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Applications of electrostatic spray technology in food preservation

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ABSTRACT

The expectations for high food quality and safety keep rising in modern societies, driving the continuous development of food preservation technologies. Recently, the advantages of electrostatic spray technology have been explored for various applications, including food preservation. In this review, we first introduce the basic mechanism and unique advantages of electrostatic spray technology (including small droplet size, high deposition, uniform coverage and reduced agent use). Afterwards, we summarize the current advances of using electrostatic spray technology in food preservation and its economic benefits. The drawbacks and future perspectives of this field are also discussed. Increasing numbers of studies have shown the advantages of electrostatic spray technology in food preservation. However, to make electrostatic spray technology commercially viable for food preservation, some aspects such as how to prepare appropriate agents, optimize operation parameters, improve production efficiency and reduce production costs, need to be further studied in the future.

1. Introduction

With the globalization of food trade and the use of centralized processing facilities for food distribution (Jafari, Engemann, & Zimmermann, 2023), the demand for safety and quality of fresh, semi-finished or ready-to-eat food is increasing. However, contamination by various spoilage and/or pathogenic microorganisms in the storage and distribution process remains a significant concern (particularly prominent in fresh agricultural products) (J. Wang, Zhao, et al., 2023; H. Wu, Zhao, Li, Huang, & Ju, 2022). Microbial contamination negatively affects the shelf-life and overall quality of food. These microorganisms degrade the food directly, causing spoilage, or degrade its organoleptic properties. In addition, microbial contamination increases the risk of foodborne diseases, and consumption of unprocessed or poorly processed fresh produce is responsible for a high burden of disease (Bolten et al., 2023). The toxins naturally produced and secreted by certain microorganisms can also affect food safety. For example, secondary metabolites produced by some putrid fungi, especially fungal toxins, seriously harm human health and safety (Ju, Guo, Cheng, & Yaoc, 2022; H. Wu et al., 2022).

Control measures based on physical and chemical means are routinely used to reduce food losses attributable to spoilage microorganisms. Physical means include shock-freezing (Vega-Galvez et al., 2021), high-pressure processing (Sehrawat, Kaur, Nema, Tewari, & Kumar, 2020), modified atmosphere packaging (Wilson, Stanley, Eyles, & Ross, 2019), or ultraviolet sterilizing (Kaczmarek-Szczepanska et al., 2021), while chemical means commonly include the application of antimicrobial agents on food surfaces by impregnation or spraying. Impregnation generally refers to dipping food into an antimicrobial solution, which is simple, and inexpensive, while also providing great coverage on uneven food surfaces. However, the impregnation method has obvious disadvantages, such as leaving a large residue of the coating material, and it often results in the growth of resistant microorganisms in the dipping container (Andrade, Skurtys, & Osorio, 2012). In addition, the solution can degrade the natural coating that is present on the surface of some foods during the impregnation process, reducing the functionality of the food. For example, the impregnation can remove the natural wax layer on the surface of fruits and vegetables (Zhou et al., 2020). In production, aqueous solutions or suspensions of antimicrobial agents are commonly sprayed onto the product using pressure nozzles. However, such spray application has disadvantages such as low surface coverage, poor deposition efficiency of droplets, and rebound or large diameter flow of the spray liquid (Law, 2001). These methods should therefore be improved from economic, environmental, and product quality standpoints.

Electrostatic spray (ES) technology breaks the droplets using an external force generated by an electrostatic field, thus obtaining more uniform and finer droplets. As a microfluidic technology, ES can achieve precise control over fluidic materials by adjusting certain parameters. Additionally, the size of droplets obtained by ES can reach the nanometer scale (Jaworek, 2007), which makes ES an emerging technology

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that opens up the versatile application prospects of nanomaterials. At present, ES has been used widely in targeted drug delivery (Chen, Lu, Pan, & Xu, 2021), biological scaffolds (Lavielle et al., 2013), film preparation (Zhu, Chen, Chen, & Yu, 2021), pesticide spraying (Hu et al., 2022), dust elimination and desulfurization (Di Natale et al., 2015), food processing (Vesely, Schick, Shrimpton, & Mashayek, 2018), packaging technology (Khan, Nazir, & Maan, 2016) and other fields. In 2001, Law and Cooper (2001) firstly utilized ES technology to spray antimicrobial agents on the surface of bananas, which increased the deposition efficiency of antimicrobial agents and improved the control of microorganisms (Law & Cooper, 2001). Subsequently, increasing studies have proved the advantages of ES technology in food preservation. There are some similar reviews focusing on the encapsulation of bioactive substances by ES technology (Castro Coelho, Nogueiro Estevinho, & Rocha, 2021; Charles, Jin, Mu, & Wu, 2021; Jayaprakash, Maudhuit, Gaiani, & Desobry, 2023). Yet, to best of our knowledge, there is no such a review that summarizes the recent advances of ES technology in food preservation application.

With the continuous development of ES technology and the increasing demand for food safety, it is important to sort out the research progress of this technology in food preservation. Herein, we conducted a comprehensive literature survey by inputting keywords (i.e., electrospray, electrospraying, electrostatic spray, electrostatic spraying, electrohydrodynamic, food, meat, fruit, vegetable, preservation, antibacterial and antimicrobial) into the widely used databases (e.g., Web of Science, Scopus, Google Scholar). On this basis, this review summarizes the principles and advantages of ES technology as well as its applications in food preservation, offering a reference for popularizing the application of ES technology in food preservation.

2. Overview of ES technology

2.1. Principle of ES technology

Electrostatic spraying is a technology using electrostatic forces to atomize droplets. A typical ES device consists of four main components (Fig. 1(a)): a pumping system, a nozzle, a high-voltage power supply, and a grounded metal collector. During the process of ES device operation, liquid is pumped into a capillary needle by a micro-flow syringe, forming a suspended droplet at the nozzle of the capillary (J. Wang, Zhang, Zhang, & Fan, 2021). The nozzle is connected to the positive electrode of the power supply, causing the liquid to carry a positive charge (Jayaprakash et al., 2023). Under the combined action of gravity, surface tension and electrostatic force, the suspended droplet forms a conical structure called the Taylor cone. The free charge at the cone tip is highly concentrated, causing an accelerated high charge density jet to eject from the nozzle. When the jet leaves the nozzle, the diameter of the charged spherical droplet decreases due to the evaporation of liquid and soon approaches the Rayleigh limit (Rayleigh, 2009). Then, the primary disintegration occurs, followed by a series of changes (Fig. 1(a)). After the primary disintegration, the droplet loses some of its charge and mass, and its size again approaches the Rayleigh limit and a second disintegration soon occurs.

2.2. Influencing factors of ES effect

The electrostatic spraying effect is mainly influenced by operation parameters (operating voltage, flow rate, and distance between the nozzle and the collector), liquid properties (surface tension, conductivity, polymer concentration, molecular weight, and volatility) and environmental conditions (temperature, humidity and atmospheric pressure) (Fig. 1(b)).

(1) Operation parameters

During the spraying process, the electrostatic force must overcome the surface tension of the liquid being sprayed. Lower voltages will result in the electrostatic force being insufficient to overcome the surface tension, resulting in a “dripping” mode and the production of larger droplets (Jain, Scott, Zustiak, & Sell, 2015). Increasing the voltage can significantly reduce droplet size; however, once the voltage exceeds a certain critical point, the droplet size becomes constant (Khan et al., 2016). Furthermore, excessive operating voltage may affect production safety. Flow rate is another significant factor that impacts the electrostatic spraying effect. If the flow rate is too low, the cone-shaped jet cannot be maintained, while a high flow rate prevents droplets from becoming fully charged, which negatively affects their dispersion (Khan et al., 2016). Therefore, the flow rate needs to be adjusted within a certain range to achieve optimal results. Furthermore, increasing the acceptance distance contributes to the formation and stability of the cone-shaped jet but affects the electric field strength, which calls for higher operating voltages (Smeets, Clasen, & Van den Mooter, 2017).

