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EDITED BY
Vinayak Ghate,
National University of Singapore, Singapore

REVIEWED BY
Thomas Matthew Taylor,
Texas A&M University, United States
Azza Silotry Naik,
Technological University Dublin, Ireland

*CORRESPONDENCE
Nilesh Prakash Nirmal
✉ nilesh.nir@mahidol.ac.th
Fahad Al-Asmari
✉ falasmari@kfu.edu.sa

†These authors have contributed equally to this work

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Extraction of natural bioactive compounds using clean label technologies and their application as muscle food preservatives

Nikheel Bhojraj Rathod[1†], Nilesh Prakash Nirmal[2*†], Sajeeb Abdullah[3], Vijay Kumar Reddy Surasani[4], Rahul Chudaman Ranveer[1], Siddhnath Kumar[4], Phatchada Chunhavacharatorn[2], Soottawat Benjakul[5] and Fahad Al-Asmari[6*]

[1]Department of Post-Harvest Management of Meat, Poultry and Fish, PG Institute of Postharvest Technology and Management, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Raigad, Maharashtra, India, [2]Institute of Nutrition, Mahidol University, Salaya, Thailand, [3]Department of Food Technology, Saintgits College of Engineering, Kottayam, Kerala, India, [4]Department of Fish Processing Technology, College of Fisheries, Guru Angad Dev Veterinary and Animal Sciences University, Ludhiana, Punjab, India, [5]International Center of Excellence in Seafood Science and Innovation, Faculty of Agro-Industry, Prince of Songkla University, Hat Yai, Songkhla, Thailand, [6]Department of Food Science and Nutrition, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa, Al-Hofuf, Saudi Arabia

Muscle foods are the main source of high protein and mineral content. However, these foods are highly perishable due to their high moisture content as well as nutritional composition. Generally, microbial changes and oxidative damage occurs during animal slaughter and storage. To avoid this quality deterioration, various chemical additives are widely practiced by the industry. Nevertheless, consumer awareness and government strict regulation on synthetic additives demand clean label foods. The potential of natural bioactive compounds exhibiting strong antioxidant and antimicrobial properties for food preservation is a promising area of research. Recently, the interest in the non-thermal extraction process of bioactive compounds is growing due to their various advantages in extraction yield, stability, and bioactivity of the compound. Besides this, a natural bioactive compound can be applied in combination with other hurdle technologies to enhance the shelf-life of muscle foods. Therefore, this review article emphasizes the current knowledge on the novel non-thermal extraction of bioactive compounds from natural sources and their application as a muscle food preservative. Application of antioxidant and antimicrobial compounds from natural sources alone and in combination with other hurdle technologies has been successfully used for preservation of muscle foods. Additionally, different application methods and their impact on muscle food preservation are suggested.

KEYWORDS

muscle foods, preservative, antioxidant, antimicrobial, non-thermal extraction techniques, shelf-life extension

1. Introduction

Muscle foods are known for their high nutritional value, especially the unsaturated fatty acids, essential amino acids, minerals, and vitamins (Gómez et al., 2020). Nutrition supplemented with muscle foods is regarded to play a vital role in maintaining human health (Pereira and

Vicente, 2022). The high nutritional value of muscle foods makes them vulnerable to spoilage due to the growth of microorganisms (Gram-positive, Gram-negative, pathogenic, and specific spoilage microorganisms), enzymatic degradation, and oxidation (lipids and proteins) (Rathod et al., 2021). Oxidative and microbial spoilage are the major factors responsible for muscle foods deterioration (Soladoye et al., 2022). Spoilage of muscle foods *via* oxidation is associated with the development of harmful components leading to several disorders, while microbial spoilage is associated with several pathogenic and toxin-producing microorganisms causing the food toxicity. Additionally, spoilage leads to the development of off-odors and off-flavors, loss of textural quality and appearance leading to financial loss (Bekhit et al., 2021). Hence the preservation of muscle foods is an important task to ensure food safety and nutritional security (Roobab et al., 2021; Rathod et al., 2022). The usage of chemical preservatives is a common practice for muscle food preservation. However, these chemical preservatives such as sulfites and sulfiting agents has been associated with reports of fatality and allergy (Grotheer et al., 2005; D'Amore et al., 2020). The toxicity in some cases is associated with higher dosages of preservatives used (Parke and DFV, 1992). Also, nitrate a common preservative in meats, may induce allergic ocular reactions. That was related to endogenous conversion of nitrate to nitrite (Furrer et al., 2002; U.S.EPA, 2006; Chazelas et al., 2022). Furthermore, these nitrogenous compounds have been reported to generate carcinogenic compounds which interaction with other biomolecules in the body (). Also, sodium benzoate and parabens which is common in food especially fish have been known to cause cancer and impact on human health related to increased exposure (Soni et al., 2005; Shaikh et al., 2016; Tade et al., 2018; Lincho et al., 2021). Hence, the repeated exposure to the food with chemical additives impact the overall well-being of consumer. Besides, the adverse effect of these chemical additives can rapidly affect the person with certain health condition such as asthmatic patients (Soni et al., 2005; Shaikh et al., 2016). However, considering the drawbacks and threat posed by excessive usage of synthetic preservatives consumer trends toward the adoption of clean-label foods are increased (Rathod et al., 2021). The foods which are minimally processed and preserved using natural preservatives, with fresh-like quality attributes are clean-label foods (Rathod et al., 2022).

Bioactive compounds extracted from natural sources such as fruits, vegetables, seeds, leaves etc. exert numerous biological activities (Vlčko et al., 2022). Generally these bioactive compounds exhibit high antioxidant and antimicrobial activity which is related to food preservation action (Rathod et al., 2021; Lv et al., 2022). However, the bioactive compounds are present in minute quantities in the natural matrix. Extraction is the first stage in the recovery of bioactive compounds and traditional extraction techniques employ the usage of chemical solvents and heat application (direct and indirect) for extraction. Besides this, these conventional techniques cause loss of activity, solvent toxicity issues which generate hazardous waste. Considering the drawbacks associated with conventional methods, the discovery of clean label technologies for the extraction of bioactive compounds has led to increased extraction efficiency and improved bioactivity. Amongst clean label technologies, novel non-thermal extraction technologies are regarded as easy to handle, having low solvent requirement, high extraction content, compounds having high bioactivity, extraction of heat-labile compounds, and are easy to use in combination with other extraction technology (Moreira et al., 2019).

This review focuses on clean label technologies especially the non-thermal techniques for extraction of bioactive compounds and their subsequent application as muscle food preservative. In this context, the principle and application of non-thermal technologies are described. Antioxidant and antimicrobial activities of various bioactive compounds extracted from natural sources have been described. Additionally, natural bioactive compounds in combination with other non-thermal technologies as hurdle concept in muscle food preservation are explained. This review also gives insights on the various application methods of bioactive compounds for muscle foods preservation.

2. Non-thermal technologies for extraction of natural bioactive compounds

The quality and quantity of the bioactive compounds extracted from natural material are a function of various parameters including extraction method, solvents, treatment time, and temperature (Gómez-Cruz et al., 2021). Soxhlet extraction, distillation, and maceration are the most common conventional techniques and employ water, ethanol, methanol, acetone, chloroform, and ethyl acetate as popular solvents used for bioactive compound extraction where water and ethanol are considered as generally recognized as safe (GRAS) (Abbas et al., 2021). However, these conventional techniques involve minimum yield, high amount of solvents, time, energy, and heat, which diminishes the quality of the extracted bioactive compounds (Sirichan et al., 2022a). These disadvantages of conventional technologies demand exploration of novel non-thermal, non-toxic, green, clean label, and less expensive technologies for the extraction of bioactive compounds from natural matrices. Ultrasound-assisted extraction (UAE), pulsed electric field-assisted extraction, supercritical CO_2-assisted extraction, microwave-assisted extraction (MAE), and high-pressure assisted extraction (HPAE) are the most promising novel technologies for bioactive extraction. Table 1 summarizes the process conditions for non-thermal technologies along with their advantages and disadvantages.

2.1. Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) uses vibrating probes to produce ultrasonic/ultrasound waves with a frequency of 20 kHz or more (in the range of 20 and 10,000 kHz), which is beyond the detection limit for human auditory. However, the extraction application of ultrasound is mostly reported between 20 and 1,000 kHz (Sirichan et al., 2022a). The ultrasonic vibrations transfer high energy to the surrounding molecule which causes the production and collapse of cavitation bubbles and ultimately leads to the generation of an extreme shear force. This phenomenon disrupts the cell membranes/walls of the food matrices and subsequently leads to the discharge of bioactive compounds from the matrix (Gadioli Tarone et al., 2021). The common process parameters that influence the quality and yield of the extract during UAE include intensity, time, temperature, power, speed, frequency, solvent, and amplitude (Castañeda-Valbuena et al., 2021). Being a non-thermal extraction technique, UAE has currently emerged as a topic of interest for extracting valuable biomolecules from different food sources.

