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The application of electrostatic field technology for the preservation of perishable foods

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Abstract

With the global promotion of healthy diet, people's demand for freshness of food has risen, so extending the shelf life of food has become a hot topic now. Electrostatic field is widely concerned because it has the advantages of simple equipment, low cost, low maintenance, low energy consumption, one investment can be used for a long time, flexible operation, no drug pollution, no secondary pollution to the environment, and can better retain the original quality and flavor of food. As a non-thermal physical preservation technology, electrostatic field preservation can produce ozone and electric ions to kill bacteria inside and outside the food and reduce the enzyme activity, so as to play the effect of preservation. In this paper, based on the introduction of the working principle and mechanism of action of electrostatic field processing technology, the research progress of the application of this technology in different perishable food sterilization and preservation is described, and the limitations of electrostatic field technology are proposed, in order to provide a theoretical basis for the processing application of electrostatic field in perishable food and to provide guidance for the industrial production of electrostatic field.

Keywords: electrostatic field; food preservation; perishable food.

Practical Application: Electrostatic field technology can sterilize and blunt enzymes to extend the shelf life and improve the freshness of food. This paper summarizes the optimum electrostatic field strength of perishable food and its effect of preservation, which will be a good guide for research scholars. In practice, a safe electrostatic field preservation cabinet can be made to store the food in the cabinet and take it out when it needs to be consumed. For some companies, it can also be made into a large storage room, after all, the electrostatic field has a wide range of field strength, good preservation effect and low energy consumption.

1 Introduction

Perishable food refers to the natural temperature environment under the influence of temperature and humidity, the storage time is prone to animal food death or deterioration, or plant food decay, mold and other abnormal quality problems (Chen et al., 2019). According to data, China consumes more than 1 billion tons of perishable food every year, but 45% of the food is spoiled due to the lack of preservation equipment. In order to extend the shelf life of perishable foods, suitable preservation techniques must be used to ensure the quality of perishable foods and improve their utilization value (Jadhav et al., 2021). Currently, the main preservation methods commonly used for perishable foods are physical, chemical and biological preservation (Zhang et al., 2019). Each method has different characteristics (Table 1). As the most common preservation method in the field of food storage, physical preservation technology is popular in the food processing industry for its advantages such as high safety and simple operation. Physical preservation mainly includes low temperature, gas conditioning, plasma and electrostatic field technology, etc (Chakka et al., 2021; Sur et al., 2020).

Usually, the heat generated by processing treatments can adversely affect the texture, color, flavor and nutrient content of food products, thus non-heat treatment methods for food products have great appeal to the food industry. Traditional preservation techniques such as low temperature preservation, gas preservation, and preservative preservation have been found to have certain shortcomings during their long-term use, while electric field technology overcomes these problems (Barbhuiya et al., 2021).

Electrostatic field (EF) as a non-thermal processing technology, through the power supply and different shapes of electrodes to form a uniform or uneven electric field, in the polarization force and corona wind (also known as ionic wind) and other electrohydrodynamics parameters, change the heat and mass transfer, a certain impact on life activities, can kill bacteria inside and outside the food, reduce the activity of enzymes, in order to achieve the effect of preservation (Dalvi-Isfahan et al., 2016b). After the treatment of perishable food by electrostatic field, the transmembrane potential of its biological cell membrane is affected by the applied electric field, which changes the physiological metabolism, and the internal bioelectric field affects the electron transfer body of the respiratory system of the organism by the internal bioelectric field, which inhibits the redox reaction in the organism, and the electrostatic field causes the resonance phenomenon of water molecules, and the water structure and the binding state of water and enzymes are changed by the applied electric field, which eventually leads to the inactivation of enzymes (Ko et al., 2016). In addition, under the action of electrostatic field, the external air ionization

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Table 1. The preservation of perishable food.

Fresh way	Preservation technology	Characteristics
Physical preservation	Electrostatic field Ultra-high pressure Modified atmosphere Low temperature preservation	Pros: The effect is obvious, the treatment time is short, the preservation time is long, retains the original flavor. Cons: The equipment is complex.
Chemical preservation	Salt preservation Smoked preservation Immersion preservation	Pros: The operation is simple and the effect is good. Cons: There are some deficiencies such as antimicrobial residue and bacterial resistance.
Biological preservation	Chitosan Tea polyphenols	Pros: Tasteless, non-toxic, safe, and will not cause secondary pollution. Cons: Making complex.

will produce a certain amount of ozone, negative ions. Using the strong oxidation characteristics of ozone to kill bacteria, fungi and viruses on the surface, oxidation and decomposition of perishable food in the storage period released ethylene, ethanol and other harmful gases; the use of negative ions strong penetration into the perishable food body to inhibit respiration, can play a perishable food spoilage, extend the storage period and shelf life of the role (Qi et al., 2021).

In the field of perishable food processing, electrostatic field technology is regarded as a key technology for sterilization and preservation, enzyme inactivation and process modification (Wang et al., 2018). Electrostatic field preservation has the advantages of simple equipment, low cost, low maintenance, low energy consumption, one investment can be used for a long time, flexible operation, no drug pollution, will not cause secondary pollution to the environment, can better retain the original quality and flavor of food, etc (Nian et al., 2022; Saletnik et al., 2022). This paper mainly summarizes the principles, types and equipment of electrostatic field technology, and focuses on the study of the inactivation of microorganisms and enzymes in perishable foods by electrostatic field equipment, in order to provide a reference for the wide application of electrostatic field technology in perishable foods.

2 Methodology

This paper completed a literature search using PubMed, Elsevier, Web of Science, and Scopus databases. The search was limited to papers published in English between January 2012 and March 2022. Articles were searched using phrases related to electrostatic fields ("EF", "HVEF", "LVEF") with respect to perishable food quality ("microbial inactivation", "enzyme inactivation", "food improvement", "food processing") were combined. In addition, this paper examines references from the search literature to identify additional eligible studies.

The information of the papers searched in this research contains first author, author affiliation, year of publication, safe storage and preservation technology, microbial control of food, electrostatic field technology in food industry, mechanism of inactivation of microorganisms by electrostatic field, effect of electrostatic field on enzymes in perishable food, processing of perishable food using electrostatic field treatment and achieving results.

3 Principles, types, and sources of EF

High-voltage electrostatic field biological effect refers to the biological stress response under the action of high-voltage electrostatic force, and the resulting biological growth and development or lethal effects. The electrostatic field biological effect was discovered as early as the mid-18th century, but it was not until recent decades that it received real attention from the scientific community and was studied systematically and intensively. The effects of electric fields on plant cell injury and plant respiration intensity have been studied by Murr (1963) and Sidaway (1966) in the 1960s. The specific research development is shown in (Figure 1).

Nowadays, electric field preservation technology has become more and more mature, and has been widely used in the field of non-thermal preservation of food, but the discussion and debate about the principle of electric field preservation has been continuous, and the industry has unified the following basic preservation mechanisms. First, the theory of cell membrane electric breakdown, high-voltage electric field through the corona discharge transient high voltage to change the cell electrical permeability, the permeabilized membrane area potential asymmetric shift, and then change the biological properties of the cell (Wasungu et al., 2014). The principle is shown in (Figure 2). Second, the water molecule

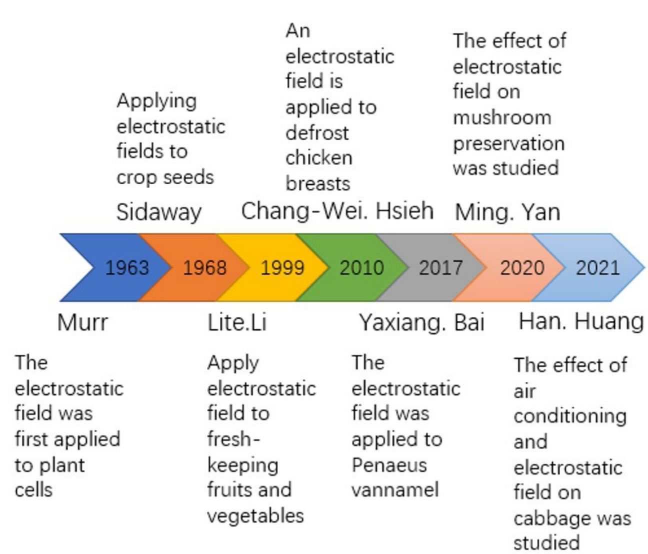

Figure 1. Evolution of electrostatic field in perishable food preservation.