(2) Liquid properties

In practical applications, droplets can only be disintegrated when electrostatic forces overcome surface tension. Therefore, the effect of surface tension reduction is consistent with the effect of voltage increase (J. Wang et al., 2021). Conductivity is another important parameter that affects the electrostatic spraying effect. Increasing conductivity can reduce droplet size because highly conductive liquids attain more charge when passing through the nozzle (Faraji, Sadri, Vajdi Hokmabad, Jadidoleslam, & Esmaeilzadeh, 2017). However, excessively high conductivity may cause current to flow back into the equipment (Khan et al., 2016), resulting in electric shock or damage to personnel and equipment.

It is worth noting that some studies dissolve polymers into organic solvents to obtain ES solutions (Basar et al., 2020; Rodrigues et al., 2020). The concentration and molecular weight of a polymer affect the viscosity and surface tension of the polymer solution (Drosou, Krokida, & Biliaderis, 2016), further affecting the size distribution of droplets. When the polymer is concentrated enough for the polymer chains to overlap and interact, strong interactions occur in the Taylor cone jet region, and the jet may not decompose into droplets, leading to electrospinning phenomenon (Bodnár, Grifoll, & Rosell-Llompart, 2018; J. Wang, Zhao, et al., 2023). Thus, it is necessary to optimize the process while considering the concentration and molecular weight of the polymer. In the process of ES of polymer solution, the formation of droplets undergoes evaporation and solidification processes. The volatility of solvents can affect the rate of droplets evaporation, and complete solvent evaporation can form dry polymer particles. In contrast, when the evaporation is incomplete, some residual solvent will reach the collector together with the material and affect the deposition effect of ES (Kingsley & Chiarot, 2023).

(3) Environmental conditions

Environmental factors usually affect the liquid properties and then affect the effect of ES. For example, the viscosity and surface tension of ionic liquids are dependent significantly on the liquid temperature (Takana, Hara, Makino, & Kanakubo, 2021). Generally, as the temperature increases, the molecular migration rate and conductivity of the liquid increase, while the viscosity and surface tension decrease (Marklund, Larsson, van der Spoel, Patriksson, & Caleman, 2009). The atmospheric pressure directly affects the evaporation rate of liquids (Y. Wu, Kennedy, & Clark, 2008). Changes in humidity may lead to changes in liquid conductivity (Sankaran, Staszel, Belknap, Yarin, & Mashayek, 2019). In addition, when ES is used to prepare polymer particles, high humidity may cause rough particle surfaces and pores (Bodnár et al., 2018; Kang et al., 2023).

In summary, the factors that influence the electrostatic spraying effect are interrelated, and optimizing them should be situation-specific.

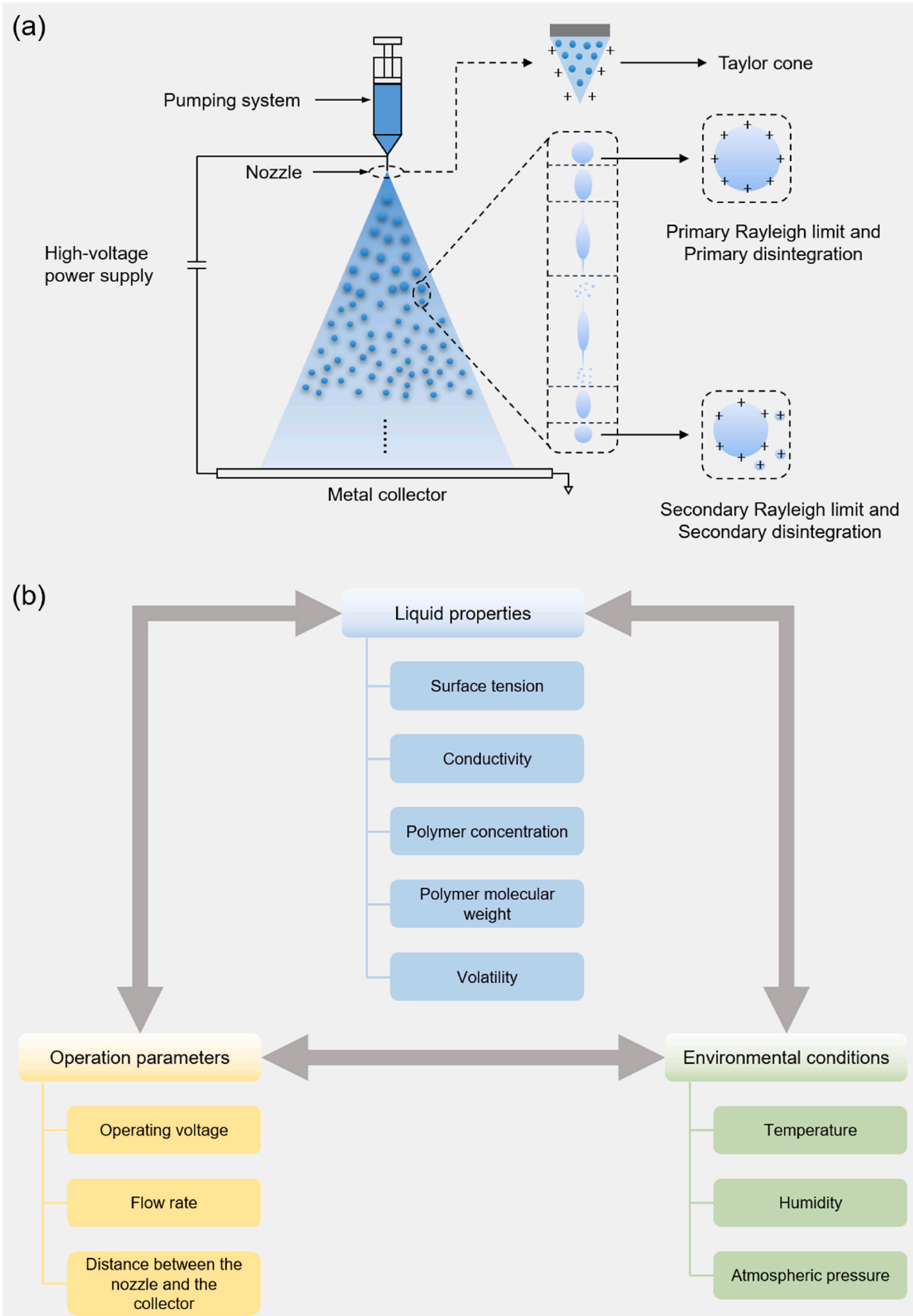

Fig. 1. (a) Schematic diagram of ES technology; (b) Influencing factors of ES effect.

Properly adjusting operation parameters and liquid properties and maintaining environmental stability can enhance the spraying effect while maintaining production safety.

2.3. Advantages of ES technology

Due to the high specific surface area of droplets, the ES technology offers some unique advantages over conventional hydraulic spray methods (Fig. 2, Table 1): (a) the charged droplets are small and uniform in size; (b) charged droplets are deposited on the target much more efficiently than uncharged droplets; (c) the coverage of the charged droplets on the target surface is uniform, especially on the back of the target; (d) reduces the use of agent.

(1) Droplet diameter

Conventional spray technology uses gravity and inertia to atomize droplets (average diameter 300–600 μm), resulting in low droplet deposition efficiency, spray liquid rebound and excessive runoff. In electrostatic spraying, the droplets disintegrate at the Rayleigh limit, and the resulting charged droplets have the same charge, therefore they do not agglomerate while flying to the target, nor do they aggregate on the target surface. Duft, Achtzehn, Muller, Huber, and Leisner (2003) utilized high-speed microscopic images to observe the disintegration of charged ethylene glycol droplets at the Rayleigh limit and the generation of a Rayleigh jet (Duft et al., 2003). They found that the glycol droplet with an initial diameter of about 116 μm and an electric charge of about 3.3 pC reached the Rayleigh limit for the first time with a diameter of about 48 μm, and the diameter of the generated secondary droplets was approximately 1.5 μm. Interestingly, the secondary droplets were affected by evaporation on their way to the collector (J. Wang et al., 2021). Therefore, the charged droplet size can reach several micrometers or even nanometers, greatly reducing the rebound and runoff of the spray liquid.