TABLE 1 Summary on the common extraction technologies.

Extraction mechanism	Process parameters	Advantages	Disadvantages	References
Ultrasound-assisted extraction				
The shear force produced by the collapse of the cavitation bubbles disrupts the cell membrane/wall.	• Pre-treatments • Particle size • Solid-solvent ratio • Amplitude • Time • Solvent type	• Applicability to more diversified samples • Reduced solvent consumption • Low cost • Simplified handling • High reproducibility • Higher extraction yield • Selectivity • Reduction of the extraction time	• Presence of solvent might be detrimental to humans • Requirement of more solvent concentration than many other techniques • Sometimes leads to the oxidation of organic matters • Difficulty in creating uniform ultrasound waves	Carreira-Casais et al. (2021), Kadam et al. (2015), Mittal et al. (2017), Sirichan et al. (2022b), and Gadioli Tarone et al. (2021)
Pulsed electric field assisted extraction				
An applied high voltage electric pulse develops an electric field potential on the surface of the cell membranes and produces pores on it. The compounds extract out through the created pores.	• Time • Solvent type • Sample to solvent ratio • Frequency • Quantity and duration of electric pulsation • Extraction temperature • Flow rate	• Non-toxic solvents • Higher extraction rate • Less solvent required compared to many other techniques • Extraction happens at low temperature • Extraction happens at shorter time • Higher selectivity and environment friendly.	• Chance of corrosion formation • Insulation is a prerequisite • Equipment is costly • Requirement of high voltage electric pulses	Jiang et al. (2022), Naliyadhara et al. (2021), Carullo et al. (2020), Einarsdóttir et al. (2021), Psarianos et al. (2022), and Tlam et al. (2017)
Supercritical CO_2 extraction				
The highly polar supercritical CO_2 penetrates quickly through the membranes of the food matrices and boosts the extraction of compounds	• Moisture content of the sample • Particle size of the sample • Temperature • Pressure • Dynamic time • Solvent density • Solvent polarity • Solvent mixture ratio • Compressibility of the solvent • Surface area of the sample	• Green, non-toxic, inert, food grade solvent • Solvent has high diffusivity and low polarity • Microorganisms may inactivate from the sample • Extract is solvent free • Low cost • Minimum oxidation of compounds • High penetration capacity	• Equipment set-up is complex • Initial capital investment is very high • Requirement of very high pressure • Presence of moisture/water might create problems • Requirement of modifiers • Cannot extract polar solvents	Pimentel-Moral et al. (2019), Uwineza et al. (2021), Sarkar et al. (2022), Rodrigues et al. (2021)
Microwave-assisted extraction				
The ionic conduction and dipole moment induced by the microwave on the solvents generates heat and pressure, which disrupts the cell wall of the food matrix.	• Time • Solvent type • Sample to solvent ratio • Extraction temperature • Particle size • Microwave density • Microwave power • Pressure	• Higher extraction yield • Minimum extraction time • Minimum solvent required • Homogeneous and volumetric heating • Easy operation • Minimum risk of oxidation	• Thermal • Undesirable for heat sensitive compounds • Oxidation of fat is reported in some studies	Bagade and Patil (2021), Mary Leema et al. (2021), Solaberrieta et al. (2022), de la Fuente et al. (2022), de Moura et al. (2018), and Kapoore et al. (2018)

Various studies have successfully extracted bioactive compounds from different food sources. During extraction, the UAE technique demonstrates higher extraction efficiency as compared to other similar extraction techniques, correspondingly, the probe-type UAE provides better quality extract as compared to the bath-type UAE (Gómez-Cruz et al., 2021). Abbas et al. (2021) compared the effect of different technology on the extraction of total phenolic content from *Lagenaria siceraria* and reported that the UAE was more effective as compared to conventional Soxhlet and MAE techniques. Similarly, Sirichan et al. (2022a) extracted phenolic and flavonoid compounds from Makiang (*Cleistocalyx nervosum* var. paniala) seeds and reported that all the process parameters of UAE, such as temperature, time, and amplitude, had significantly influenced the antioxidant properties of the extract. On the other hand Castañeda-Valbuena and colleagues

(Castañeda-Valbuena et al., 2021) extracted phenolic compounds from mango by-products (seed and peel) using UAE. The study observed that the UAE has significantly increased the antioxidant properties of the phenolic extract as compared to conventional extraction (maceration). It also observed that the solvent-to-solid ratio had the most influential effect on the antioxidant activity of the extract. Another research on the extraction of anthocyanins from the by-products of jabuticaba also observed that the solvent-to-solid ratio had the most positive influential effect on the quality of the extract and the ultrasound intensity showed a negative influence on the extract quality (Gadioli Tarone et al., 2021). In the same way, like plant sources, UAE can be utilized to extract bioactive compounds from animal and microbial sources as well (Ciko et al., 2018). All these studies reported a significant increase in the quality and quantity of the extract when the UAE technique was involved. Hence, these research findings concluded that the UAE technique can be used to extract bioactive compounds from different food matrices with superior antioxidant, functional and medicinal properties.

2.2. Pulsed electric field assisted extraction

The pulsed electric field assisted extraction (PEFAE) is also a green, non-thermal and environment-friendly extraction technique that provides maximum extraction yield with minimum treatment time and solvents (Jiang et al., 2022). During this extraction process, an electric field that is beyond the critical electric field is externally applied to the biological materials. These electric fields induce strong and synergistic electrical and mechanical stress on the cell wall to create poration and thus increase the permeability of the cell membrane (Naliyadhara et al., 2021). Along with increasing the extraction yield, PEFAE also preserves the natural quality and color of the extract (Surano et al., 2022). Besides as an extraction technique, this technology is also used for sterilizing liquid foods by killing microorganisms through electro-permeabilization and electro-poration of its cytomembranes (Liu et al., 2018).

A study on the effect of different techniques on the extraction of Jiuzao glutelin stated that the PEFAE, at optimum conditions, achieved approximately 14% more extraction yield as compared to UAE (Jiang et al., 2022). Another study explored the potential of PEFAE treatment in extracting bioactive compounds from prickly pear fruit (Surano et al., 2022). The results showed that PEFAE increased the antioxidant capacity by about 47%, polyphenol content by about 38%, betalain yield by 48%, and juice yield by 3.3 times (Surano et al., 2022). Similarly, the yield of phenolic compound, carbohydrate and antioxidant properties was highest in the brown macroalga (*Alaria esculenta*) extract obtained using PEFAE (Einarsdóttir et al., 2022). Another research on onion peel reported that the onion peel pre-treated with PEF increased the total quercetin content of the extract by 33% (Kim et al., 2022). In addition, the yield of flavonoid compounds has been enhanced by 2.7 times and phenolic compounds have been 2.2 times when onion peel was treated with PEF. Similarly, Bozinou and others (Bozinou et al., 2019) compared the extraction efficiency of conventional hot extraction, microwave, ultrasound, and PEF to obtain an antioxidant-rich phenolic extract from freeze-dried *Moringa oleifera* leaves and reported that the PEFAE has the highest extraction efficiency as compared to other techniques. This study also observed that higher extraction efficiency during PEFAE can be achieved by maintaining a high pulse interval with low pulse duration. These findings propose the beneficial applications of PEFAE for the production of bioactive compounds from biological matter.

2.3. Supercritical CO_2 extraction

Supercritical fluid extraction is a green technology employing usage of supercritical CO_2 with a high coefficient of diffusivity which is considered as GRAS (generally recognized as safe). This technique generally works at a pressure and temperature between 200 to 400 bar and 40 to 60°C, respectively (Pimentel-Moral et al., 2019; Molino et al., 2020). Supercritical fluid extraction utilizes carbon dioxide at reduced concentrations due to its recognized environmental and human safety attributes. Supercritical fluid extraction is a widely employed technique, with the most commonly utilized solvent being carbon dioxide, leading to the nomenclature of supercritical CO_2 extraction (SCE). During extraction, the SCE preserves the thermo-sensitive compounds since the critical temperature of CO_2 is moderate (31.2°C). It is also a reusable and readily available solvent possessing antioxidant activity, which enhances the popularity of this technology (Klimek et al., 2021). However, due to its reduced polarity, CO_2 is least effective against the extraction of highly polar bioactive compounds, including some polar polyphenols, entrapped inside the cell membranes of the matrix. Consequently, some polar solvents, such as water, methanol, or ethanol, are used in small quantities along with CO_2 as co-solvents or modifiers to increase their polarity and to extract highly polar bioactive compounds (Gallego et al., 2019).

