety in seafood; needs FDA/EU approval.	Harmonized guidelines and risk assessments.	Goode *et al.*, 2013; Tang, J. (2015); Bermudez-Aguirr *et al.*, 2023

Conclusion

Numerous studies have established the advantages of microwave processing for fish over conventional heating methods, demonstrating improvements in both nutritional value and food quality. However, one notable drawback of microwave technology in the fishery industry is selective heating, which can negatively impact the quality of processed fish products. In spite of the technological advancements made, further research is essential to fully integrate microwave technologies into the fish processing sector. The high initial investment costs, the need for method optimization, and the operational expenses related to the specific nature of fish products and quality control are the current limitations facing microwave applications in the industry. Nevertheless, the potential for microwave technology as an innovative processing method, along with the discovery of new applications, remains a promising and dynamic area of research with continuous growth potential.

Mandatory Disclosure on Use of Artificial Intelligence

We declare that ChatGPT 4.0 (OpenAI) was used exclusively for language refinement, including grammar, spelling, and clarity improvements in the discussion section. All AI-assisted text was thoroughly reviewed, edited, and rewritten by the authors to ensure accuracy, originality, and alignment with the study's content. We confirm that all references were manually verified for accuracy, relevance, and authenticity. Finally, the authors take full responsibility for the manuscript and confirm compliance with the journal's policies and ethical standards, reinforcing that ultimate accountability rests with them.

Declaration of Competing Interest

The authors confirm the absence of any conflicts of interest and disclose no significant financial support that may have biased the study findings.

Data Availability

Data will be made available on request.

Authors Contributions

All authors contributed equally to this article.

Conflicts of Interest

The authors declare no conflicts of interest.

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