(2) Deposition efficiency

The ES device creates highly charged droplets by applying an electrostatic field, and the target is commonly grounded or carries the opposite charge, causing the charged droplets to be attracted to the target surface by electrostatic force along the trajectory. The amount of deposition is normally measured using fluorescent tracer labeling techniques. The tracer is sprayed onto the target surface and the deposited tracer is then recovered. The fluorescence intensity of the recovered tracer is measured, allowing the calculation of the tracer mass reaching the target. Law and Cooper (2001) studied the deposition of air-assisted ES on bananas using tracer labeling technology (Law & Cooper, 2001). They found that when using metal targets, the ES deposited 1.5 to 3.4 times as much tracer at different locations on bananas as air-assisted spray. Moreover, the tracer deposition was 1.9–2.1 times that of the air-assisted spray and 27 times that of impregnation when using plastic targets. Fig. 3 visually illustrates the sharp increase in the deposition of charged droplets toward the banana string, especially the top and neck, due to electrostatic attraction. Similar results have been found in the other reports. Marques et al. (2019) evaluated the pesticide deposition of ES and hydraulic spray on maize crops and found that the pesticide deposition of ES was 1.56–2.82 times that of hydraulic spray (Marques et al., 2019). Similarly, Daniel E. Martin, Latheef, and López (2019) believed that electrostatically charged aerial application improved the deposition of pesticides on the early season cotton crops (Daniel E. Martin et al., 2019).

(3) Coverage Uniformity

The droplets generated by the ES self-disperse in the air as they have the same charge, forming a spray cloud. The charged droplets move in the spray cloud and "surround" the target surface. This "surround" effect evenly coats the target with the spray solution, providing uniform coverage of its surface, including the back. Thus, the researchers indirectly assessed the uniformity of coverage by measuring the amount of charged droplets deposited on the back side of the target. Maski and Durairaj (2010) utilized an air-assisted ES system to evaluate the deposition of fluorescent tracers on the back sides of artificial plant targets (Maski & Durairaj, 2010). The deposition density of charged spray on the back side of leaves ranged from 0.66 to 1.33 mg/cm^2, while the deposition density of uncharged spray on the back side was nearly zero. Another study confirmed that the tracer deposition on the backside of the target was 6.1 and 29.0 times that of air-assisted ES (uncharged) and hydraulic spray, respectively (Lyons, Harrison, & Law, 2011). Law and Cooper (2001) found that the deposition amount of ES on the front,

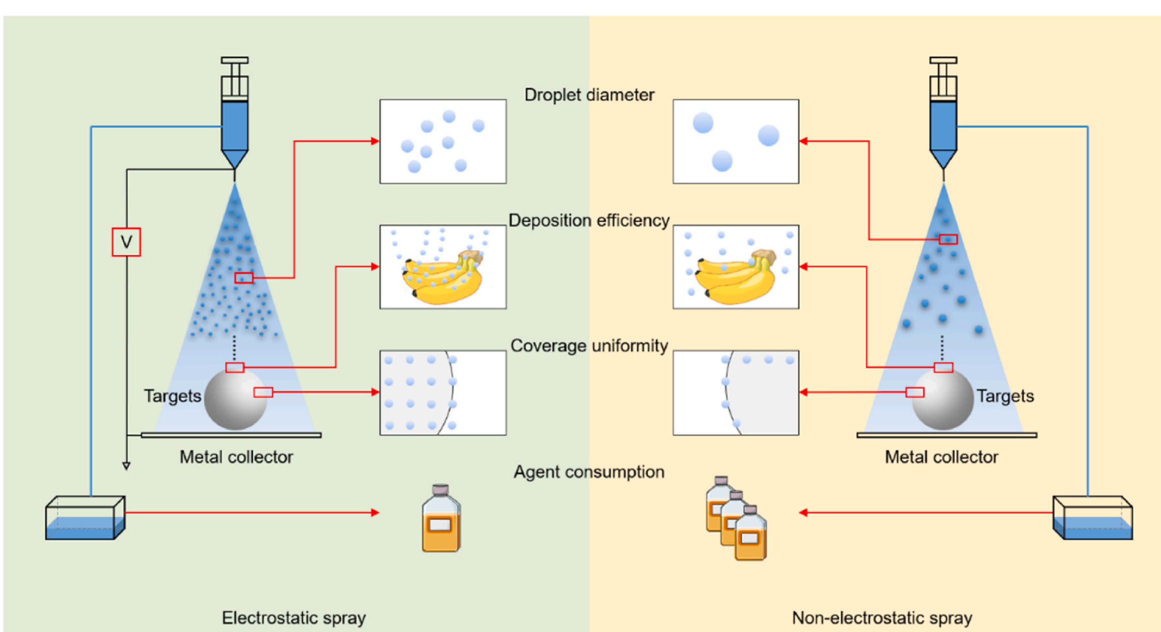

Fig. 2. Comparisons between ES technology and NES technology.

Table 1
Advantages of ES technology.

	Technologies used in Control	Targets	Key conclusions	Ref.
Deposition efficiency	Air-assisted spray	Bananas	Tracer deposition increased to 1.5–3.4 times.	Law and Cooper (2001)
	Air-assisted spray and Hydraulic spray	Ideal plane models	Tracer deposition on the front of the target was increased by 1.2 (air assisted spray) and 9.1 times (hydraulic spray).	Lyons et al. (2011)
	Air-assisted spray	Fresh strawberries	Droplet transfer efficiency was increased by 3.0 times.	Peretto et al. (2016)
	Hydraulic spray	Maize crops	Droplet deposition was increased to 1.56–2.82 times.	Marques et al. (2019)
	NES[a]	Soybean crops	Tracer deposition increased to 1.39 times.	Assunção, Silva, Alves, Zandonadi, and Cunha (2019)
	NES	Early season cotton crops	Droplet transfer efficiency was increased to 1.60 times.	(Daniel E. Martin et al., 2019)
	NES	Maize crops	Droplet deposition was increased to 1.29–1.48 times.	Assunção, Cunha, Silva, Alves, and Lemes (2020)
	NES	Greenhouse pepper crops	Tracer deposition increased to 1.59–2.08 times.	Sánchez-Hermosilla, Pérez-Alonso, Martínez-Carricondo, Carvajal-Ramírez, and Agüera-Vega (2022)
	NES	Cabbage plant canopy	Tracer deposition increased to 1.18–1.95 times.	Jyoti et al. (2022)
Coverage Uniformity	Air-assisted spray	Bananas	The change of deposition amount of ES at different positions on banana surface (c = 0.32) is smaller than that of air-assisted spray (c = 0.74).	Law and Cooper (2001)
	Air-assisted spray	Simulated plastic plants	The deposition density of charged spray was 0.66–1.33 mg/cm^2 on the backside of the leaf, while the deposition density of uncharged spray was almost zero on the backside.	Maski and Durairaj (2010)
	Air-assisted spray and Hydraulic spray	Ideal plane models	Tracer deposition on the back of the target was increases by 6.1 (air assisted spray) and 29.0 times (hydraulic spray)	Lyons et al. (2011)
	Air-assisted spray	Fresh strawberries	Electrostatic coating uniformity was increased by 35%.	Peretto et al. (2016)
Agent Consumption	Air-assisted spray	Bananas	The quality of active ingredients of bactericide used in ES was only half of that of air-assisted spray.	Law and Cooper (2001)
	Air-assisted spray and Hydraulic spray	Ideal plane models	The amount and concentration of antimicrobial medicament used in ES were 1/6 and 0.44 of hydraulic spray, respectively, but both reduced the number of bacteria to the same extent.	Lyons et al. (2011)
	Hydraulic spray	Maize crops	Hydraulic spray at 28.1 L per hectare and ES at 9.3 L per hectare reduced spider mites numbers by the same amount.	(D. E. Martin & Latheef, 2019)
	Hydraulic spray	Maize crops	Hydraulic spray at 100 L per hectare and ES at 35 L per hectare reduced Dalbulus maidis mite numbers by the same amount.	Marques et al. (2019)
	NES	Early season cotton crops	When the spray amount was 9.3 L per hectare, the application rate[b] of ES (25.4%) was higher than that of NES (18.2%).	(Daniel E. Martin et al., 2019)
	Hydraulic spray	Farmland	The growth of weeds was equally suppressed by hydraulic spray at 28.1 L per hectare and ES at 9.4 L per hectare.	(Daniel E. Martin, Latheef, Lopez, & Duke, 2020)

[a] NES refers to the use of an electrostatic spray system but off-charge.
[b] The application rate is defined as the percentage of the amount deposited on the crops and the amount applied per hectare.