Klimek et al.(Klimek et al., 2021) successfully extracted bioactive compounds, rich in terpene derivatives and organic acids (α-acids and β-acids) from Polish "Marynka" Hop variety using SCE technique. The extract showed good anti-proliferative and anti-microbial (against strains of Gram-positive bacteria) properties. While, Pimentel-Moral an others (Pimentel-Moral et al., 2019) determined the effect of co-solvent concentration, pressure, and temperature on the extraction of bioactive compounds from *Hibiscus sabdariffa* during SCE and observed that the maximum bioactive concentration was obtained at the highest co-solvent concentration, pressure, and temperature. Additionally, the study reported that the SCE improved the yield of bioactive compounds when compared with other extraction techniques (Pimentel-Moral et al., 2019). Similarly, methanol was used as a co-solvent for SCE extraction of bioactive compounds from *Lamium album* flower (Uwineza et al., 2021). The results indicated that the obtained extract had high antioxidant properties (estimated using FRAP, ABTS, and DPPH assays) and the presence of co-solvent had significantly influenced the phenolic content in the extract (Uwineza et al., 2021). Besides this, SCE also reported for the extraction of other biomolecules such as lipids (especially polyunsaturated fatty acids and omega-6 fatty acids), proteins, from the cells of microalgae (Sarkar et al., 2022). Suggesting, SCE to be selective and suitable technique for extraction of bioactive compounds from different plant, animal, and microbial sources with maximum yield, and greater qualitative properties. However, the density and polarity of CO_2, type and concentration of co-solvent, pressure, and temperature significantly influence the quality and quantity of the extract.

2.4. Microwave-assisted extraction

The microwave-assisted extraction (MAE) technology was initially used for digesting different types of geological, environmental, and biological samples. However, with its higher extraction efficiency in minimum time, this technology is currently one of the most acceptable techniques for extracting bioactive compounds from different natural materials (Bagade and Patil, 2021). In addition to rapid extraction, MAE is an energy-efficient, less waste-generating technique that consumes fewer solutes and hence minimum solvent exposure by humans and the environment. This is also a green extraction technique focusing mainly on heat-sensitive compounds (Patra et al., 2021). The MAE operates within the electromagnetic spectrum's frequency range of 300 MHz to 300 GHz. When food samples are subjected to heat, the available moisture causes a significant increase in pressure on the surface of the cell wall. This pressure weakens and breaks the cell wall and leads to the release of cell components including bioactive compounds (Bagade and Patil, 2021). Mary Leema et al. (2021) conducted a scanning electron microscope analysis of the biomass after the MAE process and confirmed the destruction of the cell wall. Patra et al. (2021) developed a process to extract bioactive compounds from cashew apple bagasse and observed that a 1:30 bagasse to solvent (1%citric acid)ratio, 110 s treatment time, and 560 W microwave power was the optimum MAE condition for extraction of bioactive. A similar study was conducted by Solaberrieta et al. (2022) on tomato seed and reported that as compared to UAE, the antioxidant activity and total phenolic content were higher for MAE extract. Recently, Boli et al. (2022) reported that the temperature and solvents play a significant role in the extraction of bioactive compounds from olive leaves using MAE. There was a significant increase in antioxidant activity and phenolic content with a decrease in microwave power and an increase in biomass-to-solvent ratios and temperature (Boli et al., 2022). MAE has reported both stances as complete elimination and reduction of solvent requirement for extraction. Hence it can be clearly suggested MAE as a technique that can reduce or eliminate the need for organic solvents in the extraction process, leading to benefits in terms of safety, environmental impact, and cost (Klimek et al., 2021; Uwineza et al., 2021; Sarkar et al., 2022).

Nevertheless, MAE can be used to extract biomolecules from animal and microbial sources as well. Quitério et al. (2022) reported extraction of bioactive compounds such as fatty acids, proteins, carotenoids, polysaccharides, and polyphenols from seaweeds using the MAE technique. Mary Leema et al. (2021) noted that the extraction of lutein from algal (*Chlorella sorokiniana*) biomass was increased 3.26 folds when MAE was used as compared to traditional extraction method. By the same token, de la Fuente et al. (2022) utilized microwave-assisted extraction (MAE) to extract lipids from fish by-products (*Sparus aurata* and *Dicentrarchus labrax*). The results showed that more than 50% of the total lipids were successfully extracted without altering the fatty acid compositions. Additionally, the MAE method had a shorter extraction time compared to other methods.

2.5. High-pressure assisted extraction

High-pressure assisted extraction (HPAE) works on the principle of disrupting the organelles, membrane, cell walls, and tissues of living organisms by pressure application (Alexandre et al., 2017b). This disruption leads to the release of cellular components including bioactive compounds outside the cell membrane. Subsequently, this technique operates at a non-thermal condition and acts as a cold pasteurization technique, the thermo-sensitive components was preserved and the extract got decontaminated from microbe (Pinto et al., 2022). In addition, it is also considered a green technology since HPAE can increase extraction yield and efficiency with minimum solvent requirement and impurity generation (Alexandre et al., 2017a).

A study was conducted to examine the effect of the HPAE technique on the extraction of bioactive compounds from the fig by-product and reported that the HPAE at optimum conditions increased the yield of tannins, flavonoids, and total phenolics content by 8–11% and antioxidant activity by 8–13% (Alexandre et al., 2017b). Another research by Alexandre et al. (2017a) reported increase in the yield of anthocyanins, flavonoids, tannins, and total phenolics from pomegranate peel by application of HPAE. Therefore, HPAE can be a useful tool to enhance cell disruption and extract potential bioactive compounds from food matrix with higher extraction yield. On the other hand, when compared with other extraction technologies such as MAE, UAE, and ultrasound–microwave-assisted extraction, the extraction yield of HPAE is lower, which indicates a limitation of this technology (Garcia-Vaquero et al., 2021).

3. Natural antioxidants and antimicrobials in muscle food preservation

Shelf life is an important factor for the industry as well as consumers and longer shelf life of meat products can be achieved by protecting the meat and meat products against microbial growth and lipid oxidation (Ribeiro et al., 2019).

3.1. Natural antioxidants

Antioxidants are generally classified into two categories: (a) Preventive antioxidants; which are responsible to stop the initiation of the radical process, and (b) Chain-breaking antioxidants; which inhibit the radical propagation chain reaction. However, the current classification identifies antioxidants as synthetic nano-antioxidants, synthetic antioxidants with phenolic structures, natural endogenous enzymatic and non-enzymatic antioxidants, including natural exogenous antioxidants (Flieger et al., 2021). The chemical composition of some traditional plants, such as *Mentha piperita* (peppermint), *Thymus vulgaris*, *Ocimum basilicum* (basil), *Rosmarinus officinalis* (rosemary), *Origanum vulgare* (oregano), *Piper nigrum* (black pepper) and *Cinnamomum zeylanicum* (true cinnamon) contains natural compounds that are related to the antioxidant activity of its essential oils. Additionally, it has been demonstrated that specific molecules in these essential oils, including eugenol, thymol, menthol, eucalyptol, and carvacrol, are primarily responsible for their antioxidant activity (Rathod et al., 2021; Balikçi et al., 2022; Rathod et al., 2023).

The natural antioxidants possess high radical absorption capacity or sequestered metal catalysts or very strong H-donating ability thus making them non-reactive. Some antioxidants control or prevent the propagation of reactive oxygen species or free radical formation, while others control it by chelating transitional metals and scavenging the free radicals. The ability to act as an antioxidant of these substances depends on the pattern of functional groups on the skeleton (Rathod et al., 2021). The position and number of free-OH groups on the skeleton decide the ability to scavenge free radicals. The antioxidant potential of phenolics is enhanced by the presence of multiple ortho-3, 4-dihydroxy structures, and hydroxyl groups.

The factors that initiate the oxidation of lipids and proteins are the presence of transition metal ions and oxygen, light, moisture, and heat. Oxidation of lipids in meat is a complex process that enables the reaction of polyunsaturated fatty acids with molecular oxygen through free radical mechanisms resulting in the formation of primary metabolites, i.e., fatty acyl hydroperoxides (Rathod et al., 2021). This is followed by the further deterioration of lipids through the occurrence of a secondary reaction resulting in oxidative rancidity. Antioxidants play a vital role in controlling this auto-oxidation of lipids and for this purpose synthetic antioxidants have been used in the food industry for a long time. However, these chemical additives create various health issues for consumers hence researchers and government focus has been shifted to natural antioxidants (Sen and Mandal, 2017).