vibration theory, the same frequency electric field of positive and negative charge movement between the water molecules polarized to form more metal bonds and produce water molecule vibration, the random direction of the hydrogen bond is broken, and in the direction of the electric field produced a stronger hydrogen bond, which leads to an increase in the potential energy of water molecules, water molecules freezing point is changed, and thus play a role in improving the final quality of frozen products (Xanthakis et al., 2013). The principle is shown in (Figure 3) .Third, the ice crystal nucleation theory, the electric field will cause water molecules to form ordered clusters, as the electric field strength increases, the ice crystal nucleation temperature gradually rises, the nucleation rate accelerates, the ice crystal in the muscle tissue becomes smaller, the protein structure is retained intact, the taste and chewiness of food is enhanced (Xie et al., 2021b). The principle is shown in (Figure 4). Fourth, the ozone sterilization theory, oxygen in the air is ionized by an electric field to form ozone, ozone can directly oxidize and destroy the cell wall and cytoplasmic membrane of bacteria, and then enter the cell and act on its DNA (Ma et al., 2017). The principle is shown in (Figure 5).

Electrostatic field treatment of perishable food is a process in which the perishable food to be processed is packaged in a suitable form or specification, placed in an airtight electrostatic field container, the voltage inside the container is increased using an electrostatic field device, and the generated ozone and negative ions are applied to the processed perishable food through an electrical discharge (Ranalli et al., 2002). The graph is shown in (Figure 6).

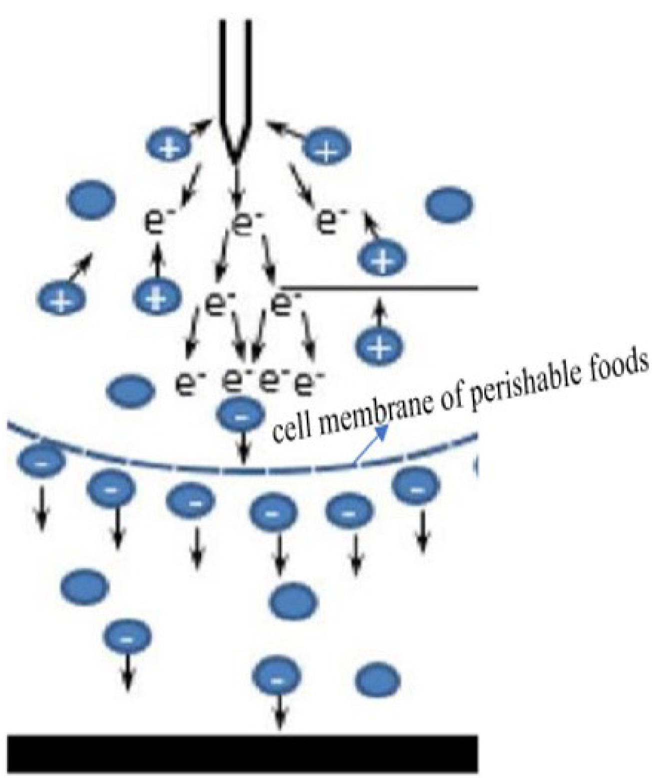

Figure 2. Preservation Principle 1.

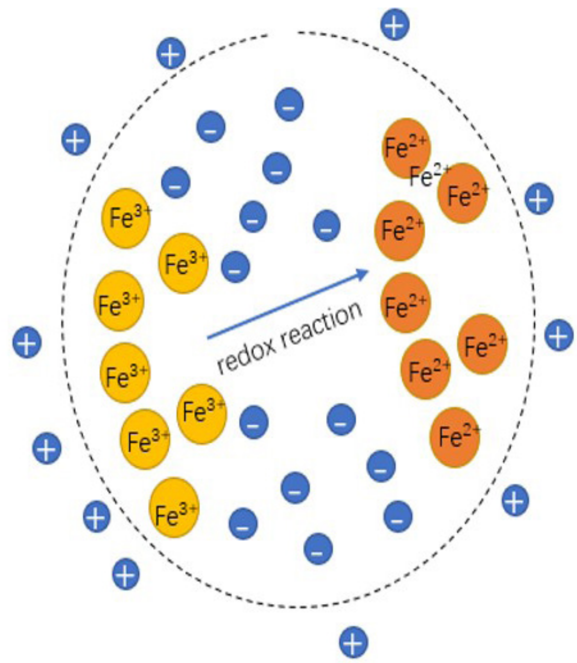

Figure 3. Preservation Principle 2.

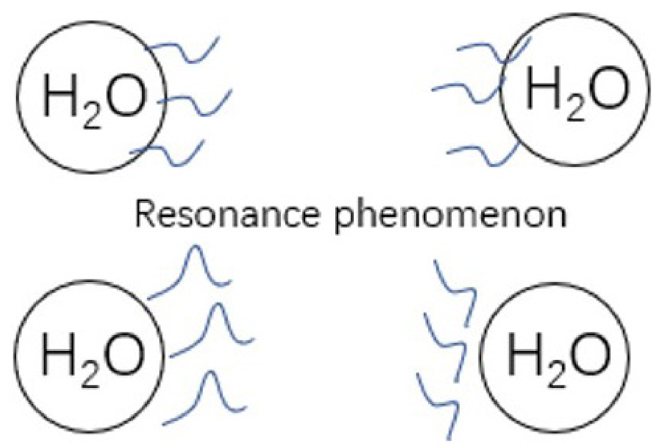

Figure 4. Preservation Principle 3.

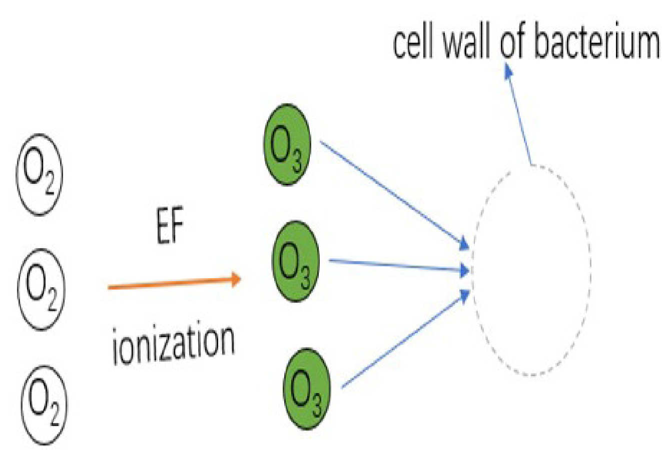

Figure 5. Preservation Principle 4.

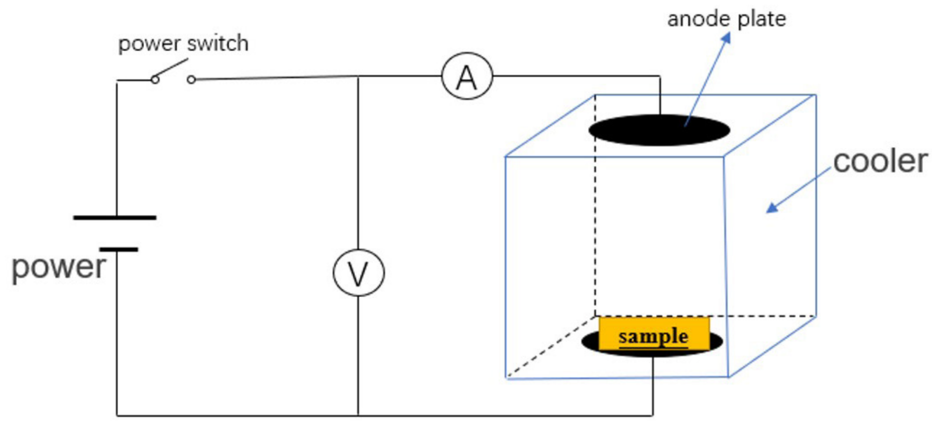

Figure 6. Schematic representation of a Electrostatic Field (EF) procedure.