Fig. 3. Electrostatic attractions between bananas and the uncharged droplets (a) and charged droplets (b). (c) Showed the charged droplets spraying on the crowns of bananas. Reprinted from Law and Cooper (2001) with permission from Ieee Transactions on Industry Applications, Copyright 2001.

top and back of bananas did not differ significantly (cv = 0.32), while the deposition amount of air-assisted spray had large variation (cv = 0.74), which indirectly confirmed that ES had better coverage uniformity (Law & Cooper, 2001).

(4) Agent Consumption

Smaller charged droplets, higher deposition efficiency, and better coverage uniformity mean that less agent is used in practical production. D. E. Martin and Latheef (2019) sprayed maize crops with ES and hydraulic spray, and found that ES at 9.3 L per hectare and hydraulic spray at 28.1 L per hectare reduced spider mites numbers by the same amount. (D. E. Martin & Latheef, 2019). In another report, the researchers targeted maize crops and found that the target application rate of ES (25.4%) was significantly higher than that of non-electrostatic spray (NES) (18.2%) (The application rate is defined as the percentage of the amount deposited on the crops and the amount applied per hectare) (Daniel E. Martin et al., 2019).

3. Application of ES technology in food preservation

Compared with non-electrostatic spraying, ES technology has higher deposition efficiency and better coverage uniformity, which means that antimicrobial agents can adequately cover uneven food surfaces. In the field of food preservation, ES technology is commonly utilized to spray antimicrobial agents, prepare antimicrobial films, or disinfect liquid foods (Fig. 4).

3.1. Spraying antimicrobial agents directly onto food

In the food industry, ES technology was initially used to coat the surface of food with one or more layers of materials to improve their appearance, aroma, taste and other qualities (Barringer & Sumonsiri, 2015). Given that foodborne pathogens are a major factor affecting the shelf life of food, some researchers utilized ES technology to inhibit the growth of microorganisms on food surfaces (Table 2). Mohammadi-Aragh, Linhoss, and Evans (2022) evaluated the disinfection efficacy of Virocid and BioShield 75 on hatching eggs using ES, and found that the electrostatic application of Virocid and BioShield 75 significantly reduced the bacterial load of broiler incubated eggs, and the bacterial count decreased 2.66 and 2.09 log CFU/egg respectively after 3 h of incubation (Mohammadi-Aragh et al., 2022). In another study, Almasoud, Hettiarachchy, Rayaprolu, Horax, and Eswaranandam (2015) found a strong antimicrobial effect of electrostatic spraying of malic acid and lactic acid on *Escherichia coli* O157:H7 biofilms on spinach leaves, as well as *Salmonella enterica* serovar Typhimurium biofilms on cantaloupe peels (Almasoud et al., 2015). The combination of lactic acid (2.0% w/v) and malic acid (2.0% w/v) resulted the highest live-count reduction of 4.14 and 3.6 log for *Escherichia coli* strain ED 14 attached to spinach leaves and *Salmonella enterica* serovar Typhimurium strain SD 10 on cantaloupe peels, respectively. Lee, Woo, Kang, and Song (2021) evaluated the antimicrobial activity of electrostatic spraying of passion fruit peel extract (PPE) against *Escherichia coli* O157:H7 and *Listeria monocytogenes* on fresh-cut Lollo Rossa lettuce and beetroot leaves, and compared it with conventional PEE washing (Lee et al., 2021). The initial cell counts of *Escherichia coli* O157:H7 and *Listeria monocytogenes* were 6.38 and 6.45 log CFU g^{-1} on Lollo Rossa leaves and 6.40 and 6.44 log CFU g^{-1} on beetroot leaves, respectively. The number of pathogens decreased by 2.22–2.86 log CFU g^{-1} after ES treatment with 6 mg mL^{-1} PPE, which was the optimal antimicrobial concentration determined in the pre-experiment, while the number of pathogens decreased by 1.13–2.09 log CFU g^{-1} after conventional washing with the same concentration of PPE. Quality analysis indicated that there was no significant difference in overall color and hardness among all treatment groups during storage.

In order to validate the advantages of ES technology in food preservation, some researchers compared the antimicrobial efficiency of ES and NES technology. Law and Cooper (2001) treated bananas infected with fungi (mixture of *Fusarium* spp., *Verticillium* spp., and *Acremonium* spp.) utilizing different air-assisted spray techniques (charged and uncharged) and visually observed the incidence of different rot levels after 26 days of storage (Law & Cooper, 2001). The results indicated that 14%, 26% and 64% of bananas in the ES, air-assisted spray and control groups showed obvious rot after 26 days of storage, respectively. Notably, the concentration of antimicrobial active ingredient used in the ES group was only 0.192 mg mL^{-1}, which was half that of the NES group (0.4 mg mL^{-1}). Kerr and Kerr (2015) studied the effect of ES treatment on the shelf life of cupcakes (Kerr & Kerr, 2015). They sprayed the targets with a potassium sorbate solution containing bromocresol purple and analyzed the area coverage of the ES and NES treatments using image analysis software. As shown in Fig. 5(a and b), the ES treatment significantly improved the surface coverage of the potassium sorbate solution. Moreover, at 85% RH and 25 °C, 7.8% and 2.1% of the surface