Polyphenols are the major naturally occurring antioxidants abundantly available in vegetables, plants, fruits, seaweeds, and some herbs that find wide applications in meat products (Sen and Mandal, 2017; Rathod et al., 2023). Many antioxidants extracted from natural sources and used in meat and meat products (Table 2). Phytochemicals such as phenolic acids, flavonoids, isoflavonoids, and carotenoids are important natural antioxidants that are non-nutrient plant compounds and possess functional activities like inhibiting cancer cell proliferation, preventing lipid oxidation, and regulating inflammatory and immune response (Makhaik et al., 2021). Among these, phenolic compounds were found to give major protection against oxidation. The antioxidant potential of grape pomace extract is 20–50 times higher than vitamin C and E, which is a rich source of phenolic acids, catechins, flavanols, anthocyanins, and proanthocyanidins (Milinčić et al., 2021). The fruit part of Pomegranate is a rich source of anthocyanins and flavonoids (Mabrouk et al., 2019). Tomatoes are a rich source of natural antioxidants such as vitamin C, β-carotene, lycopene, and vitamin E (Gheribi and Khwaldia, 2021). Mir and others (Mir et al., 2022) assessed the antioxidant capacity of barley leaf and lotus leaf powder in cooked ground pork and reported a significant reduction in lipid oxidation. The antioxidant activity of spices wasrelatedto the presence of compounds such as lignans, flavanoids, terpenoids, and polyphenolics (Jabeen et al., 2022). The extracts from herbs and spices such as clove, thyme, oregano, and rosemary have been studied for their efficacy in cooked fermented meat products (Amiri et al., 2021). Rosemary and rosemary extracts have been widely used as antioxidant additives in meat products. Rosemary and lemon balm extracts in cooked pork patties reduced the TBARS values and hexanal contents (Shah and Mir, 2022). Paterio and others (Pateiro et al., 2021) evaluated inclusion of extracts of rosemary, sage and marjoram to ground beef and observed the significant reduction in its TBARS values in meat-based products. Polyphenols present in rosemary extract have been found to exhibit scavenging activity against free radicals, chelate metal ions, and disrupt bacterial cell membranes. Similarly, Carnosic acid that was extracted from rosemary leaves was found to show significant antioxidant activity in cooked ground buffalo meat at low concentrations (22.5 ppm) (Zang et al., 2022). Pennyroyal (*Mentha pulegium* L.) powder when added to beef patties significantly reduced in lipid oxidation (Guliyeva and Turhan, 2021). Extracts from rosemary (rosmaridiphenol, rosmariquinone), green tea (epigallocatechins, catechins), and red pepper (capsaicinoids) were tested for their efficacy to control oxidation in pork meat products and it was found that these extracts effectively controlled the lipid oxidation (Yoon et al., 2021).

3.2. Natural antimicrobials

The natural antimicrobial can be obtained from various natural sources including plants, microorganisms, and animals. The plant extracts containing polyphenols showed considerable inhibitory effect on microorganisms thus lowering the occurrence of food-borne illness (Premanath et al., 2022). Extracts from galangal, mountain pepper, lemon iron bark, and goraka were found to have great potential as antimicrobial agents against *Escherichia coli*, *Salmonella typhimurium*, *Listeria monocytogenes* and *Staphylococcus aurus* (Batiha et al., 2021). Essential oils present in natural extracts possess biologically active compounds such as terpenoids, aldehydes, phenolic acids, ketones, etc., contributing to the antimicrobial activities to retard or control the growth of pathogenic organisms in foods (Salanță and Cropotova, 2022). Moreover, compounds like geraniol, carvacrol, and thymol were found to have considerable antimicrobial potency against *E. coli*, *Shigella flexneri*, *L. monocytogenes* and *Enterobacter aerogenes* (Žunić, 2018).

Furthermore, it is possible to hypothesize about the emergence of resistance in microorganisms, which poses challenges for their management and control. Therefore, natural bioactive compounds inhibiting pathogenic and spoilage microorganisms are in demand. Phenolic compounds from various natural sources such as cloves, coriander, sage, rosemary, thyme, basil, etc. were found to have good efficacy in preventing the growth of microorganisms and food pathogens (Singh and Yadav, 2022). In addition to plant sources, natural antimicrobials can be obtained from microorganisms and animal sources. The diverse mechanisms of natural antimicrobials provide them with an advantage in controlling microorganisms, particularly in the context of developing resistance (Davidson et al., 2020; Rathod et al., 2021).

A study conducted to see the efficacy of clove, grape seed extract, oregano, cinnamon stick, and pomegranate peel reported that these substances showed a significant reduction in oxidation and microbial count in uncooked pork meat stored at room temperature (Chen et al., 2021). Clove was one of the effective ingredients that control food spoilage and rancidity (Rahman et al., 2022). Clove can be used for food preservation, especially for meat because of its excellent antimicrobial and antioxidant properties (El-Saber Batiha et al., 2020). Essential oils from rosemary and liquorice showed inhibiting activity against *Lactobacillus sake*, *P. fluorescens, E. coli, L. monocytogenes* in some foods. The usage of oregano essential oils in combination with modified atmospheric packaging caused a significant increase in the shelf life of cattle and poultry meat (Žunić, 2018). It was observed that the addition of sugar and probiotic bacteria to dried sausages, resulted in a considerable enhancement in their shelf life (Kourkoutas and Proestos, 2020).

4. Natural bioactive compounds in combination with other hurdles for muscle food preservation

Hurdle technology is an integrated approach to food preservation that combines two or more preservation techniques to prolong the

TABLE 2 Application of natural antioxidants and antimicrobials in the preservation of meat and meat products.

Bioactive compounds or extract	Meat product	Influence on physico-chemical quality	Reference
Spray dried plum powder and plum juice concentrate	Meat and meat products	The study found that the incorporation of plum ingredients resulted in a significant reduction of TBARS values by 50%. Moreover, the sensory attributes and tenderness of the final product were minimally affected by the addition of plum ingredients.	Manessis et al. (2020)
Packaging film containing lysozyme, lactoferin and carvacrol	Salmon fillets	The application of a carvacrol multilayer film resulted in a decrease in microbial load from 5.0 to 4.0 log CFU/g in comparison to the control sample. Similarly, the implementation of Lysozyme/lactoferrin-coated PET led to a reduction in bacterial count from 4.7 log CFU/g to 2.7 log CFU/g in comparison to the control sample.	Rollini et al. (2016)
Sodium nitrite substitution with 1. Grape seed extract and olive pomace hydroxytyrosol(GSE); 2. Chestnut extract and olive pomace hydroxytyrosol (CHE)	Dry-fermented pork sausages	The combination of GSE and CHE resulted in a marginal reduction in antioxidant activity, as evidenced by TBARS values of 1.05 and 0.98 mg MDA/kg, respectively, in contrast to the control group (0.93 mg MDA/kg).	Aquilani et al. (2018)
Extracts of pomegranate peel and bagasse powder	Chicken meat patties	The incorporation of pomegranate peel and bagasse powder extracts in patties resulted in decreased TBARS values (ranging from 0.81 to 1.0 mg MDA/kg) as compared to the control group (which had a TBARS value of 1.95 mg MDA/kg).	Sharma and Yadav (2020)
Tiger Nut (*Cyperusesculentus* L.) Oil.	Fresh Lamb Sausage	Turmeric extract displayed a high antioxidant capacity with TBARS values of 0.5–1.5 1.95 mg MDA/kg compared to control (2.75 mg MDA/kg).	de Carvalho et al. (2020)
Pink pepper extract	Chicken Burger	Pink Pepper extract and BHT showed antioxidant capacity by causing reduction in TBARS values by 79.44 and 67.29% compared to control.	Menegali et al. (2020)
Clove extract	Cooked Beef Patties at Refrigerated Storage	The inclusion of clove extract at a concentration of 0.1% exhibited notable antioxidant properties, as evidenced by the regulation of TBARS value to 0.2 mg MAD/kg, in contrast to the control group which displayed a TBARS value of 2.8 mg MAD/kg following a storage period of 10 days.	Zahid et al. (2020)
Black garlic powder	Spent duck meat nuggets	Adding black garlic powder to duck meat nuggets increased DPPH inhibition to 31.33% compared to 17.41% of control group after 30 days of storage. Similarly, TPC values were reduced to 4.28 log cfu/g compared to 5.44 log cfu/g of control group.	Talukder et al. (2020)
Pennyroyal (*Mentha pulegium* L.) powder	Beef patties	The Pennyroyal powder addition showed antioxidant activity by controlling the TBARS values to 2. 41 mg MAD/kg after 9 days of storage compared to 4.06 mg MAD/kg for control group.	Guliyeva and Turhan (2021)
Chokeberry extract	Pork meat	The Chokeberry extract addition showed antioxidant activity by significantly inhibited the formation of thiobarbituric acid reactive substances (TBARS), which was 2.3 times lower than control group after 16 days storage	Tamkutė et al. (2021)
Green tea extract and rosemary	Naturally cured pork sausages	When the amount of green tea extract powder or rosemary extract powder was increased to 0.1% lipid oxidation was reduced significantly with overall TBARS values ranging between 0.12–0.14 mg MAD/kg.	Yoon et al. (2021)
Sesame oil and Sesamol	Meat balls	Meatballs treated with either sesame oil (50 g/kg) or sesamol (0.3 and 0.5 g/kg) revealed significant reduction in APCs by 1.5 logs, 1.7 logs and 2.6 logs, respectively when compared with the control (5.8 log_{10} CFU/g).	Sallam et al. (2021)
Plant extracts and essential oils	Ground pork	Cinnamon oil at 0.5% and olive extract at 3% induced a 1.0 and a 0.9 log CFU/g reduction at day 7 from 6-log CFU/g of initial inoculum. At 3%, olive extract showed a 1.06 log CFU/g maximum reduction of *Salmonella* from a 4-log CFU/g initial inoculum.	Chen et al. (2021)
Essential oil of *LitseaCubeba*	Deer Meat	EO caused reduction in the total viable count to 5.17 log CFU/g against 5.50 log CFU/g in the untreated samples. Coliforms and *Pseudomonas* were not detected in the treated samples, while they were present in untreated samples.	Kunová et al. (2022)
Sugar and probiotic bacteria	Dried sausages	The incorporation of sugar and probiotic culture into sausages led to a notable extension of their shelf-life by up to 66 days, in contrast to the control group which exhibited a shelf-life of only 22 days.	Kourkoutas and Proestos (2020)