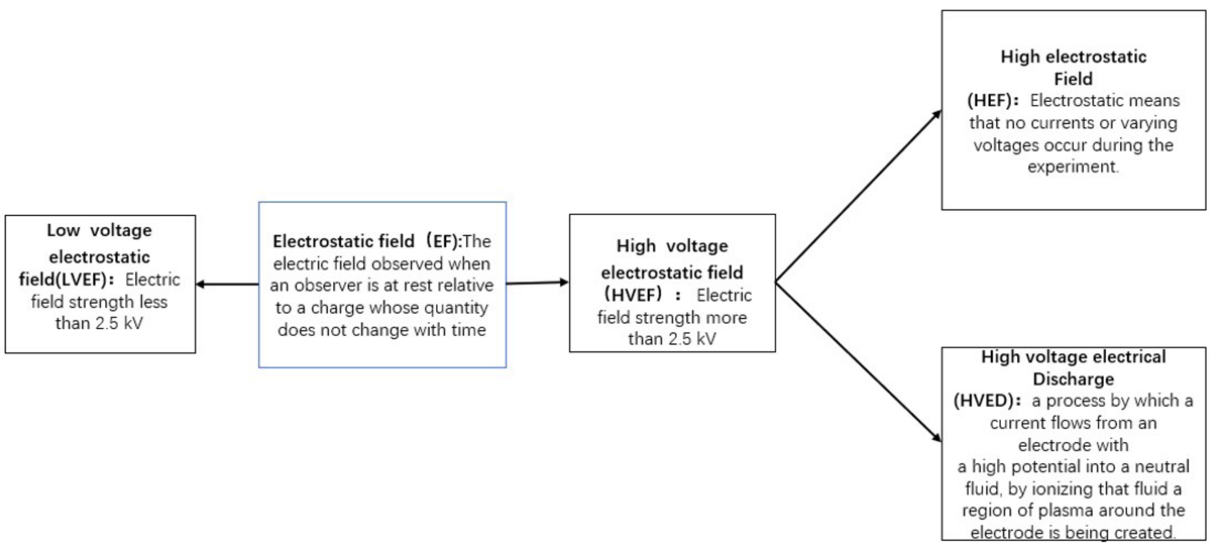

Figure 7. Characteristics of different EF plant.

Electric field preservation is divided into two modes: high voltage instantaneous preservation and low voltage continuous preservation. High voltage instantaneous preservation mode of electric field field strength is stronger than 10 kv/m, with fast, convenient, high-quality features, but the limitations of this method is its safety, electric field around a certain security risk, once the short circuit is easy to cause dangerous accidents. The field strength of low-voltage continuous preservation mode is less than 10 kv/m, although the preservation effect is slightly inferior, but the safety factor is high and easily accepted by the market (Dalvi-Isfahan et al., 2016b). The classification is shown in (Figure 7).

Electrostatic field can kill bacteria inside and outside the food, reduce enzyme activity, thus playing a fresh effect. An important process in food processing is sterilization, can be divided into heat sterilization and cold sterilization, heat sterilization is a long-standing and widely used sterilization method in the food industry, although this method has good results and high efficiency characteristics, but for the heat-sensitive substances are more destructive, and will cause a series of flavor, sensory quality of the decline (Mousakhani-Ganjeh et al., 2015). Electrostatic technology is a good non-thermal sterilization technology, unlike the traditional thermal sterilization method, which can effectively preserve the original flavor, nutrients and sensory quality of food, in addition to inactivating microorganisms. The number of E. coli and Salmonella typhimurium in the fillets of red carp treated with high voltage electrostatic field gradually decreased. That is, it can significantly inactivate E. coli and Salmonella typhimurium (Subakti et al., 2019). E. coli and Saccharomyces cerevisiae have similar experimental results when treated with high voltage electric fields, after which holes appear on their cell surfaces, intracellular protoplasts are deformed, while intracellular proteins and nucleic acids appear to exude. The electrostatic field can change the binding state of water molecules and active enzymes, and the water molecules appear resonance phenomenon under the influence of electric field, slowing down the enzyme active state (Tao et al., 2015). The activity of papain was different when it was placed in different frequencies, different electric field strengths and different treatment times, where the higher the strength and the longer the treatment time, the better the activity effect, i.e. the high voltage electrostatic field led to denaturation and possible aggregation of the enzyme (Meza-Jime, 2017). Optimal inhibition conditions for HVEF against radioactive immobilized bacilli is 30 kV/15 min. RecG, RadA, RecN and Dps gene expressions were upregulated 1.62-, 2.16-, 2.92- and 1.23-fold in Bacillus radiodurans after HVEF treatment (Huang et al., 2021a). After HVEF treatment, bacterial numbers and OD600 values of Acinetobacter JohnsonII decreased, cell content (nucleic acids and proteins) of Mononas Gianseri leaked, conductivity and reactive oxygen species (ROS) numbers increased 16.88-fold and Na+ K+ - atpase activity decreased (Huang et al., 2022).

4 Contributions of EF for food preservation

As mentioned earlier, electrostatic field technology is well able to extend the shelf life of perishable foods. Currently, the main applications of electrostatic field technology for preservation are divided into the following areas (Figure 8).

4.1 Application in the preservation of fruits and vegetables

At present, electrostatic field, as a high-tech physical preservation technology, has been used in the post-harvest storage and preservation of fruits and vegetables. Fruits and vegetables in the body of proteins and other substances with electrical charge, under the electrostatic field treatment, directional movement, affecting the flow of material and energy distribution in the cells of fruits and vegetables, can inhibit the process of various biochemical reactions after harvesting fruits and vegetables, has a positive effect on the preservation of fruits and vegetables. At the same time, the electrostatic field ionizes the air to produce ozone, which can effectively inhibit external microbial infestation and extend the storage period (Saletnik et al., 2022). In the actual application of fruit and vegetable preservation process, through the energized parallel electrode plate will generate a high-voltage electrostatic field between the transformer to change the strength of the electrostatic field, the fruits and vegetables to be treated into the parallel electrode plate, so that it is in a certain strength of the electrostatic field range, to achieve the preservation effect (Basak & Chakraborty, 2022). Electrostatic field in fruit and vegetable preservation applications are more research, the synergistic effect of air conditioning preservation and high voltage electrostatic field can extend the shelf life of fresh-cut cabbage to 60 days and small corn to 48 days (Huang et al., 2021b). Persimmon has the ability to retard tissue deterioration, inhibit tissue enzyme activity and suppress metabolism under high voltage electrostatic field treatment (Liu et al., 2017). High-voltage electrostatic fields can extend the shelf life of fresh-cut broccoli up to 40 days and have a potential impact on the storage quality of fresh-cut broccoli (Kao et al., 2019). The applications are shown in (Table 2).