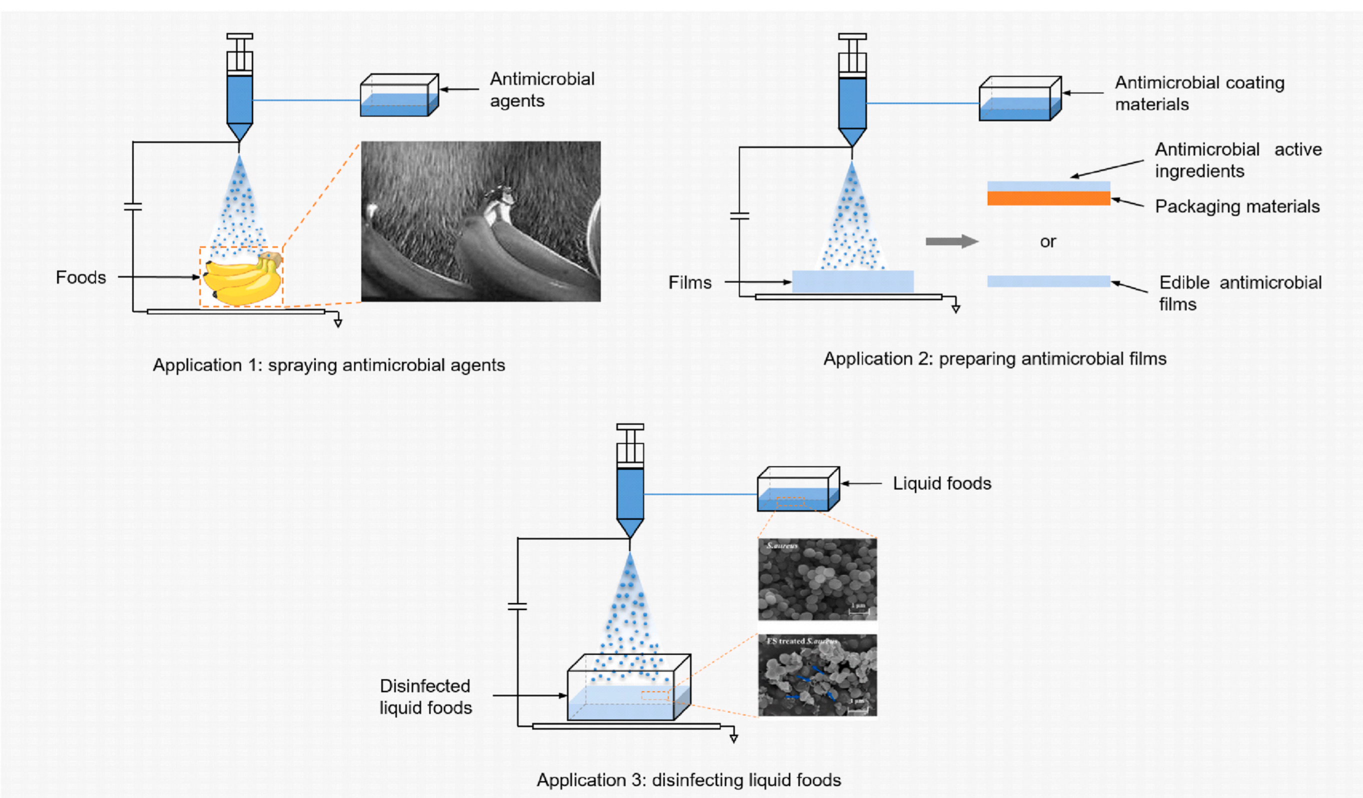

Fig. 4. Applications in food preservation of ES technology. The application 1 picture reprinted from Law and Cooper (2001) with permission from Ieee Transactions on Industry Applications, Copyright 2001; application 3 picture reprinted from Zhang et al. (2023) with permission from Journal of Food Engineering, Copyright 2023.

Table 2
Antimicrobial agents sprayed on food surface and antimicrobial films prepared by the ES technique.

Antimicrobial agents	Foods	Key conclusions	Ref.
Malic acid, tartaric acid, lactic acid and grape seed extract	Spinach and Lettuce	The growth of *Escherichia coli* O157:H7 was inhibited by electrostatic spraying of malic acid, tartaric acid, lactic acid and grape seed extract.	Ganesh, Hettiarachchy, Griffis, Martin, and Ricke (2012)
4% malic acid and 2% lactic acid	Fresh-cut cantaloupe blocks	When combined with malic acid and lactic acid, cantaloupe blocks had the largest bacterial log value reduction (4.6 logs) after 12 days storage at 4 °C.	Massey, Hettiarachchy, Martin, and Ricke (2013)
Lactic acid (2.0% w/v) and malic acid (2.0% w/v)	Spinach leaves and cantaloupe peels	The combination of lactic and malic acid springs showed the highest logarithmic reduction rates of 4.14 and 3.6 for *Escherichia coli* attached to spinach and *Salmonella* Typhimurium on cantaloupe skin, respectively.	Almasoud et al. (2015)
10^9 CFU mL^{-1} lactic acid bacteria aqueous solution	Spinach plants	The *Escherichia coli* O157: H7 concentrations in leaves and soil were reduced by spraying lactic acid solution during the first four weeks of the growth cycle.	Laury-Shaw, Gragg, Echeverry, and Brashears (2019)
5% lauric arginate and 1500 ppm of peracetic acid	Chicken thigh meat	After 45 s of electrostatic spraying with 5% lauric arginate and 1500 ppm peracetic acid, *Salmonella* decreased by 5 and 1.157 log, respectively, without significant differences in the color, texture, and water retention of the chicken thigh meat.	Punchihewage-Don et al. (2021)
6 mg mL^{-1} passion fruit peel extract (PPE)	Fresh-cut Lollo Rossa and beetroot leaves	The number of pathogens was reduced by 2.22–2.86 log CFU g^{-1} after PPE treatment and by 1.13–2.09 log CFU g^{-1} after PPE cleaning, without significant differences in the total color difference and hardness between the groups.	Lee et al. (2021)
Virocid and BioShield 75	Eggs	The electrostatic application of Virocid and BioShield 75 reduced bacterial loads by 2.66 (P < 0.0001), 2.09 (P < 0.0001) log CFU/egg.	Mohammadi-Aragh et al. (2022)
Imazalil and thiabendazole, air-assisted spray group 0.4 mg mL^{-1} and ES group 0.192 mg mL^{-1}	Bananas	After 26 days storage, 14%, 26% and 64% of the bananas in the ES, air-assisted spray and control groups showed significant decay, respectively.	Law and Cooper (2001)
Malic acid (2% v/v) and grape seed extract (3% v/v)	Spinach	14 days after the spraying of malic acid and grape seed extract on spinach, the log value of viable *Salmonella* Typhimurium was 3.5 log CFU g^{-1}, which was lower than that of blank control and NES groups.	Ganesh et al. (2010)
5% potassium sorbate solution	Cupcakes	After 5 days at 85% RH and 25 °C, 0.4%, 2.1% and 7.8% of the surfaces in the ES, NES and control groups were covered with mold.	Kerr and Kerr (2015)
Malic acid (4% w/v)	Cantaloupe blocks	On the 11th day, the bacterial logarithm values of surviving cantaloupe blocks in ES, NES and control groups were 3.7, 5.9 and 6.6 log CFU g^{-1}, respectively, without significant differences in the color and hardness of cantaloupe blocks.	Massey et al. (2018)
Lactic acid (4.5% w/v)	Fresh beef	NES and ES sprayed with lactic acid produced 3.3 and 1.2 log CFU cm^{-2} *Escherichia coli* reductions, respectively.	Hudson et al. (2019)
0.25% hydrogen peroxide and 0.5% peracetic acid	Apples	The impregnation method was the most effective method for reducing pathogens	Stearns et al. (2022)

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Table 2 (*continued*)

Antimicrobial agents	Foods	Key conclusions	Ref.
		(2.31–2.41 log CFU per apple), followed by conventional spray (1.44–1.70 log CFU per apple) and ES (0.84–1.20 log CFU per apple).	
Chitosan solution	Corona pretreated low-density polyethylene (LDPE)	The mass densities of chitosan deposited on LDPE surface by impregnation, conventional spraying and electrostatic spraying were 399.0 μg cm^{-2}, 489.0 μg cm^{-2} and 1.7 μg cm^{-2}, respectively, and the coating thickness was 40–80 μm, 30–90 μm and 8.5 × 10^{-3} μm respectively.	Munteanu et al. (2014)
Chitosan (2.3 wt %) and vitamin E (0.5 wt%-3 wt %) complex solution	Corona pretreated polyethylene (PE)	Chitosan solution with vitamin E was a non-Newtonian shear-thinning fluid that favored electrostatic spraying. The electrostatic deposition of the chitosan/vitamin E complex on the PE surface formed a coating of about 8.5 nm, which demonstrated antimicrobial activity against all three tested bacteria.	Stoleru et al. (2016)
Chitosan acetic acid solution, sodium alginate aqueous solution and soybean protein isolate aqueous solution	Cheeses	The coatings formed by conventional spraying and electrostatic spraying had smaller thicknesses, and the quality (weight loss, hardness and color) of cheese during storage was not affected by different coating methods.	Zhong, Cavender, and Zhao (2014)
Sodium alginate aqueous solution (2% w/v) containing carvacrol (0.98% w/w) and methyl cinnamate (1.45% w/w)	Strawberries	Strawberries in control (uncoated), NE and ES groups showed signs of fungal infection after 7-, 10- and 11-days storage, respectively. After 13 days storage, the decay rates of strawberries in control, NES and ES groups were 16.6%, 8.3% and 5.6%, respectively.	Peretto et al. (2016)
Guava seed oil (15%) and soy lecithin (2%) emulsion	Guava fruits	The total bacterial count of guava fruit at the end of the storage period decreased by 61%, and the shelf life was extended to 10 days (6 days for the control group).	Kapoor et al. (2022)
Chitosan acetic acid aqueous solution (0.5% w/w) containing citronella oil (0.5% w/w)	Salmon fillets	The total number of bacteria in the coating group (4.78 log CFU/g) was significantly lower than that in the control group (6.42 log CFU/g) after 10 days of storage.	Yin et al. (2022)
Chitosan acetic acid aqueous solution (1.5% w/v) containing garlic leaf extract (4% w/v) and stem cellulose nanocrystal (0.8% w/v)	black garlic	Electrostatic spraying of edible coating reduced the degree of browning during 90 days of storage.	Ding et al. (2023)