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shelf-life of foods. Various potential hurdle techniques are reported to improve the stability and quality of foods. Traditional thermal treatments disrupt the stability of thermolabile constituents of food so the non-thermal techniques using the hurdle technique could be one of the alternatives to protect the quality and safety of foods (Putnik et al., 2020; Table 3).

4.1. Ultrasound

Ultrasonication is non-destructive technology that offers several advantages such as rapid processes, high efficiency, and improved quality and shelf life (Figure 1A). The ultrasonication can be used for different processes like tenderization, brining, cooking, thawing, and microbial inactivation in muscle foods (Bhargava et al., 2021). However, application requires high energy input increasing cost, sometimes incomplete (microbial inactivation and enzyme inhibition) results are obtained and induced quality deterioration (Li and Farid, 2016). Nano coating was prepared with an ultra-sonication technique using carboxymethyl chitosan and garlic aqueous extract and this was applied to the Ready-to-Eat (RTE) spiced chicken meat for shelf life extension. The TVB-N and TBARS were considered microbial indicators and these parameters were found well within the control during storage (Diao et al., 2020). The combination of ultrasound and slightly acidic electrolyzed was used to enhance the shelf life of sea bass (*Lateolabrax japonicus*) fillets. This treatment combination showed a distinct effect to prevent protein degradation and improved sensorial quality during storage (Lan et al., 2021).

4.2. Pulsed electric field

Figure 1B represents the muscle food preservation process using pulsed electric field instrument. Electroporation introduced by the PEP increases the penetration of phenolic compounds and also helps to dissolve CO_2 which leads to the formation of carbonic acid. Polyphenol oxidase (PPO) is mainly responsible for the browning of food products, which was significantly reduced during the application of PEF in Pacific white shrimps (Shiekh and Benjakul, 2020a). It was also recorded a further reduction in PPO activity when Pacific white shrimps were treated with 1% Chamuang leaf extract (CLE) under higher CO_2 concentration. Shiekh et al. (2021b) studied the effect of PEF

TABLE 3 Natural bioactive compounds in combination with other hurdles (non-thermal techniques, packaging, etc) for muscle food preservation.

Sample	Hurdles	Observation	Reference
Ready to eat spiced chicken meat	Carboxymethyl chitosan, garlic aqueous extract and ultrasound treatment.	The application of ultrasound treatment resulted in an extension of the shelf life of ready-to-eat spiced chicken meat for up to six days.	Diao et al. (2020)
Pacific white shrimp (*Litopenaeus vannamei*)	Chamuang leaf extract, vacuum packaging and pulsed electric field.	Pulsed electric field treated and vacuum packed Pacific white shrimp attained a shelf life of 18 days with minimum protein carbonyl content, total volatile bases, pH, microbial count and lipid oxidation.	Shiekh et al. (2021a)
Pacific white shrimp (*Litopenaeus vannamei*)	Chamuang leaf extract, vacuum impregnation, pulsed electric field and high voltage cold atmosphere plasma	Pacific white shrimp treated with 2% chamuang leaf extract with the aid of vacuum impregnation, pulsed electric field and cold atmosphere plasma has significantly reduced the melanosis score and extended its shelf life to 18 days at 4°C.	Shiekh et al. (2021b)
Pacific white shrimp (*Litopenaeus vannamei*)	Chamuang leaf extract, pulsed electric field and cold atmosphere plasma	*Litopenaeus vannamei* showed lower protein carbonyl content, total volatile base, pH, peroxide value and microbial content and a shelf life extension of 9 days when treated with pulsed electric field and cold atmospheric plasma.	Shiekh et al. (2021c)
Squid rings	Custard apple leaf extract, pulsed electric field	Pulsed electric field treated ethanolic custard apple leaf extract increased the shelf life and storage quality of the squid rings by more than 6 days	Olatunde et al. (2021)
Schizothorax prenati	Zein/potato starch-based film incorporated with chitosan nanoparticles and curcumin.	Delayed the quality alterations on *Schizothorax prenati* fillets and extended its shelf life up to 15 days	Xin et al. (2020)
Active packaging of foods	Agar, chitosan, and carrageenan-based film incorporated with curcumin	Improved its antimicrobial property, antioxidant activity, water vapor barrier property, surface hydrophobicity, swelling ratio and UV-blocking of the film and can be successfully used for active packaging of foods.	Roy and Rhim (2020)
Beef slices	Sodium alginate with ginger essential oil.	Extended the shelf life of fresh beef chilled beef by 9 days.	Zhang et al. (2021)
Chicken breast patties	Rosemary extract and cold plasma treatment.	Reduced lipid oxidation, microbial count and increased colour and pH of chicken breast patties. The shelf life of chicken breast patties was of 6 days	Gao et al. (2019)
Breast chicken fillets	Atmospheric cold plasma and essential oils.	The breast chicken fillets treated with atmospheric cold plasma and essential oils reduce the microbial content without significantly altering the sensory quality of the fillets up to 14 days of refrigerated storage	Sahebkar et al. (2020)
Asian sea bass slices	High voltage cold atmospheric plasma and squid pen chitooligosaccharides.	Incorporation of chitooligosaccharides on the cold atmospheric plasma treated Asian sea bass slices resulted in a reduction in the peroxide value, thiobarbituric acid reactive substances, thiobarbituric acid reactive substances and increase in its shelf life for at least 12 days at 4°C.	Singh and Benjakul (2020)