4.2 Application of livestock preservation

Compared with fruits and vegetables, the application of electric field preservation in livestock and poultry is relatively less studied. Unlike plant cells, animal cells do not have a cell wall. When an electric field is applied, the voltage across the cell membrane increases, and when the membrane voltage exceeds its own strength, micro-pores are formed in the membrane (Cai et al., 2019). If the voltage on both sides of the membrane is larger than the critical value, the micropores become larger, and the cell itself cannot heal, the membrane permeability keeps increasing, and the cell endoplasm loses too much leading to death. Both pork and rabbit meat thawed by high voltage electrostatic field technology showed a significant reduction in the number of viable bacteria compared with air thawed samples, and the freshness of the thawed meat improved and the storage time increased (He et al., 2016). The size of ice crystals of pork loin muscle fibers treated with high voltage transients was reduced by 56% and the curvature of

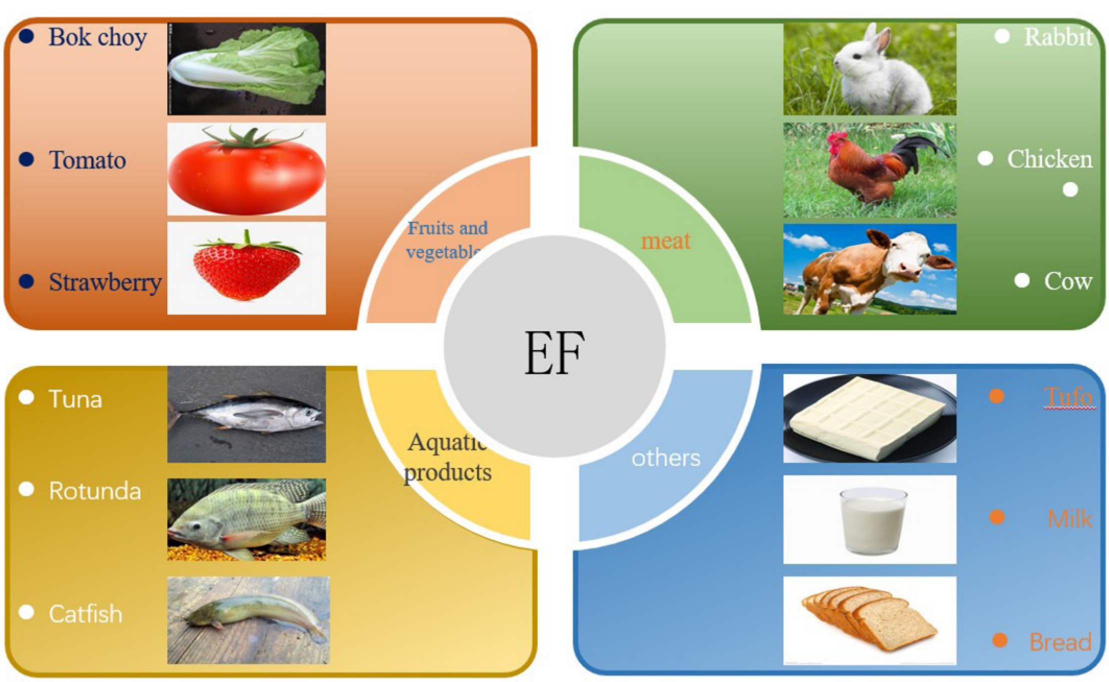

Figure 8. Main contributions of EF in perishable food preservations based on recently published research papers.

Table 2. Application in the preservation of fruits and vegetables.

Treated food	EF source	Results	References
apple	40/800v/cm -40/20 °C 90 h	Shorten thaw time Resulted in uniform distribution of osmotic pressure Has better texture and peel color retention	Parniakov et al., 2015
persimmon	600 kV/m 23 °C 15 d	Reduced the rate of weight loss by 1.0e3.4-fold Delayed the rate of decreasing hardness by 1.0e1.3-fold Suppressed the rate of malondialdehyde (MDA) production by 1.46e1 1.22-fold Delayed the decreasing rate of carbon dioxides yield by 1.0e2.3-fold	Liu et al., 2017
strawberry	500 v 3~5 °C 10 d	Resulted in a resultant respiration rate between 11.69 and 14.56 mL CO2 kg^{-1} h^{-1} after the first week of storage inhibited the accumulation of malondialdehyde, hydrogen peroxide and superoxide anion induced an increase of superoxide dismutase, catalase and ascorbate peroxidase activities Extended shelf life	Xu et al., 2022
Sorbus pohuashanesis	100~250 kv/m 25 °C 5~10 min	Improved the water absorption ability of dry seeds of S. po-huashanensis Raised contents of total chlorophyll, soluble protein, and total soluble sugar Promoted seedling height growth, affect leaf SOD activity	Yang & Shen, 2011
sweet potato	4 kv/m 13 °C 60 d	Maintained the integrity of sweet potato cell membranes Reduced breathing rate Delayed the loss of starch and water in sweet potato root	Pang et al., 2021
peanut	40 kv/cm 25 °C 4 h	Reduced the microbial loads to < 3 log CFU g^{-1}FW Improved nutritional quality and microbial control Increased germination rate,increased the sprout's total Se and resveratrol contents after HVEF + Se treatment	Chiu, 2022
Grapefruit Slices	5 kv/cm 4 °C 24 h	Improved color preservation effect Maintained color stability	Shen et al., 2022
pineapples	150 v 5 °C 12 d	Decreased by 0.25-4.38% moisture loss Inhibited the decline in hardness Maintained good sensory quality	Cheng et al., 2023
potato	60 kv/m 5 °C 24 h	Slowed the browning rate of fresh-cut potatoes, Inhibited the activity	Cao et al., 2021
mushroom	3000 v 4 °C 12 d	Prevented the accumulation of malondialdehyde (MDA) Delayed loss of total phenolic Enhanced the superoxide dismutase (SOD) and catalase (CAT) activity Had the better microstructure	Yan et al., 2020
potato starch	30 kv 40 °C 30 min	Showed a relatively high average size distribution Showed a lower level of conclusion temperature and resistant starch content Exhibited the most desirable properties	Cao & Gao, 2020
Agaricus bisporus	960 kv/m -30 ± 1 °C 90 min	Decreased ice crystal size and drip loss Improved textural properties Decreased the average equivalent diameter of ice crystals in frozen mushrooms	Fallah-Joshaqani et al., 2021
broccoli and cauliflower	1/3/5 kV/cm -20/-18/-5/4 °C 12 h	Improved freezing parameters Reduced nucleation time and phase transition Time Reduced drip loss Increased dry weight Improved the quality	Jiang et al., 2022
Cabbage	5.9-48.76 kv/m 23 °C 12 h	Promoted growth	Wang et al., 2022

ice crystals was increased by 4% (Xanthakis et al., 2013). Under the action of high voltage electrostatic field, the juice retention rate of frozen steak was significantly improved, and the pressing loss of steak decreased by 21.2% and the melting loss decreased by 47.4%, indicating that the low voltage continuous electric field preservation means can improve the hardness and tenderness of thawed steak, promote faster and more uniform formation of crystal nuclei and ice nuclei, and reduce the migration of fixed water to free water (Xie et al., 2021b). The free radical-mediated oxidation of myogenic fibrin was inhibited during the high voltage electrostatic field-assisted thawing process, in which the best thawing effect was achieved under 10 kV electric field conditions, and the quality of thawed pork was optimal (Jia et al., 2018). The applications are shown in (Table 3).

4.3 Application of aquatic products preservation

With the continuous development of electrostatic field technology, the research on the application of electric field technology in the preservation of aquatic products has also received attention, especially in the preservation of fish (Okumura et al., 2016). Spanish mackerel were treated with different voltages and then stored at 4 °C. The preservation effect of this method was evaluated by measuring bacterial counts, total volatile basic nitrogen (TVB-N), sensory index, proximity composition and ph. The results showed that the high voltage electrostatic field inhibited bacterial growth, reduced TVB-N and delayed the decline of sensory scores; 45 kV for 20 min was the best treatment parameter for extending the shelf life of Spanish mackerel by high voltage electrostatic field (Bai et al., 2015). Streptococcus decay us was incubated on the surface of red carp fillets, and ultrasound + high voltage electric field (US&HVEF) was used to study its antibacterial activity. The results showed that US&HVEF had good antibacterial performance against Streptococcus decayus with a lethality rate of 96.73%. In addition, US&HVEF could reduce thawing losses, preserve the fillet structure, stabilize the secondary and tertiary conformations of myogenic fibronectin (MFP), and inhibit the aggregation and oxidation of MFP (Nian et al., 2022). The applications are shown in (Table 4).

4.4 Others

In addition to the above categories of perishable food, the electrostatic field also has the effect of preserving the freshness of other foods. The applications are shown in (Table 5).

Table 3. Application of livestock and poultry preservation.