in control and NES groups were covered with mold after 5 days, while only 0.4% of the samples in the ES group were covered with mold. Massey et al. (2018) treated cantaloupe blocks inoculated with *Salmonella enterica* serovar Typhimurium with ES at different concentrations of malic acid and monitored the number of live bacteria within 11 days of storage at 4 °C compared with NES treatment (Massey et al., 2018). The results indicated that malic acid (4% w/v) significantly inhibited the growth of *Salmonella enterica* serovar Typhimurium on cantaloupe blocks. On day 11, the number of viable bacteria in the ES group was 3.7 log CFU g^{-1}, compared with 5.9 and 6.6 log CFU g^{-1} in the NES and control groups, respectively. In addition, electrostatic spraying of malic and lactic acid had no obvious effect on the color and hardness of cantaloupe blocks.

In NES treatment, the uneven coverage of antimicrobial solution on the sample surface resulted in a low solution retention rate, and the aggregation of large droplets resulted in runoff. By contrast, the ES treatment ensured that every part of the sample surface was uniformly covered by the antimicrobial solution and reduced runoff, which can explain the higher antimicrobial effect of the ES treatment compared to the NES group in most studies. Nevertheless, some studies have come to the opposite conclusion. Hudson et al. (2019) compared the inhibitory effect of spraying antimicrobial agents onto the surface of fresh beef contaminated with *Escherichia coli*, using conventional sprayers and electrostatic sprayers (Hudson et al., 2019). They found that NES and ES treatment with lactate (4.5% w/v) produced a 3.3 and 1.2 log CFU cm^{-2} reduction in *Escherichia coli*, respectively. This may be due to the temperature difference between the LA solution released by NES (55 °C) and that released by ES (25 °C). A study has shown that the inhibitory effect of lactic acid on food surface microorganisms increases with the increase of temperature (Anderson & Marshall, 1990). Furthermore, the NES and

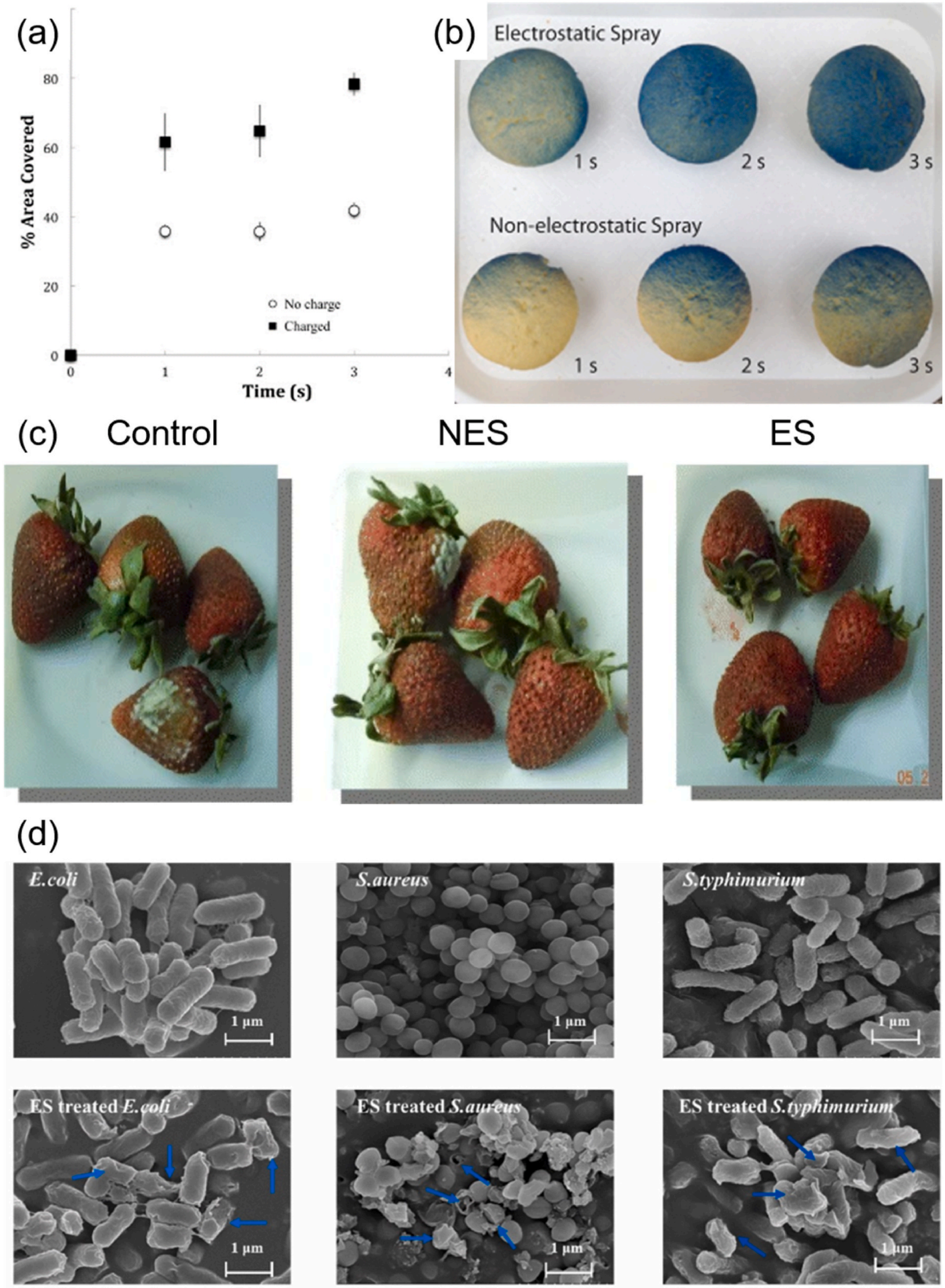

Fig. 5. (a) The variation of the area covered by potassium sorbate solution as the spraying time increased; (b) Images of cupcakes sprayed with 5% potassium sorbate solution and 0.5% Bromocresol Purple solution. Reprinted from Kerr and Kerr (2015) with permission from Journal of Food Processing and Preservation, Copyright 2015. (c) Appearance of uncoated (control), NES, and ES coated strawberries after stored for 13 days. Reprinted from Peretto et al. (2016) with permission from Food and Bioprocess Technology, Copyright 2016. (d) FSEM images of the untreated (native) bacteria and the high-voltage ES treated bacteria. Reprinted from Zhang et al. (2023) with permission from Journal of Food Engineering, Copyright 2023. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ES groups were respectively sprayed with 500 mL and 126 mL of lactic acid solution during the 60 s treatment time, which might also explain the lower antimicrobial effect of the ES treatment compared to the NES.

In general, ES tends to have a higher inhibitory effect on food surface microorganisms than NES due to its high deposition efficiency and uniform coverage. The use of ES to spray antimicrobial agents can effectively reduce food decay and spoilage during storage without affecting food quality (such as color and hardness). ES technology can also reduce the use of agents. However, when applying ES technology, attention should be paid to the selection of appropriate antimicrobial agents, as antimicrobial solutions with low electrical conductivity may not be suitable for ES (Bolton et al., 2013).