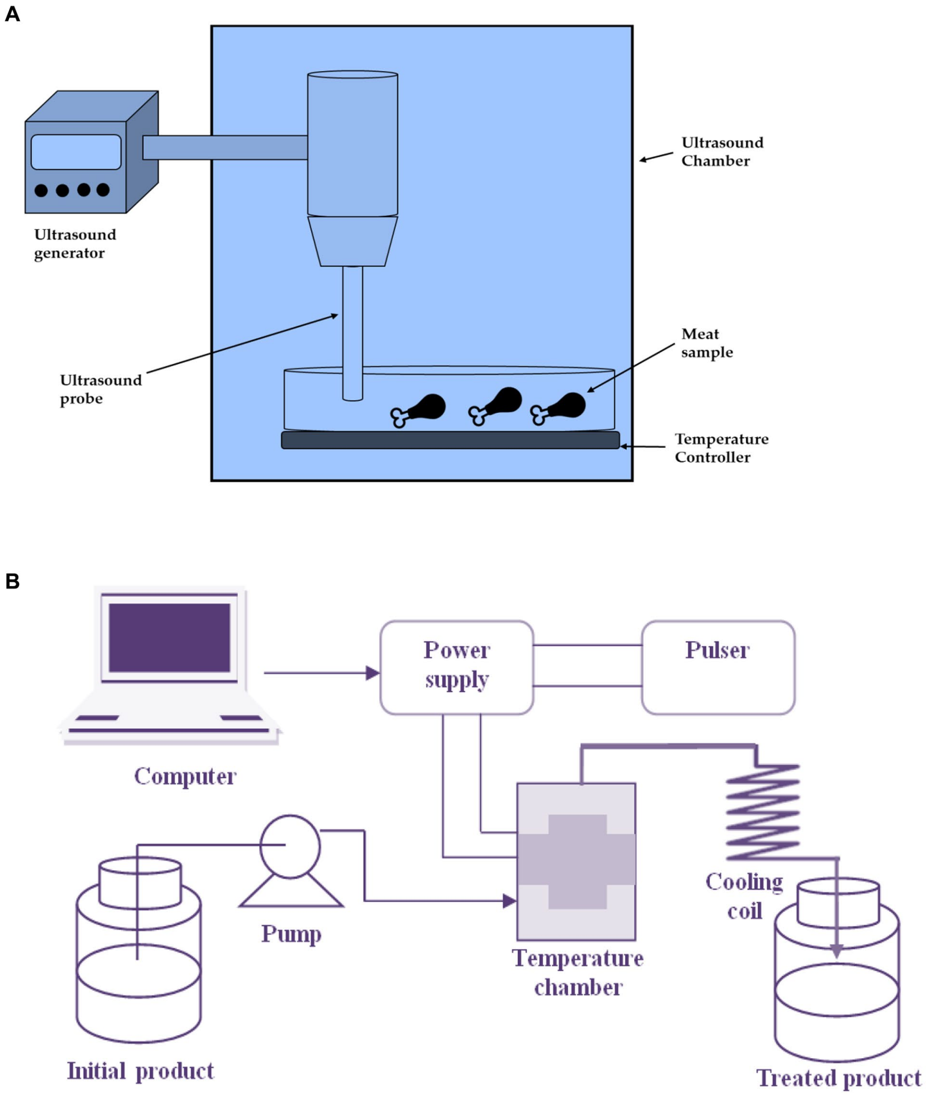

FIGURE 1
Schematic presentation of muscle food treatment using ultrasonication **(A)**, and pulsed electric field operation **(B)**. PEF was reproduced from Mohamed and Amer Eissa (2012).

subsequently soaking in 1%CLE followed by modified atmospheric packaging with N_2, Ar or $CO_2$of shrimp. The combination of PEF- CLE and CO_2 showed lower pH, carbonyl content, TVB-N, peroxide value, and TBARS. Also, it was observed that it was more effective against Psychrophile, *Enterobacteriaceae*, *Pseudomonas*, lactic acid bacteria, and H_2S-producing bacteria. Therefore, it can be concluded that PEF- CLE, and CO_2 can be used to prolong the shelf life of refrigerated shrimps (Shiekh et al., 2021b). The Pacific white shrimps were pre-treated vacuum impregnation of CLE before PEF and packed high voltage cold atmosphere plasma using Ar/Air to improve shelf life (Shiekh et al., 2021a). This treatment showed lowered lipid oxidation, pH, TVB, and protein carbonyl content during 18 days of storage, which concluded that this hurdle combination can be feasible to extend the shelf life in muscle foods.

The *Litopenaeus vannamei* were pre-treated with PEF and immersed in Chamuang leaf extract and followed by High Voltage Cold Atmospheric Plasma and packed in the modified Atmospheric packaging to improve storage stability (Shiekh et al., 2021c). The combination of all these techniques significantly inhibits the microbial growth in *Litopenaeus vannamei* resulting in increased shelf life (Shiekh et al., 2021c). The antibacterial and antibiofilm properties of the ethanolic extract derived from custard apple leaf have been demonstrated. When custard apple leaf extract was combined with PEF it showed better bactericidal properties against *Bacillus subtilis, Listeria monocytogenes, Escherichia coli*, and *Pseudomonas aeruginosa* (Olatunde et al., 2021). It was recorded that the custard apple leaf (400 mg/kg) pre-treatment before PEF extended the shelf life of refrigeratedsquid rings more than 6 days (Olatunde et al., 2021).

4.3. Cold plasma

Recently the application of novel non-thermal processing technology, cold plasma (CP), for the preservation of food has attracted a lot of interest from both processors and consumers. In-package dielectric barrier discharge (DBD) atmospheric cold plasma (CP) (Figure 2) is a recent non-thermal method to destroy food-borne pathogens and enhance the shelf life of fresh food products (Rathod et al., 2021, 2022). CP generates several reactive species such as ozone, hydroxyl radical, atomic oxygen, UV, Radiation energetic ions, etc. within the package (Rathod et al., 2021). These active components are well known for bactericidal, fungicidal, and virucidal actions. Many authors have reported the antimicrobial effect of DBD CP against food spoilage organisms for muscle foods (Gavahian et al., 2019; Panpipat and Chaijan, 2020). CP has exhibited its ability to inhibit the growth of gram-positive, negative, and pathogenic microorganisms and the inactivation of enzymes thereby, assuring food safety and security to the consumers.

On the other hand, some slight negative impacts of CP were reported to induce the oxidation of lipids and a slight deterioration in sensory qualities. These were due to the interaction of radicals generated. While some interventions reported in the literature were said to be reducing the abrupt impacts on oxidation and sensory qualities. Gaviahian and others (Gavahian et al., 2019) reported that the lipids oxidation induced by an oxygen-containing cold plasma process can eventually affect the acceptability and shelf-life of foods. Higher peroxide and thiobarbituric acid reactive substances (TBARS) values were recorded in the CP-treated meat samples, which indicates that CP can induce the acceleration of primary and secondary lipid oxidation (Pérez-Andrés et al., 2020). Meat products contain higher amounts of lipids, and the reactive species generated during cold plasma processing stimulate the oxidation of these lipids, thereby deteriorating food quality (Jadhav and Annapure, 2021).

The oxidation of chicken meat can be reduced in cold plasma when it is pre-treated with 1% rosemary extract (Gao et al., 2019). Essential oil and cold plasma treatments when used in combination resulted in low oxidation of lipids and ultimately extended shelf life

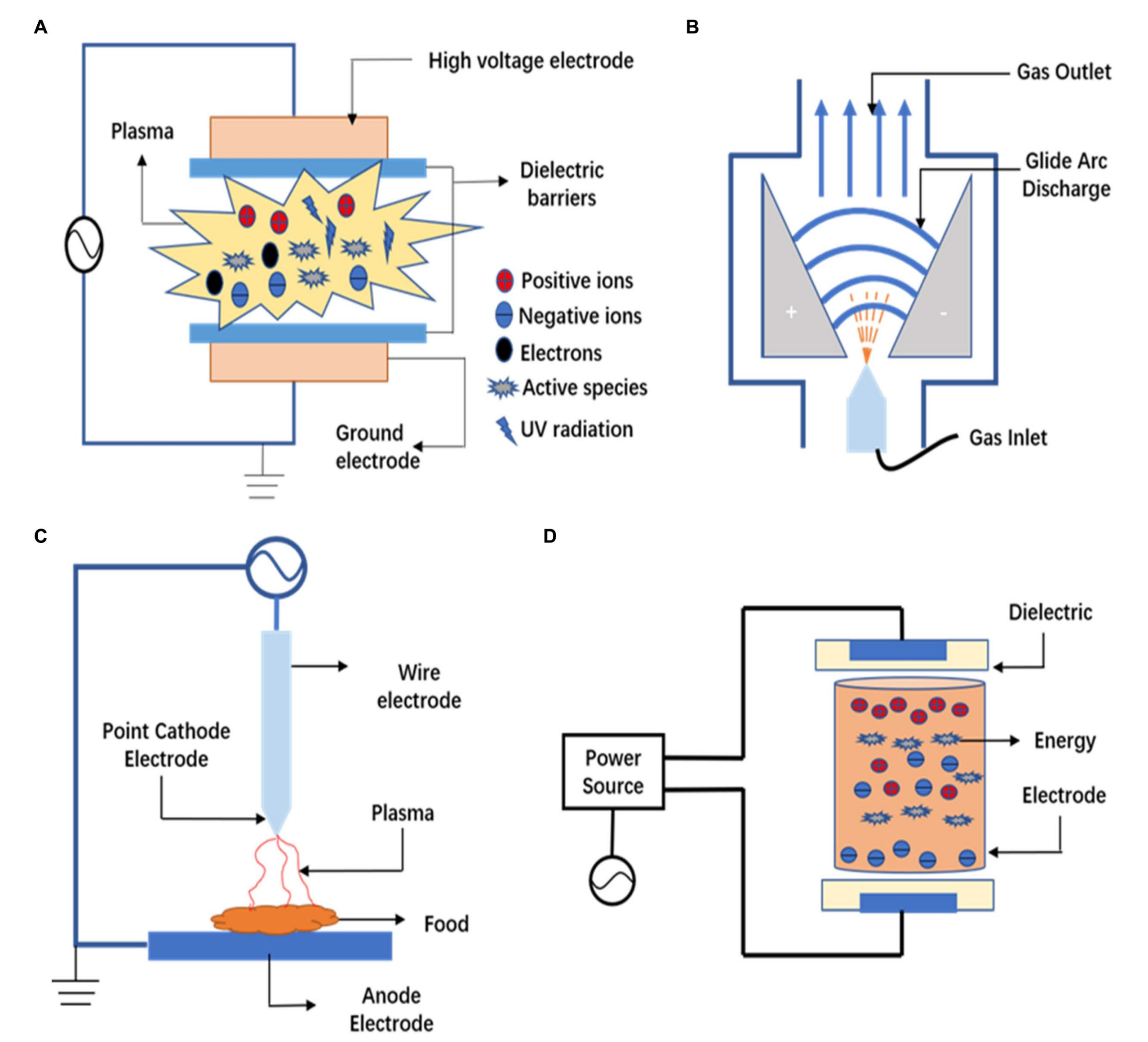

FIGURE 2
Schematic presentation of plasma discharge using various equipment's **(A)** dieletric barrier, **(B)** corona, **(C)** glow and **(D)** glide arc instrument. Reproduce from Zhang et al. (2022).