Treated food	EF source	Results	References
beef	2.5 kv	Reduced thawing loss and shear force	Qian et al., 2019
	4 °C	Shorten thaw time	
	10/20/30 min	Reduced the loss of beef quality	
Rabbit meat	-15/-20/-25 kv	Resulted in 0.5-1.7 log reductions in the number of microorganisms	Jia et al., 2017b
	17.63° ± 0.43 °C	Reduced the thawing time by 60%	
	1/2/3/4 min	led to less denaturation of the myofibrillar proteins by EF	
Chicken breast	1.5/2.25/3 kv/cm	Shorten thaw time	Rahbari et al., 2018
	-18~0 °C	Maintained product quality	
	15 min	Reached its maximum value of myofibrillar proteins at 2.25 kV/cm	
Chicken thigh meat	100 kv/m	Increased from 11.24 mg/100 g to 21.9 mg/100 g of TVB-N On day 8	Hsieh et al., 2010
	-3/4 °C	Shorten thaw time	
	8 d		
pork tenderloin meat	4/6/8/10 kv	Reduced by 0.5-1 log CFU/g in the total microbial population	He et al., 2013
	-5/0 °C	Increased from 10.64 to 16.38 mg/100 g in TVB-N	
	40/46/52/70 min		
Dry-Cured Beef	3 kv	Delayed the decrease in pH and moisture content	Xu et al., 2020
	4 °C	Kept the dry-cured beef with a higher color stability	
	0/3/7/10/14 d	Enhanced characteristic flavor	
Frozen Beef	0/12/16/20/24/28 kv	Shorten thaw time	Zhang & Ding, 2020
	-10~10 °C	Improved the flavor	
	30 min		
Lamb Meat	0~58 kv/m	Led to the significant microstructural changes	Dalvi-Isfahan et al., 2016a
	-20 °C	Decreased up to 60% in the average ice crystal size	
	1/3 h	Decreased with increasing the electrostatic field strength in the drip loss	
beef steak	2.5 kv	Improved fiber compactness	Xie et al., 2021a
	-30/4 °C	Reduced protein oxidation in the freezing process	
	2 h	Minimized the changes in protein secondary and tertiary struc-tures during freezing	
pork	10 kv	Showed that the total area of ice crystal for the cross sections of pork tenderloin treated with 10 kV HVEF was much smaller than that without HVEF.	Jia et al., 2017a
	-20 °C		
	24 h		

Table 4. Application of aquatic products preservation.

Treated food	EF source	Results	References
tilapia	300/600/900 kv/m	Showed that the K value was close to 60% under 600 kV/M HVEF treatment on day 8	Ko et al., 2016
	4 °C	Showed that under 300 kV/m HVEF treatment, TVB-N was only 20.47 mg/100 g	
	8 d	Showed that at 900 kv/m HVEF, TPC (tetraphenylchlorine) still did not exceed the health standard	
tilapia	100 kv/m	Showed that the K value increased from 20% to 61.7% for HVEF storage and 94.7% for non-HVEF storage Reduce the thawing time by 60% on day 6	Hsieh et al., 2011
	4 °C	Led to less denaturation of the myofibrillar proteins by EF	
	6/7/10 d		
tuna	4/6/7.5/10/10.5 kv	Showed that the TBA (Total Bile Acids) and ΔE values the higher the voltage, the faster the oxidation	Mousakhani-Ganjeh et al., 2016
	20 °C		
	6 d		
tuna	4.5~14 kv	Improved thawing rate and TVB-N	Mousakhani-Ganjeh et al., 2015
	20 ± 0.1 °C	Declined color, texture, and protein solubility of fish samples	
	20/25 min	Decreased protein solubility and affected the hardness, gumminess, cohesiveness, and chewiness of the fish samples as compared to the control	
catfish fillets	30 kv	Inhibited the growth of Acinetobacter and Streptococcus after 7 d storage	Huang et al., 2020
	4 °C	Showed that the lower thiobarbituric acid reactive substances (TBARS) and higher water holding capacity	
	0/1/3/5/7 d	Showed that TVB-N and TVC (Total Viable Count) were 20.5 mg/100 g and 5.64 log CFU/g in HVEF treatment and 32.4 mg/100 g and 7.42 log CFU/g in untreated treatment on day 7	
Penaeus vannamei	0/15/35/45 kv	Had better post-thawing qualities such as lower thawing loss, lower total bacteria count and lower total volatile basic nitrogen (TVB-N).	Bai et al., 2017
	20 °C	Shorten thaw time	
	48 h		
common carp	-12 kv	Lowered counts of Aeromonas, Pseudomonas, and halophilic bacteria by 0.5-1 log CFU/g in thawed fish cubes after 8 days	Li et al., 2017
	4 °C	Showed that the activity of adenosine monophosphate deaminase (AMPD) was enhanced, but the activity of acid phosphatase (ACP) was decreased	
	6/8/30 d	Shorten thaw time	
shrimp (Solenocera melantho)	0/5/10/15/20 kv/m	Improved the freezing quality of S. melantho	Liu et al., 2022
	-20 °C	Improved the texture of the shrimp muscle	
	24 h	Decreased the degeneration of myofibrillar protein isolates	
sea cucumber	22.5 kv	Reduced the drying time of sea cucumber	Bai & Luan, 2018
	-5 °C	Saved drying energy	
	5 min	Improved the rehydration rate of sea cucumber	
Larimichthys crocea fillets	0/5/10/15 kv/m	Delayed the decrease in springiness and hardness	Qian et al., 2022
	-1 ± 0.5 °C	Improved the quality of fish during refrigerated storage Extended the shelf-life of Larimichthys crocea fillets	
	0/4/8/12/16/20/24 d		

5 EF safety and limitations

Due to voltage induced protein denaturation and gel formation, etc., the sensory quality of perishable foods will change when exceeding a certain voltage value or when the processing time is too long, and although there will be no obvious cooked flavor, the texture will change. In addition, in the processing process, the electrostatic field voltage is high and has a certain degree of danger. Operators need to have a certain knowledge of physical electricity, know self-protection, equipped with certain measures, such as insulated gloves, insulated shoes, etc. Electrostatic field on the high requirements of environmental humidity, humidity is too large electric field is easy to break through the air, resulting in electric field short circuit and operation of the stop, so the environmental humidity to control. It can be seen that, within a certain range of the use of electrostatic field treatment of fresh perishable food, can play a sterilization, enzyme inactivation and better maintain its quality, but with the increase in processing intensity, will have a certain impact on the perishable food color, texture, and even change the appearance of perishable food.

6 Conclusions and prospects

With the improvement of people's living standard, consumers are more concerned about food safety and diet health. Electrostatic field treatment as a non-thermal preservation technology applied to the food field, with its unique processing method

Table 5. Application of other products preservation.

Treated food	EF source	Results	References
Bread	50 kv	Increased the ability of gluten fibers to absorb and retain water	Esaki et al., 1996
	20/30 °C	Decreased in the water loss of the baked gluten	
	20 min		
potato chips	0~60 kV	Improved in the drying rate of potato	Bai et al., 2013
	20 °C	chips	
	1/2/3 h	Showed that the shrinkage rate of potato chips dried by HVEF was 1.1% lower than that by oven drying method.	
		Showed that the rehydration rate of HVEF was 24.6% higher than that by oven drying method.	
Milk	40 kv/cm	Reduced microorganisms	Mogla et al., 2020
	4 °C	Extended shelf-life	
	5 min		
Tofu	0/4/8/12/16/kv		Ding et al., 2018
	20 °C	Shorten thaw time	
	5/10/15 min	Increased thaw rate	
Canola oil	10-12 kv	Reduced losses	Zhou et al., 2022
	21 °C	Refined Canola oil quickly	
	8 h		
soybean oil	10/20 kv	Improved bleaching ability	Abedi et al., 2020
	35-65 °C	Demonstrated a higher ability to significantly remove metal ions and pigments from soybean oil	
	0-30 min		
duck oil	4 kv	Restrained the speed of the thermal oxidation reaction	Sun et al., 2022
	180 ± 1 °C	occurring in the duck oil heating	
	0/2/4/6/8 h	Produced more oxidation products	

and can maintain the original nutritional flavor of food, and gradually be respected. At the same time, electrostatic field sterilization technology is a physical process that does not involve chemical changes and does not have adverse effects on human body. However, electrostatic field technology in its superiority increasingly prominent at the same time, but also accompanied by some technical problems, such as electrostatic field voltage is too high, there are hidden dangers to the safety of the operator, although it is now increasingly obvious that the effect of low-voltage electrostatic field preservation, but its voltage is still more than the normal voltage that the human body can withstand. In addition, the voltage and processing time for different perishable foods are very different, so if you can control the voltage and time in real time, you will get twice the result with half the effort. I believe that in the future will be a good improvement. Electrostatic field technology, in the unique basic conditions, and environmental conditions may play an excellent role in preservation, especially in combination with other treatment methods, it is more integrated and compensates for a series of problems caused by the use of a single technology, recently there has been a synergistic effect of electrostatic field and modified atmosphere packaging on cabbage, I believe that electrostatic field technology combined with low temperature preservation, electrostatic field technology combined with plasma technology and other integrated technology will not be far away. It is believed that as researchers continue to study electrostatic fields, their future commercial applications will become more and more widespread.