3.2. Preparing antimicrobial films

Another application of ES technology in food preservation is the preparation of antimicrobial films (Table 2). The ideal antimicrobial film can not only inhibit the growth of microorganisms on the food surface, but also block ultraviolet rays and prevent associated food oxidation (Priyadarshi, Kim, & Rhim, 2021). Moreover, the film acts as a barrier to gas exchange and changes the atmosphere around fresh produce (Sapper & Chiralt, 2018), thereby regulating respiration rates to delay ripening and deterioration.

(1) Spraying antimicrobial active ingredients onto packaging materials

Commonly used food packaging films such as polyethylene have excellent mechanical properties, but do not have antimicrobial activity. Spraying antimicrobial active ingredients such as chitosan, curcumin or poly-lysine onto film substrates is a useful strategy to imbue them with added functionality (Hao et al., 2011; Theapsak, Watthanaphanit, & Rujiravanit, 2012; Zhai et al., 2020). Because ES technology has high deposition efficiency and great coverage uniformity, some researchers utilized it to prepare antimicrobial films by spraying active ingredients. Munteanu et al. (2014) coated corona pretreated low-density polyethylene (LDPE) films with chitosan solutions of different concentrations by impregnation, conventional spraying and electrostatic spraying (Munteanu et al., 2014). They found that the mass density of chitosan deposited on the LDPE surface by impregnation and conventional spraying was 399.0 and 489.0 μg cm^{-2}, and the thickness of the chitosan coating was 40–80 and 30–90 μm, respectively, while the mass density of chitosan applied by electrostatic spraying was only 1.7 μg cm^{-2}, and the thickness of the coating was 8.5×10^{-3} μm. The authors suggested that the amount of chitosan deposited onto the LDPE surface could be precisely controlled by changing the deposition time using the ES. More importantly, all three types of films achieved similar inhibition of *Salmonella enteritidis*, *Escherichia coli* and *Listeria monocytogenes*. In another report, Stoleru et al. (2016) immobilized a layer of chitosan and vitamin E on the surface of polyethylene (PE) by electrostatic spraying, thus endowing the film with antimicrobial and antioxidant properties (Stoleru et al., 2016). ATR-FTIR and XPS results indicated that the chitosan and vitamin E formed a relatively stable complex via electrostatic and hydrogen bonding. When the pretreated PE film was coated by ES, the functional groups generated by coronal discharge reacted with the amino groups of chitosan, forming stable amide or N-alkyl carbamate bonds (Paslaru et al., 2013). Further rheological analysis indicated that the chitosan solution containing vitamin E behaved as a non-Newtonian shear-thinning fluid, favoring electrostatic spraying. The electrostatic deposition of the chitosan/vitamin E complex on the PE surface formed a coating of 8.5 nm, which showed antimicrobial activity against *Salmonella enterica* serovar Typhimurium, *Escherichia coli* and *Listeria monocytogenes*. Therefore, the authors suggested that a very thin coating of chitosan was sufficient to confer antimicrobial activity on PE.

(2) Preparing edible antimicrobial films

Considering the growing demand for higher safety and quality of fresh, semi-finished or ready-to-eat foods, edible coatings have attracted increasing attention. Edible coatings have been widely used in food preservation to prevent physical damage, delay deterioration and reduce mass loss by establishing a semi-permeable barrier that reduces the transfer of gasses, water vapor and volatile compounds (Andrade et al., 2012). Some researchers have evaluated the effect of edible coatings prepared with static and NES on food preservation. Peretto et al. (2016) applied an edible alginate coating containing carvacrol and methyl cinnamate to fresh strawberries and compared the effects of electrostatically and conventionally sprayed alginate-based natural antimicrobials on the quality of strawberries (Peretto et al., 2016). The transfer efficiency and coating uniformity were measured by the color shift of water-sensitive paper in different parts of the strawberry. This water-sensitive paper changed color from yellow to blue when it came into contact with water droplets. The results showed that the transfer efficiency of electrostatic spraying was twice that of NES, and the coating uniformity was increased by 35%. In addition, the authors observed that the strawberries in the control group (uncoated), NES group and ES group showed signs of fungal infection after 7, 10 and 11 days of storage, respectively. After 13 days of storage, the decay rate of strawberries in the ES group was only 5.6%, which was significantly lower than that in the control group (16.6%) and NES group (8.3%). The appearance of strawberries in the control, NES and ES group after 13 days of storage is shown in Fig. 5(c). Furthermore, there was no significant difference in weight loss or color between NES and ES strawberries during storage, but the ES strawberries exhibited a significant improvement of hardness and other mechanical properties.

Electrostatic liquid coating of edible film-forming materials is considered a promising novel food preservation technology, which can improve the shelf life and overall quality of food. Kapoor et al. (2022) used guava seed oil (GSO) and soybean lecithin to prepare emulsion-based edible coating, and utilized ES equipment to evenly spray charged particles of emulsion onto guava fruit (Kapoor et al., 2022). The electrospray coated and control fruits (without coating) were stored at environmental conditions. They found that the guava fruits coated with 15% GSO showed the best results in weight reduction, firmness, spoilage and microbial load, and the shelf life was extended to 10 days (6 days for the control fruits). In another study, Yin et al. (2022) explored the effects of different concentrations of chitosan (CS), citronella oil (CNO) and surfactant Tween 80 (TW) on the antimicrobial and physical properties of edible films prepared by electrostatic spraying (Yin et al., 2022). In addition, the storage effects of the optimal formulation (OF) on salmon slices were also evaluated during 10 days storage at 4 °C. The OF obtained by response surface optimization method was 0.50% CS, 0.50% CNO and 0.30% TW. At the end of the storage, the total bacterial count in the uncoated and OF treatment salmon samples were 6.42 and 4.78 log CFU g^{-1}. In addition, the samples from the OF treatment group had less thiobarbituric acid and total volatile basic-nitrogen, and retained better hardness and color at the end of storage.

Overall, the films prepared by electrostatic spraying have good uniformity and very small thickness, while offering comparable or better antimicrobial activity than other methods (conventional spraying, impregnation or embedding), and have obvious advantages in saving raw materials, which means that the application of electrostatic spraying in the food industry will reduce production costs. However, in order to control the deposition uniformity of the coating and obtain the best antimicrobial effect, the operation parameters of electrostatic spraying, such as voltage, injection flow rate, active component concentration, solvent, etc., need to be optimized.

3.3. Disinfecting liquid foods

In liquid foods processing, heat treatment is often utilized to inhibit the growth of microorganisms, but long-term high-temperature treatment may negatively affect food quality. ES technology is a new non-thermal sterilization technology. In addition to spraying antimicrobial agents and preparing antimicrobial films, several researchers have explored the feasibility of using ES technology to disinfect liquid foods.

(1) Microbial inactivation mechanisms of ES technology

There are several possible mechanisms of disinfecting liquid foods by ES technology. Firstly, most bacterial cell membranes have a negative charge on their surface, and positively charged particles can attract and destroy the cell membrane structure through electrostatic interactions (Luo, Jiang, & Tan, 2022). In general, the ES technology uses a positive high-voltage power supply to make the droplet carry a positive charge. Therefore, when using ES technology to disinfect liquid foods, the electro-disintegration effect caused by high voltage destroys the microbial cell membrane (Y. Wang, Zhao, et al., 2023). Secondly, charged droplet disintegrate during ES process, and strong shear effect during droplets formation may induce microbial cell rupture. Fig. 5(d) showed field emission scanning electron microscope (FSEM) images of *Escherichia coli*, *Staphylococcus aureus* and *Salmonella* Typhimurium before and after ES spraying. Thirdly, ES affected some key enzymes in microbial cells through the enzyme-blunting property, thereby achieving non-thermal inactivation of the microorganism. Wang, Zhao, et al. (2023) sprayed suspensions of *Escherichia coli* and *Staphylococcus aureus* with ES (Y. Wang, Zhao, et al., 2023), and found that the ES treatment significantly reduced ATPase activity in *Escherichia coli* and *Staphylococcus aureus*.