(Sahebkar et al., 2020). Inguglia et al. (2020) reported a reduction in the microbial load up to 0.85 log CFU/gm of lean beef when treated with air plasma and activated brine. The ground ham combined with ascorbic acid before cold plasma treatment reduces lipid oxidation during storage (Lee et al., 2018). Fish treated with chito-oligosaccharides and cold plasma were reported to arrest the oxidation of fatty acids in storage (Singh and Benjakul, 2020).

Modified atmospheric packaging with higher CO_2 concentration and lower O_2 concentration when used in combination with cold plasma treatment resulted in the improved shelf life of chicken meat patties at refrigerated condition (Zhuang et al., 2020).Vacuum-packed beef samples treated with cold plasma resulted in low TBRAS values during 13 days of storage (Bauer et al., 2017).The cold plasma when combined with a pulsed electric field (PEF) reported to lower the microbial load and extend the shelf life of shrimps (*Litopeaneus vannamei*). These combinations predominantly lower the *Pseudomonas* count up to 4.95 log CFU/g (Shiekh et al., 2021c). The *Escherichia coli* and *Staphylococcus aureus* were significantly reduced when chicken meat was treated with ultrasonication and cold plasma-activated water (Royintarat et al., 2020).

5. Impacts of different methods of application on muscle food preservation

The application method and concentration of bioactive compounds interact with the food matrix impacting quality attributes (Hassoun and Çoban, 2017; Vlčko et al., 2022). Hence different application methods have a vital role in the preservation of foods.

5.1. Soaking or dipping

Direct addition of natural bioactive compounds is also practiced; however, the direct additions compounds requiring severe mixing. The mixing process is known to alter the quality of the food matrix and even in cases leading to oxidation and negatively affecting the quality of muscle foods. With the advent of novel technologies, their application in proper encapsulated and nanoform reduced the negative impacts on the quality and ensured uniform distribution in the food matrix (Rathod et al., 2023). Dipping herring co-products in rosemary extract containing antioxidants for preservation was evaluated (Wu et al., 2021). In comparison to other commercial antioxidants, rosemary extract in oil-soluble form (0.2%) inhibited lipid oxidation and bacterial growth. Similarly, treatment of shrimp with natural extract from CLE preceded by pulsed electric field application lowered the melanosis, lipid oxidation, and microorganisms in comparison to sodium metabisulfite treatment (Shiekh and Benjakul, 2020b). Application of low-intensity PEF resulted in denaturation of enzymes and further penetration of polyphenols from leaf extract lowered further development of melanosis. The direct dipping in combination was also found to inhibit the growth of total viable count, Psychrotrophic bacteria, *Pseudomonas*, hydrogen sulfide-producing bacteria, and *Enterobacteriaceae* count. The direct dipping in bioactive compounds present in natural extracts inhibit the oxidation and growth of microorganisms (Ribeiro et al., 2019; Rathod et al., 2021).

Similarly, inclusion of red pitaya extracts and banana inflorescence in value added meat products made from pork lowered oxidation and microbial population (Rodrigues et al., 2020; Bellucci et al., 2021). The inclusion of plant-based bioactive extracts, based on their diverse bioactivity lowers the oxidation of fatty acids and inhibits the growth of microorganisms used in the preservation of foods (Rathod et al., 2021).

5.2. Packaging

Recently, active packaging of foods to ensure food safety and quality has been focused (Rathod et al., 2023). Natural bioactive compounds from natural sources are being evaluated and utilized by the food packaging industry (Pateiro et al., 2019). Inclusions of bioactive natural compounds are included in packaging material to interact with food packed inhibiting the growth of microorganisms and oxidation (Kapetanakou and Skandamis, 2016). Further advances in nanotechnology encapsulating the natural compound ensure prolonged delivery of the compound (Chawla et al., 2021). Recently, Venkatachalam and Lekjing (Venkatachalam and Lekjing, 2020) evaluated the ability of chitosan (2%) based film containing clove essential oil and nisin as a natural bioactive agent for the preservation of pork patties. The film containing a combination of clove oil and nisin was found to inhibit lipid oxidation (free fatty acid, peroxide value, and thiobarbituric acid reactive system) followed by clove oil alone during 15 days of storage of pork patties. Similarly, the effectiveness for inhibition of total viable count, psychrotrophic bacteria, *Enterobacteriaceae*, and lactic acid bacteria were found (Venkatachalam and Lekjing, 2020). Authors suggested inhibition of microbial population, chelation of metal ions, free radical scavenging action inhibited lipid oxidation and microbial proliferation by synergistic effects of natural additives used. Similarly, role of chitosan film containing grape seed extract and carvacrol microcapsules was found to inhibit lipid oxidation and microorganisms growth (Alves et al., 2018). The natural extract-based packaging exhibited antibacterial effects extending shelf life by retarding the microbial proliferation and physical and chemical deterioration in muscle foods.

5.3. Coating

Bioactive agents from natural materials such as antimicrobial compounds (phenolic compounds, organic acids, nisin, and bacteriocin) and antioxidants (plant extracts and essential oils) are usually used as coatings to inactive the food-spoiling organisms and shelf life extension (Table 4). Applications of agents by proper encapsulation material have also been reported to extend preservative action.

The water buffalo meat was coated with a combination of chitosan and laurel essential oil and packed in aerobic conditions and stored at 4°C to study the shelf life. The results of the microbial and sensory analysis showed improved shelf life in the sample coated with chitosan and laurel essential oil up to 14 days as compared to the untreated sample which shows only a 5–6 days shelf life (Karakosta et al., 2022). Flavonoids, known for their antioxidant properties, are present in extracts of laurel and sage. The presence of tannins in the extracts has been found to enhance the texture of meat by binding to proteins. The essential oils present in the extracts exhibit antibacterial properties that effectively eliminate or hinder the growth of bacteria, thereby impeding the spoilage of the meat balls. Martínez and others

TABLE 4 Impacts of soaking/dipping and edible coating of natural bioactive compound for the preservation of muscle foods.

Base material	Bioactive ingredient for film/ coating	Food item	Action recorded	Reference
Soaking/dipping				
Scallion, Garlic and Kiwi	Lyophilized extracts	Chicken breast	Reduced microorganisms and lipid oxidation	Kim et al. (2019)
Cinnamon	Cinnamon oil nanoemulsion	Asian seabass fillets	Inhabited proliferation of Total viable count and lipid oxidation	Chuesiang et al. (2020)
Rosemary extract	Ethanol extract of rosemary	Beef	Inhibited *Listeria monocytogenes*, *Salmonella enteritidis* and Coliform	Soyer et al. (2020)
Tulsi	Tulsi extract	Tuna fish chunks	Inhibited lipid oxidation (PV)	Suyani et al. (2020)
Pomegranate peel	Pomegranate peel extract	Beef meatballs	Retarded oxidation (protein and lipid)	Turgut et al. (2016)
Edible coating				
Chitosan and alginate	Resveratrol	Sea bass (*Dicentrarchus labrax*) fillets	Antioxidant and antimicrobial activity	Martínez et al. (2018)
Chitosan film	Clove essential oil and nisin	Pork patties	Shelf –life extension	Venkatachalam and Lekjing (2020)
Chitosan	*Trachyspermum ammi* essential oil	Chicken fillets	To Improve shelf life	Karimnezhad et al. (2017)
Carrageenan	Olive leaves extract	Lamb meat	Antioxidant and antimicrobial activity	Martiny et al. (2020)
Agar	Fish protein hydrolysate or clove essential oil	Flounder (*Paralichthy sorbignyanus*) fillets	Shelf –life extension	Da Rocha et al. (2018)
Whey protein isolate	Laurel and sage extracts	Cooked meat balls	Antioxidant and antimicrobial activity	Akcan et al. (2017)
Soybean protein	Curry leaves power	Boneless chicken breasts	Improve sensory quality	Di Giorgio et al. (2019)
Gelatin film	*Caesalpinia decapetala Extract*	Beef patties	Improve mechanical and sensorial properties	Gallego et al. (2016)
Fish myofibrillar protein	Catechin–Kradon leaves extract	Bluefin tuna	Antioxidant and antimicrobial activity	Kaewprachu et al. (2017)
Gelatin	Garlic peel extract	Rainbow trout (*Oncorhynchus mykiss*) fillets	Shelf life extension	Ucak (2019)
Gelatin/chitosan	Betel Leave Extract	Tilapia slices	Shelf life extension	Tagrida et al. (2022)