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References

Abedi, E., Amiri, M. J., & Sahari, M. A. (2020). Kinetic, isotherm and thermodynamic investigations on adsorption of trace elements and pigments from soybean oil using high voltage electric field-assisted bleaching: a comparative study. *Process Biochemistry*, 91, 208-222. http://dx.doi.org/10.1016/j.procbio.2019.12.013.

Bai, Y., & Luan, Z. (2018). The effect of high-pulsed electric field pretreatment on vacuum freeze drying of sea cucumber. *International Journal of Applied Electromagnetics and Mechanics*, 57(2), 247-256. http://dx.doi.org/10.3233/JAE-180009.

Bai, Y., Huo, Y., & Fan, X. (2017). Experiment of thawing shrimps (Penaeus vannamei) with high voltage electric field. *International Journal of Applied Electromagnetics and Mechanics*, 55(3), 499-506. http://dx.doi.org/10.3233/JAE-170020.

Bai, Y., Shi, H., & Yang, Y. (2013). Application of high voltage electric field (HVEF) drying technology in potato chips. *Journal of Physics: Conference Series*, 418, 012144. http://dx.doi.org/10.1088/1742-6596/418/1/012144.

Bai, Y.-X., Hu, Y.-C., & Qu, M. (2015). Preliminary studies on Spanish mackerel fresh-keeping method in high-voltage electric field. *Journal* *of Aquatic Food Product Technology*, 24(8), 732-739. http://dx.doi.org/10.1080/10498850.2013.808724.

Barbhuiya, R. I., Singha, P., & Singh, S. K. (2021). A comprehensive review on impact of non-thermal processing on the structural changes of food components. *Food Research International*, 149, 110647. http://dx.doi.org/10.1016/j.foodres.2021.110647. PMid:34600649.

Basak, S., & Chakraborty, S. (2022). The potential of nonthermal techniques to achieve enzyme inactivation in fruit products. *Trends in Food Science & Technology*, 123, 114-129. http://dx.doi.org/10.1016/j.tifs.2022.03.008.

Cai, L., Cao, M., Regenstein, J., & Cao, A. (2019). Recent advances in food thawing technologies. *Comprehensive Reviews in Food Science and Food Safety*, 18(4), 953-970. http://dx.doi.org/10.1111/1541-4337.12458. PMid:33337005.

Cao, J., Ma, S., Zhang, L., Wang, R., & Shi, J. (2021). Browning inhibition on fresh-cut potatoes by high voltage electrostatic field (HVEF) pre-treatment. *Acta Horticulturae*, 1319, 153-162. http://dx.doi.org/10.17660/ActaHortic.2021.1319.18.

Cao, M., & Gao, Q. (2020). Effect of dual modification with ultrasonic and electric field on potato starch. *International Journal of Biological Macromolecules*, 150, 637-643. http://dx.doi.org/10.1016/j.ijbiomac.2020.02.008. PMid:32027905.

Chakka, A. K., Sriraksha, M. S., & Ravishankar, C. N. (2021). Sustainability of emerging green non-thermal technologies in the food industry with food safety perspective: a review. *LWT*, 151, 112140. http://dx.doi.org/10.1016/j.lwt.2021.112140.

Chen, S., Berretta, R., Clark, A., & Moscato, P., 2019. Lot sizing and scheduling for perishable food products: a review. In *Reference module in food science* (p. B9780081005965214443). Amsterdam: Elsevier. http://dx.doi.org/10.1016/B978-0-08-100596-5.21444-3.

Cheng, R., Li, W., Wang, Y., Cheng, F., Wu, H., & Sun, Y. (2023). Low voltage electrostatic field treatment of fresh-cut pineapples with slightly acidic electrolytic water: influence on physicochemical changes and membrane stability. *Scientia Horticulturae*, 308, 111602. http://dx.doi.org/10.1016/j.scienta.2022.111602.

Chiu, K. Y. (2022). Effect of selenium fortification during sprouting of peanut seeds receiving HVEF and selenium soaking combination on yield, selenium and resveratrol contents, anti-oxidative properties, and microbial control. *International Journal of Food Science & Technology*, 57(8), 5297-5306. http://dx.doi.org/10.1111/ijfs.15859.

Dalvi-Isfahan, M., Hamdami, N., & Le-Bail, A. (2016a). Effect of freezing under electrostatic field on the quality of lamb meat. *Innovative Food Science & Emerging Technologies*, 37, 68-73. http://dx.doi.org/10.1016/j.ifset.2016.07.028.

Dalvi-Isfahan, M., Hamdami, N., Le-Bail, A., & Xanthakis, E. (2016b). The principles of high voltage electric field and its application in food processing: a review. *Food Research International*, 89(Pt 1), 48-62. http://dx.doi.org/10.1016/j.foodres.2016.09.002. PMid:28460942.

Ding, C., Ni, J., Song, Z., Gao, Z., Deng, S., Xu, J., Wang, G., & Bai, Y. (2018). High-voltage electric field-assisted thawing of frozen tofu: effect of process parameters and electrode configuration. *Journal of Food Quality*, 2018, 1-8. http://dx.doi.org/10.1155/2018/5191075.

Esaki, K., Ninomiya, F., Hisaki, K., Higasa, T., Shibata, K., Murata, K., & Aibara, S. (1996). Effects of high-voltage electric field treatment on the water activity of bread. *Bioscience, Biotechnology, and Biochemistry*, 60(9), 1444-1449. http://dx.doi.org/10.1271/bbb.60.1444.

Fallah-Joshaqani, S., Hamdami, N., & Keramat, J. (2021). Qualitative attributes of button mushroom (Agaricus bisporus) frozen under high voltage electrostatic field. *Journal of Food Engineering*, 293, 110384. http://dx.doi.org/10.1016/j.jfoodeng.2020.110384.

He, X., Jia, G., Tatsumi, E., & Liu, H. (2016). Effect of corona wind, current, electric field and energy consumption on the reduction of the thawing time during the high-voltage electrostatic-field (HVEF) treatment process. *Innovative Food Science & Emerging Technologies*, 34, 135-140. http://dx.doi.org/10.1016/j.ifset.2016.01.006.

He, X., Liu, R., Nirasawa, S., Zheng, D., & Liu, H. (2013). Effect of high voltage electrostatic field treatment on thawing characteristics and post-thawing quality of frozen pork tenderloin meat. *Journal of Food Engineering*, 115(2), 245-250. http://dx.doi.org/10.1016/j.jfoodeng.2012.10.023.

Hsieh, C.-W., Lai, C.-H., Ho, W.-J., Huang, S.-C., & Ko, W.-C. (2010). Effect of thawing and cold storage on frozen chicken thigh meat quality by high-voltage electrostatic field. *Journal of Food Science*, 75(4), M193-M197. http://dx.doi.org/10.1111/j.1750-3841.2010.01594.x. PMid:20546409.

Hsieh, C.-W., Lai, C.-H., Lee, C.-H., & Ko, W.-C. (2011). Effects of high-voltage electrostatic fields on the quality of tilapia meat during refrigeration. *Journal of Food Science*, 76(6), M312-M317. http://dx.doi.org/10.1111/j.1750-3841.2011.02218.x. PMid:22417503.