(2) Factors affecting the antimicrobial efficiency of ES technology

ES treatment parameters are the main impacts on microbial inactivation efficiency, including operating voltage, needle size and flow rate. Zhang et al. (2023) optimized the parameters of the ES process for raw bovine milk (Zhang et al., 2023). They found that the inactivation rate of microorganisms increased with the increase of operating voltage after the raw bovine milk was sprayed with ES. The inactivation rate of microorganisms reached the maximum value (39.29%) at 50 kV, which was not significantly different from the low-temperature long-time (LTLT, the microbial inactivation rate was 39.12%) and high-temperature short-time (HTST, the microbial inactivation rate was 37.41%) thermal pasteurization treatment. Additionally, the smaller the needle size, the higher the inactivation rate of microorganisms. There are several explanations for this: 1) the reduction of the needle size enhanced the point discharge phenomenon (Yakut, Yakut, Sabolsky, & Kuhlman, 2021); 2) when the flow rate was constant, a smaller needle size will produce a higher shear rate (Ghandi, Powell, Howes, Chen, & Adhikari, 2012); 3) the smaller the needle size, the smaller the size of the droplets produced (Yakut et al., 2021), and the stronger the shear effect when the droplets formed. Moreover, the microbial inactivation rate decreased significantly as the flow rate increased. This was probably due to the shorter residence time of the droplets at the increased flow rate, which resulted in a single conical jet. The single conical jet reduced the surface charge of the droplets (Kong et al., 2022), thus reducing the microbial inactivation effect.

In addition to the ES treatment parameters, the species and the living environment of microorganisms also affected the inactivation efficiency. Zhang et al. (2023) utilized ES to spray the suspensions of *Escherichia coli*, *Staphylococcus aureus* and *Salmonella* Typhimurium, and found that the inactivation rates of the three kinds of bacteria were 99.1%, 83.7% and 93.7% respectively (Zhang et al., 2023). The resistance of the three kinds of bacteria to ES treatment was different. Gram-positive bacteria were significantly stronger than Gram-negative bacteria, possibly due to the thicker peptidoglycan layer of Gram-positive bacteria (Park & Ha, 2019). Wang, Zhao, et al. (2023) investigated the influence of the environment on ES inactivated microorganisms (Y. Wang, Zhao, et al., 2023). The results showed that when the environment was changed from normal saline to honey raspberry wine, the efficiency of ES inactivation of microorganisms was significantly enhanced. The author believed that honey raspberry wine contained more sugar and organic acids, making it more conductive and lower in pH, thus enhancing the microbial inactivation effect of ES.

(3) Influence on the liquid foods quality

ES disinfecting liquid foods is a novel technology; therefore, it is necessary to explore the influence of ES treatment on the quality of liquid foods. Wang, Zhao, et al. (2023) compared the effects of ES treatment and heat treatment on flavor substances (mainly esters and ketones) of honey raspberry wine (Y. Wang, Zhao, et al., 2023). They found that after ES treatment, honey raspberry wine had 5.41% less ketones and 1.10% more esters; heat treatment had a large impact on flavor substances, with ketones and esters decreasing by 75.40% and 13.46%, respectively. The results suggested that the ES treatment had less effect on the flavor substances of the honey raspberry wine than the heat treatment. Zhang et al. (2023) evaluated the quality of raw bovine milk after ES treatment and compared it with LTLT and HTST thermal pasteurization treatment (Zhang et al., 2023). The results showed that there was no significant difference between the fat content of the raw bovine milk and the bovine milk after high-voltage ES treatment and thermal pasteurization treatment. Additionally, the soluble protein content of raw bovine milk did not change significantly after high-voltage ES treatment. However, treatment with LTLT and HTST reduced it from 3.42 g/100 g to 3.15 g/100 g and 3.17 g/100 g, respectively. Interestingly, the high-voltage ES treatment better preserved the secondary and tertiary structural features of bovine milk protein compared to the thermal pasteurization. Notably, the shelf life of raw milk extended to 14 days after high-voltage ES treatment, compared to 6 days after LTLT and 8 days after HTST treatment.

Generally, using ES equipment can effectively disinfect liquid foods. The microbial inactivation efficiency is related to ES treatment parameters (operating voltage, needle size and flow rate), microbial species and microbial living environment. Compared to the traditional thermal pasteurization technologies, the ES treatment is considerably more microbial inactivation efficient, better retains the flavor of liquid foods, and has less impact on nutrients.

4. Economic feasibility of ES technology

Due to the electrostatic attraction between the droplets and the target, the ES enables the antimicrobial agents to cover the target surface more evenly, while consuming less agent and solvent than traditional NES technologies. However, the high cost of procuring ES equipment limits the broader application of ES technology. Thus, it is necessary to analyze the economic feasibility of ES and traditional methods (such as conventional spray or impregnation). Jiang, Etienne, Li, and Shen (2018) compared the inactivation of *Salmonella enterica*, *Listeria monocytogenes* and *Campylobacter jejuni* on eggs by electrostatic and conventional spray technology and analyzed the economic feasibility of these treatments (Jiang et al., 2018). Electrostatic or conventional spraying of antimicrobial agents for 30 s resulted in significantly higher inactivation of *Salmonella enterica* and *Listeria monocytogenes* than conventional spraying, while the effect on *Campylobacter jejuni* was not significantly different from conventional spraying. However, the consumption of the antimicrobial agent in the conventional spray was eight times that of the ES, resulting in a higher cost of the conventional spray. Economic analysis showed that the total annual cost of electrostatic spraying of eggs with antimicrobials (based on a farm size producing 1500 eggs per day) was 20–40% lower than that of conventional spraying. In another report, Shen et al. (2019) investigated the inactivation of *Campylobacter jejuni* on broiler wings by ES or impregnation, and evaluated the economic feasibility of both methods (Shen et al., 2019). There was no significant difference in the viability reduction of *Campylobacter jejuni* by ES and impregnation, but the water consumption of ES (58.2 mL min^{-1}) was significantly lower than that of impregnation (500 l). The final cost comparison indicated that the impregnation method was more economical for small scale farms. However, with the increase of production scale, the economic advantage of the ES method became more apparent.

5. Summary and outlook

In this paper, we reviewed three applications of ES technology in food preservation: spraying antimicrobial agents, preparing antimicrobial films, and disinfecting liquid foods. Comparing with conventional technologies, ES technologies have obvious advantages in inhibiting microbial growth, saving agents and maintaining food flavor. To expand the application of ES technology in food preservation, we suggest the following points should be considered in the future.

(a) Using ES technology to spray antimicrobial agents is a relatively well-established technology. Section 4 demonstrates the feasibility of large-scale application of this technology in agricultural production. In order to obtain a better spray effect and further reduce the production cost, it is necessary to optimize the operation parameters and select antimicrobial agents with appropriate surface tension and conductivity.

(b) The edible coating films prepared by ES have uniform surface and small thickness, and have the same or better antimicrobial ability as other methods, which is conducive to the promotion and application of this technology. At present, however, most of the relevant studies use chitosan as the film-forming material and add other biologically active substances. Other edible film-forming materials, such as zein (Fan et al., 2022) and corn starch (Liu & Liu, 2022), could be attempted to broaden the application range of this technology.

(c) Disinfecting liquid foods with high-voltage ES is a novel non-thermal sterilization technology that has less impact on the quality of liquid foods than traditional heat treatment. However, there have been few reports on this technology. ES is only used to disinfecting honey raspberry wine and raw bovine milk, and therefore it is necessary to explore the disinfection effects of this technology on other liquid foods. In addition, it is necessary to analyze the economic feasibility, production efficiency and production safety of high-voltage electrostatic disinfecting of liquid foods, so as to provide a reference for the industrial promotion of this technology. At present, the technology is still at the laboratory level, and it can be considered to expand the industrial scale and improve the production efficiency by modifying the spray device (such as using disk array needles or array needles).

CRediT authorship contribution statement

Xinchen Gui: Conceptualization, Investigation, Writing – original draft. **Baoya Shang:** Investigation, Methodology. **Yadong Yu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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