(Martínez et al., 2018) studied the effect of resveratrol pre-treated and Alginate – Chitosan coating on Sea bass (*Dicentrarchus labrax*) filets. The results revealed of resveratrol and Alginate – Chitosan coating was better when the samples were vacuum packed and stored at 4°C. The protective effects of resveratrol on products can be attributed to its ability to scavenge free radicals and damage microbial cell membranes, thereby preventing oxidation and infection. The enzyme activity is reduced by resveratrol, which leads to the inhibition of bacterial and fungal growth. It is well-known that Nisin is not effective to avoid lipid oxidation. However, when it is combined with the Clove essential oil, it provides protection against oxidation and microbial spoilage, which improved the shelf life of pork patties almost two-fold in a combination of low temperature 4°C (Venkatachalam and Lekjing, 2020). The antimicrobial activity of clove essential oil is attributed to the presence of Eugenol, a potent antimicrobial agent. Eugenol has the potential to damage the cell membranes of bacteria and fungi, leading to their death. Additionally, eugenol may interfere with the metabolism of bacteria and fungi, thereby inhibiting their growth. The mechanism of action of nisin involves the disruption of bacterial cell membranes. The binding of the compound to a particular receptor on the bacterial surface facilitates its cellular entry and subsequent bactericidal activity. The Olive leaves extract and Carrageenan coating to possess high antioxidant activity due to the presence of phenolic content in the olive leaf extract (Martiny et al., 2020). Also, Carrageenan shows a lower water vapor transmission rate (WVTR) which can beneficial for shelf life extension. When Olive leaves extract and Carrageenan coating were applied to the Lamb meat the shelf life was improved (Martiny et al., 2020). Polyphenols such as Oleuropein, hydroxytyrosol, and tyrosol are the primary antioxidants found in olive leaf extracts. These antioxidants have been shown to effectively scavenge free radicals and prevent the oxidation of lipids and proteins. The antimicrobial activity of the substance is demonstrated through its ability to disrupt the cell membranes of bacteria and fungi. The Flounder (*Paralichthys orbignyanus*) fillets were noted higher shelf life at 5°C when coated with Agar film combined with fish protein hydrolysate and clove oil (Da Rocha et al., 2018). The disruption of cell membranes of bacteria and fungi is a known mechanism by which small peptides and amino acids exhibit antimicrobial activity. Also, the author reported that prepared coating was more effective against mesophiles and sulfur-producing organisms.

The boneless chicken breasts packed in soy protein containing curry leave powder showed better stability against oxidation as well as improved consumer acceptability (Di Giorgio et al., 2019). The formation of flavor compounds is observed as a result of the reaction between the volatile compounds of curry leaves and the amino acids present in chicken. The research findings suggest that the carotenoids present in curry leaves contribute to the enhancement of color, while the enzymes present in curry leaves powder facilitate the improvement of tenderness in chicken meat. This is achieved through the process of proteolysis, which breaks down the proteins in the chicken. Improved inhibitory effect against oxidation and microorganism was recorded in the Fish myofibrillar protein coating when combined with Catechin–Kradon leaves extract (*Careya sphaerica Roxb.*) (Kaewprachu et al., 2017). When this coating applied to the Bluefin tuna (*Thunnus thynnus*) slices the shelf life increases from 2 to 8 days (Kaewprachu et al., 2017). The extract of Catechin-Kradon leaves contains Catechins, flavonoids, and tannins, as evidenced by previous research. The chelation of metal ions and the disruption of bacterial and fungal cell membranes are among the effects of catechins, as reported by research. According to research, flavonoids have been found to possess inhibitory properties against enzymes that are essential for the growth of bacteria and fungi. Additionally, tannins have been observed to bind with proteins, thereby causing disruption of the cell membranes of bacteria and fungi. The gelatine combine with garlic peel extract and applied to Rainbow trout (*Oncorhynchus mykiss*) fillets increased shelf life from 5 to 10 days (Ucak, 2019).The active components of garlic peel extract, namely allicin, ajoene, and sallyl cysteine, have been found to possess the ability to cause damage to the cell membranes of bacteria and fungi. The antioxidant activity of garlic peel extract is attributed to the presence of flavonoids, which act by scavenging free radicals and inhibiting the oxidation of lipids and proteins. The application of garlic peel extract has been found to exhibit antioxidant properties that can potentially prevent the oxidation of carotenoids. This may result in the preservation of the color of fish fillets. It was noted that the incorporation of betel leaf ethanolic extract in gelatine/chitosan coating not only improves the antioxidant and antimicrobial activity but also improves mechanical strength and barrier properties (Tagrida et al., 2022). Further, the coating incorporated with betel leaf ethanolic extract improves the shelf life of Tilapia slices from 3 to 9 days (Tagrida et al., 2022).The Betel Leave Extract has been found to contain polyphenols, flavonoids, and tannins, which have been observed to exhibit inhibitory effects against bacteria and fungi. This is believed to be due to the disruption of the cell membranes of these microorganisms. The study investigated the potential of BLEE to scavenge free radicals and prevent oxidative damage in tilapia slices. Additionally, the study aimed to determine whether BLEE could protect carotenoids from oxidation.

5.4. Feed supplement

Feed supplementations by using natural sources of bioactive compounds are known to exhibit positive results on animal health and improve the preservation of muscle foods. The Source of bioactive compounds such as curcumin, carvacrol, thymol, cinnamaldehyde were evaluated as feed supplements for the broiler chicken (Galli et al., 2020a,b). The results exhibited inhibition in lipid oxidation based on dietary supplementation with curcumin (12.5 nmol MDA/mg), phytogenic (18.7 nmol MDA/mg) and a combination of curcumin and phytogenic (9.23 nmol MDA/mg) in comparison to control sample (25.6 nmol MDA/mg). Additionally, significant inhibition of bacteria counts (total bacterial count, *E. coli*, and oocyst) was observed. Similarly, positive impacts on lipid oxidation and total bacterial count due to dietary supplementation with curcmin and curcumin with yucca extracts were observed (Galli et al., 2020b). Dauksiene et al. (2021) investigated the effects of dietary supplementation of organic acids for preserving broiler chickens. An organic acid-supplemented diet inhibited the growth of a wide range of microorganisms ensuring meat safety.

6. Future prospects and conclusion

Muscle foods are prone to spoilage during postharvest storage, hence to preserve them several preservatives are employed. Considering the recent consumer trend toward food preserved using natural preservatives is increased. Natural bioactive compounds exhibit different preservation mechanisms, helping in the shelf life extension of muscle foods. The extraction of bioactive compounds without the usage of chemicals and at lower operating temperature conditions helps in improving bioactivity without the issue of chemical residue. The current review has demonstrated the improvement in the bioactivity of natural compounds extracted using non-thermal technologies. Furthermore, the inclusion of natural bioactive compounds for the preservation of muscle foods exhibited preservative action. Also, the preservative action could be further enhanced when the samples are used in combination with other methods (hurdle technology). The application of natural bioactive compounds inhibits the microorganisms responsible for food spoilage, and oxidation of lipids and proteins. Additionally, the application of natural bioactive compounds had no detrimental impacts on sensory quality in muscle foods.

However, a large number of studies have reported the impacts of natural bioactive compounds on the preservation of muscle foods. Further studies are required to scale up the standardized process for formulation of effective bioactive compounds from a natural source, and assess their compatibility for food preservation. Special focus should be given to novel non-thermal techniques for extraction and technologies to improve the delivery efficiency extend the preservative impact and lower the undesired characters. From the reports analyzed it was observed that the application of natural bioactive compounds in combination with other preservation could extend the shelf life of muscle foods.

Author contributions

NN: conceptualization. NR, NN, SA, VS, RR, SK, and PC: writing—original draft preparation. NR, NN, SB, and FA-A: writing—review and editing. NN and FA-A: supervision. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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