Huang, H., Gao, T., Qian, X., Wu, W., Fan, X., Shi, L., Xiong, G., Ding, A., Li, X., Qiao, Y., Liao, L., & Wang, L. (2022). In vitro antibacterial mechanism of high-voltage electrostatic field against Acinetobacter johnsonii. *Foods*, 11(7), 955. http://dx.doi.org/10.3390/foods11070955. PMid:35407042.

Huang, H., Sun, W., Xiong, G., Shi, L., Jiao, C., Wu, W., Li, X., Qiao, Y., Liao, L., Ding, A., & Wang, L. (2020). Effects of HVEF treatment on microbial communities and physicochemical properties of catfish fillets during chilled storage. *LWT*, 131, 109667. http://dx.doi.org/10.1016/j.lwt.2020.109667.

Huang, H., Xiong, G., Shi, L., Wu, W., Li, X., Qiao, Y., Liao, L., Ding, A., & Wang, L. (2021a). Application of HVEF treatment in bacteriostasis against Acinetobacter radioresistens. *Food Control*, 124, 107914. http://dx.doi.org/10.1016/j.foodcont.2021.107914.

Huang, Y. C., Yang, Y. H., Sridhar, K., & Tsai, P.-J. (2021b). Synergies of modified atmosphere packaging and high-voltage electrostatic field to extend the shelf-life of fresh-cut cabbage and baby corn. *LWT*, 138, 110559. http://dx.doi.org/10.1016/j.lwt.2020.110559.

Jadhav, H. B., Annapure, U. S., & Deshmukh, R. R. (2021). Non-thermal technologies for food processing. *Frontiers in Nutrition*, 8, 657090. http://dx.doi.org/10.3389/fnut.2021.657090. PMid:34169087.

Jia, G., He, X., Nirasawa, S., Tatsumi, E., Liu, H., & Liu, H. (2017a). Effects of high-voltage electrostatic field on the freezing behavior and quality of pork tenderloin. *Journal of Food Engineering*, 204, 18-26. http://dx.doi.org/10.1016/j.jfoodeng.2017.01.020.

Jia, G., Liu, H., Nirasawa, S., & Liu, H. (2017b). Effects of high-voltage electrostatic field treatment on the thawing rate and post-thawing quality of frozen rabbit meat. *Innovative Food Science & Emerging Technologies*, 41, 348-356. http://dx.doi.org/10.1016/j.ifset.2017.04.011.

Jia, G., Nirasawa, S., Ji, X., Luo, Y., & Liu, H. (2018). Physicochemical changes in myofibrillar proteins extracted from pork tenderloin thawed by a high-voltage electrostatic field. *Food Chemistry*, 240, 910-916. http://dx.doi.org/10.1016/j.foodchem.2017.07.138. PMid:28946361.

Jiang, Q., Zhang, M., Mujumdar, A. S., & Chen, B. (2022). Comparative freezing study of broccoli and cauliflower: effects of electrostatic field and static magnetic field. *Food Chemistry*, 397, 133751. http://dx.doi.org/10.1016/j.foodchem.2022.133751. PMid:35914456.

Kao, N.-Y., Tu, Y.-F., Sridhar, K., & Tsai, P.-J. (2019). Effect of a high voltage electrostatic field (HVEF) on the shelf-life of fresh-cut broccoli (Brassica oleracea var. italica). *LWT*, 116, 108532. http://dx.doi.org/10.1016/j.lwt.2019.108532.

Ko, W.-C., Shi, H.-Z., Chang, C.-K., Huang, Y.-H., Chen, Y.-A., & Hsieh, C.-W. (2016). Effect of adjustable parallel high voltage on biochemical indicators and actomyosin Ca2+-ATPase from tilapia (Orechromis niloticus). *Lebensmittel-Wissenschaft + Technologie*, 69, 417-423. http://dx.doi.org/10.1016/j.lwt.2016.01.074.

Li, D., Jia, S., Zhang, L., Li, Q., Pan, J., Zhu, B., Prinyawiwatkul, W., & Luo, Y. (2017). Post-thawing quality changes of common carp (Cyprinus carpio) cubes treated by high voltage electrostatic field (HVEF) during chilled storage. *Innovative Food Science & Emerging Technologies*, 42, 25-32. http://dx.doi.org/10.1016/j.ifset.2017.06.005.

Liu, C.-E., Chen, W.-J., Chang, C.-K., Li, P.-H., Lu, P.-L., & Hsieh, C.-W. (2017). Effect of a high voltage electrostatic field (HVEF) on the shelf life of persimmons (Diospyros kaki). *LWT*, 75, 236-242. http://dx.doi.org/10.1016/j.lwt.2016.08.060.

Liu, J., Wang, Y., Zhu, F., Yang, J., Ma, X., Lou, Y., & Li, Y. (2022). The effects of freezing under a high-voltage electrostatic field on ice crystals formation, physicochemical indices, and bacterial communities of shrimp (Solenocera melantho). *Food Control*, 142, 109238. http://dx.doi.org/10.1016/j.foodcont.2022.109238.

Ma, L., Zhang, M., Bhandari, B., & Gao, Z. (2017). Recent developments in novel shelf life extension technologies of fresh-cut fruits and vegetables. *Trends in Food Science & Technology*, 64, 23-38. http://dx.doi.org/10.1016/j.tifs.2017.03.005.

Meza-Jime, M. L. (2017). Efecto del campo eléctrico de alto voltaje en papaína grado alimentario. *Revista Mexicana de Ingeniería Química*, 16(1), 101-108.

Mogla, A., Hemant, & Chaturvedi, D. K. (2020). Milk preservation by using HVEF. *International Journal of Current Microbiology and Applied Sciences*, 9(7), 537-544. http://dx.doi.org/10.20546/ijcmas.2020.907.059.

Mousakhani-Ganjeh, A., Hamdami, N., & Soltanizadeh, N. (2015). Impact of high voltage electric field thawing on the quality of frozen tuna fish (Thunnus albacares). *Journal of Food Engineering*, 156, 39-44. http://dx.doi.org/10.1016/j.jfoodeng.2015.02.004.

Mousakhani-Ganjeh, A., Hamdami, N., & Soltanizadeh, N. (2016). Effect of high voltage electrostatic field thawing on the lipid oxidation of frozen tuna fish (Thunnus albacares). *Innovative Food Science & Emerging Technologies*, 36, 42-47. http://dx.doi.org/10.1016/j.ifset.2016.05.017.

Murr, L. (1963). Plant growth response in a simulated electric field-environment. *Nature*, 200(4905), 490-491. http://dx.doi.org/10.1038/200490b0.

Nian, L., Wang, M., Pan, M., Cheng, S., Zhang, W., & Cao, C. (2022). A potential spoilage bacteria inactivation approach on frozen fish. *Food Chemistry: X*, 14, 100335. http://dx.doi.org/10.1016/j.fochx.2022.100335. PMid:35663602.

Okumura, T., Yaegashi, T., Yamada, K., Ito, T., Takahashi, K., Aisawa, S., Takaki, K., Yamazaki, S., & Syuto, B. (2016). Long period preservation of marine products using electrostatic field. *Japanese Journal of Applied Physics*, 55(7S2), 07LG07. http://dx.doi.org/10.7567/JJAP.55.07LG07.

Pang, L., Lu, G., Cheng, J., Lu, X., Ma, D., Li, Q., Li, Z., Zheng, J., Zhang, C., & Pan, S. (2021). Physiological and biochemical characteristics of sweet potato (Ipomoea batatas (L.) Lam) roots treated by a high voltage alternating electric field during cold storage. *Postharvest Biology and Technology*, 180, 111619. http://dx.doi.org/10.1016/j.postharvbio.2021.111619.

Parniakov, O., Lebovka, N. I., Bals, O., & Vorobiev, E. (2015). Effect of electric field and osmotic pre-treatments on quality of apples after freezing–thawing. *Innovative Food Science & Emerging Technologies*, 29, 23-30. http://dx.doi.org/10.1016/j.ifset.2015.03.011.

Qi, M., Zhao, R., Liu, Q., Yan, H., Zhang, Y., Wang, S., & Yuan, Y. (2021). Antibacterial activity and mechanism of high voltage electrostatic field (HVEF) against Staphylococcus aureus in medium plates and food systems. *Food Control*, 120, 107566. http://dx.doi.org/10.1016/j.foodcont.2020.107566.

Qian, C., Pan, H., Shao, H., Yu, Q., Lou, Y., & Li, Y. (2022). Effects of HVEF treatment on the physicochemical properties and bacterial communities of *Larimichthys crocea* fillets during refrigerated storage. *International Journal of Food Science & Technology*, 57(12), 7691-7700. http://dx.doi.org/10.1111/ijfs.16115.

Qian, S., Li, X., Wang, H., Mehmood, W., Zhong, M., Zhang, C., & Blecker, C. (2019). Effects of low voltage electrostatic field thawing on the changes in physicochemical properties of myofibrillar proteins of bovine Longissimus dorsi muscle. *Journal of Food Engineering*, 261, 140-149. http://dx.doi.org/10.1016/j.jfoodeng.2019.06.013.

Rahbari, M., Hamdami, N., Mirzaei, H., Jafari, S. M., Kashaninejad, M., & Khomeiri, M. (2018). Effects of high voltage electric field thawing on the characteristics of chicken breast protein. *Journal of Food Engineering*, 216, 98-106. http://dx.doi.org/10.1016/j.jfoodeng.2017.08.006.

Ranalli, G., Iorizzo, M., Lustrato, G., Zanardini, E., & Grazia, L. (2002). Effects of low electric treatment on yeast microflora. *Journal of Applied Microbiology*, 93(5), 877-883. http://dx.doi.org/10.1046/j.1365-2672.2002.01758.x. PMid:12392536.

Saletnik, B., Zagula, G., Saletnik, A., Bajcar, M., Slysz, E., & Puchalski, C. (2022). Effect of magnetic and electrical fields on yield, shelf life and quality of fruits. *Applied Sciences*, 12(6), 3183. http://dx.doi.org/10.3390/app12063183.

Shen, J., Zhang, M., Mujumdar, A. S., & Chen, J. (2022). Effects of high voltage electrostatic field and gelatin-gum Arabic composite film on color protection of freeze-dried grapefruit slices. *Food and Bioprocess Technology*, 15(8), 1881-1895. http://dx.doi.org/10.1007/s11947-022-02839-8.

Sidaway, G. (1966). Influence of electrostatic fields on seed germination. *Nature*, 211(5046), 303. http://dx.doi.org/10.1038/211303a0.

Subakti, D. J., Pramono, H., & Triastuti, J. (2019). The application of a high voltage electric field (HVEF) to reduce *Escherichia coli* and *Salmonella thyphimurium* bacteria in red snapper (*Lutjanus* sp.) fillets. *IOP Conference Series. Earth and Environmental Science*, 236, 012117. http://dx.doi.org/10.1088/1755-1315/236/1/012117.

Sun, H., Li, F., Li, Y., Guo, L., Wang, B., Huang, M., Huang, H., Liu, J., Zhang, C., Feng, Z., & Sun, J. (2022). Effect of high-voltage electrostatic field heating on the oxidative stability of duck oils containing diacylglycerol. *Foods*, 11(9), 1322. http://dx.doi.org/10.3390/foods11091322. PMid:35564044.

Sur, A., Sah, R. P., & Pandya, S. (2020). Milk storage system for remote areas using solar thermal energy and adsorption cooling. *Materials Today: Proceedings*, 28, 1764-1770. http://dx.doi.org/10.1016/j.matpr.2020.05.170.

Tao, X., Chen, J., Li, L., Zhao, L., Zhang, M., & Sun, A. (2015). Influence of pulsed electric field on *Escherichia coli* and *Saccharomyces cerevisiae*. *International Journal of Food Properties*, 18(7), 1416-1427. http://dx.doi.org/10.1080/10942912.2014.917098.

Wang, Q., Li, Y., Sun, D.-W., & Zhu, Z. (2018). Enhancing food processing by pulsed and high voltage electric fields: principles and applications. *Critical Reviews in Food Science and Nutrition*, 58(13), 2285-2298. http://dx.doi.org/10.1080/10408398.2018.1434609. PMid:29393667.

Wang, Y., Liu, Y., Liu, X., Tang, H., & Huang, F. (2022). Effect of plasma and electrostatic field on the growth and nutrients of Chinese cabbage. *IEEE Transactions on Plasma Science*, 50(4), 835-840. http://dx.doi.org/10.1109/TPS.2022.3158931.

Wasungu, L., Pillet, F., Bellard, E., Rols, M.-P., & Teissié, J. (2014). Shock waves associated with electric pulses affect cell electro-permeabilization. *Bioelectrochemistry*, 100, 36-43. http://dx.doi.org/10.1016/j.bioelechem.2014.06.011. PMid:25027311.

Xanthakis, E., Havet, M., Chevallier, S., Abadie, J., & Le-Bail, A. (2013). Effect of static electric field on ice crystal size reduction during freezing of pork meat. *Innovative Food Science & Emerging Technologies*, 20, 115-120. http://dx.doi.org/10.1016/j.ifset.2013.06.011.

Xie, Y., Chen, B., Guo, J., Nie, W., Zhou, H., Li, P., Zhou, K., & Xu, B. (2021a). Effects of low voltage electrostatic field on the microstructural damage and protein structural changes in prepared beef steak during the freezing process. *Meat Science*, 179, 108527. http://dx.doi.org/10.1016/j.meatsci.2021.108527. PMid:33962166.

Xie, Y., Zhou, K., Chen, B., Wang, Y., Nie, W., Wu, S., Wang, W., Li, P., & Xu, B. (2021b). Applying low voltage electrostatic field in the freezing process of beef steak reduced the loss of juiciness and textural properties. *Innovative Food Science & Emerging Technologies*, 68, 102600. http://dx.doi.org/10.1016/j.ifset.2021.102600.

Xu, C., Zhang, X., Liang, J., Fu, Y., Wang, J., Jiang, M., & Pan, L. (2022). Cell wall and reactive oxygen metabolism responses of strawberry fruit during storage to low voltage electrostatic field treatment. *Postharvest Biology and Technology*, 192, 112017. http://dx.doi.org/10.1016/j.postharvbio.2022.112017.

Xu, C.-C., Yu, H., Xie, P., Sun, B.-Z., Wang, X.-Y., & Zhang, S.-S. (2020). Influence of electrostatic field on the quality attributes and volatile flavor compounds of dry-cured beef during chill storage. *Foods*, 9(4), 478. http://dx.doi.org/10.3390/foods9040478. PMid:32290142.

Yan, M., Yuan, B., Xie, Y., Cheng, S., Huang, H., Zhang, W., Chen, J., & Cao, C. (2020). Improvement of postharvest quality, enzymes activity and polyphenoloxidase structure of postharvest Agaricus bisporus in response to high voltage electric field. *Postharvest Biology and Technology*, 166, 111230. http://dx.doi.org/10.1016/j.postharvbio.2020.111230.

Yang, L., & Shen, H. (2011). Effect of electrostatic field on seed germination and seedling growth of Sorbus pohuashanesis. *Journal of Forestry Research*, 22(1), 27-34. http://dx.doi.org/10.1007/s11676-011-0120-9.

Zhang, Y., & Ding, C. (2020). The study of thawing characteristics and mechanism of frozen beef in high voltage electric field. *IEEE Access: Practical Innovations, Open Solutions*, 8, 134630-134639. http://dx.doi.org/10.1109/ACCESS.2020.3010948.

Zhang, Z.-H., Wang, L.-H., Zeng, X.-A., Han, Z., & Brennan, C. S. (2019). Non-thermal technologies and its current and future application in the food industry: a review. *International Journal of Food Science & Technology*, 54(1), 1-13. http://dx.doi.org/10.1111/ijfs.13903.

Zhou, L., Shen, J., Tse, T. J., Chicilo, F., Purdy, S. K., Meda, V., & Reaney, M. J. T. (2022). Electrostatic field treatment as a novel and efficient method for refining crude canola oil. *Journal of Cleaner Production*, 360, 131905. http://dx.doi.org/10.1016/j.jclepro.2022.131905.