Electrostatic Coating Technologies for Food Processing

Sheryl A. Barringer[1] and Nutsuda Sumonsiri[2]

[1]Department of Food Science and Technology, Ohio State University, Columbus, Ohio 43210; email: barringer.11@osu.edu

[2]Department of Agro-Industrial, Food, and Environmental Technology, King Mongkut's University of Technology North Bangkok, Bangsue, Bangkok 10800, Thailand; email: nutsudas@kmutnb.ac.th

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Abstract

The application of electrostatics in both powder and liquid coating can improve the quality of food, such as its appearance, aroma, taste, and shelf life. Coatings can be found most commonly in the snack food industry, as well as in confectionery, bakery, meat and cheese processing. In electrostatic powder coating, the most important factors influencing coating quality are powder particle size, density, flowability, charge, and resistivity, as well as the surface properties and characteristics of the target. The most important factors during electrostatic liquid coating, also known as electrohydrodynamic coating, include applied voltage and electrical resistivity and viscosity of the liquid. A good understanding of these factors is needed for the design of optimal coating systems for food processing.

1. INTRODUCTION

Electrostatic coating of the target surface with one or more layers of material is one process used to improve the quality of the product (Castle 2001). According to Spice Application Systems Ltd. (**http://www.spiceapplications.com/your-product**), several food industries have been successfully testing electrostatic coating on their products, including pretzels, fresh and processed meat, fresh fish, cheese, cereals, tortilla chips, nuts, French fries, confectionery, rice cakes, pet food, apples, and frozen vegetables. Although various studies have been done on the application of electrostatic coating to food processing, almost all of them come from one laboratory (**Table 1**). Before its application in snack food processing, electrostatic powder coating was used in the automotive painting industry in the 1960s (Bailey 1998). This technique produces more even, uniform, and reproducible coating with minimal waste or overuse of expensive food powders when compared to nonelectrostatic coating, because the powder particles are charged and repel one another, resulting in an even dispersion across the target surface.

Several food processes, especially in the snack food industry, include food powder coating, such as potato chips, cakes, donuts, pretzels, crackers, and shredded cheese, to produce better appearance and taste, resulting in enhanced consumer acceptability. Food powder coating is also used to create more variety in seasoned snack foods. There are two coating systems commonly used to coat foods, the tumble drum coating system and the conveyor belt coating system (Hanify 2001). The tumble drum consists of a horizontal rotating cylinder with internal baffles to flip the food targets, producing even coating on both sides. A gun, spray nozzle, or scarf plate installed inside the drum creates a spray or curtain of powder. The conveyor belt coating system (**Figure 1**) consists of a pneumatic sprayer or roll salter installed over the conveyor belt. In this system, only one side of the target will be coated but the other sides can be coated if equipment is used to flip the target over. However, on many products the consumers do not notice during consumption that only one side is coated. An electrostatic field is created during powder coating by wire electrodes in the coating chamber or at the end of a charging gun. When a pneumatic system is used, the air flow creates aerodynamic force in addition to the gravitational and Coulombic forces, by which the charged powder particles are carried from the dispenser to the target surface (Bailey 1998). The physical properties of the powders, including particle size, shape, charge, flow characteristics, resistivity, and density, as well as the target properties, have a great effect on the coating performance, including transfer efficiency, dust, adhesion, evenness, and functionality of the electrostatically coated product.

Oil and other liquids are sometimes applied to product surfaces to act as release or tack agents, to improve appearance or to add flavors or vitamins. The liquid surface is charged electrostatically to produce very small droplets, which are prevented from agglomerating by repulsion between the droplets, resulting in an even droplet dispersion (**Figure 2**). The factors that affect the coating quality of a liquid-coating system include applied voltage, electrical resistivity, and viscosity of the liquid (Abu-Ali & Barringer 2008).

2. ELECTROSTATIC FOOD POWDER COATING

2.1. Effect of Food Powder Properties on Electrostatic Transfer Efficiency

Transfer efficiency is defined as the ratio of powder deposited on a target to the mass of powder entering into the coating system (Ratanatriwong et al. 2003). It can be affected by powder properties such as powder particle size, density, flowability, and resistivity, as well as by target surface characteristics.

Table 1 Studies on the application of electrostatic coating to food processing

Coating system	Coating material(s)	Target(s)	Measurement(s)	Reference(s)
Food powder coating: tumble drum coating system	Salts with different shapes and sizes	Popcorn	Coating efficiency, adhesion	Miller & Barringer (2002)
Food powder coating: tumble drum coating system	Salt, sugar, cornstarch, maltodextrin, cellulose, flour	Popcorn	Coating efficiency, adhesion	Biehl & Barringer (2003)
Food powder coating: conveyor belt coating system	Flavors	Candy and chocolate	Flavors	Clarke (1968)
Food powder coating: conveyor belt coating system	Salt	Potato chips, crackers, pretzels	Seasoning	Madl (2000), Matz (1984)
Food powder coating: conveyor belt coating system	Antimicrobial agents	Meat	Shelf life	Ahlberg (2001)
Food powder coating: conveyor belt coating system	Natamycin, cellulose	Cheese	Shelf life	Elayedath & Barringer (2002)
Food powder coating: conveyor belt coating system	Sodium erythorbate, glucono-delta-lactone	Meat	Shelf life and color	Barringer et al. (2005)
Food powder coating: conveyor belt coating system	Sodium erythorbate, smoke extract, glucose, cellulose with natamycin	French fries, cheese	Shelf life and color	Amefia et al. (2006)
Food powder coating: conveyor belt coating system	Seasonings	Potato chips, fried banana chips	Coating efficiency and consumer acceptance	Ratanatriwong et al. (2003, 2009)
Food powder coating: conveyor belt coating system	Calcium	Diced tomatoes	Firmness	Rao & Barringer (2006)
Food powder coating: conveyor belt coating system	Salt, maltodextrin, cellulose, cornstarch, sour cream powder, whey powder, nonfat dry milk, soy flour, sugar, cocoa	Potato chips, crackers, pork rinds, white bread, aluminum foil	Coating adhesion	Halim & Barringer (2007)
Food powder coating: conveyor belt coating system	Salt	Potato chips	Coating adhesion	Buck & Barringer (2007)
Food powder coating: conveyor belt coating system	Starch, salt, cocoa powders, cheese powder, protein, sugar	Metal, wood, paper, plastic, bread	Coating efficiency, percent side coverage	Sumonsiri & Barringer (2010, 2011)
Liquid electrostatic coating system	Oils, emulsions with additives	Crackers	Reproducibility, droplet size	Abu-Ali & Barringer (2005)
Liquid electrostatic coating system	Soybean oil	Cheese, milk chocolate, and crackers	Reproducibility, efficiency	Abu-Ali & Barringer (2008)
Liquid electrostatic coating system	Cocoa butter, confectionary coating, lauric butter	Glass slides, aluminum foil	Droplet size, coating quality	Marthina & Barringer (2012)
Liquid electrostatic coating system	Malic, tartaric and lactic acid, grape seed extract	Spinach and lettuce	Antimicrobial activity against *Escherichia coli* O157:H7	Ganesh et al. (2012)
Liquid electrostatic coating system	Malic and lactic acid, grape seed extract	Cantaloupe cubes	Antimicrobial activity against *Escherichia coli* O157:H7	Massey et al. (2013)
Liquid electrostatic coating system	Soybean oil	Oil-sensitive paper	Number of droplets, droplet size range	Aykas & Barringer (2014)
Liquid electrostatic coating system	Alginate and chitosan	Fresh-cut melon	Coating adhesion and antimicrobial activity	Poverenov et al. (2014)

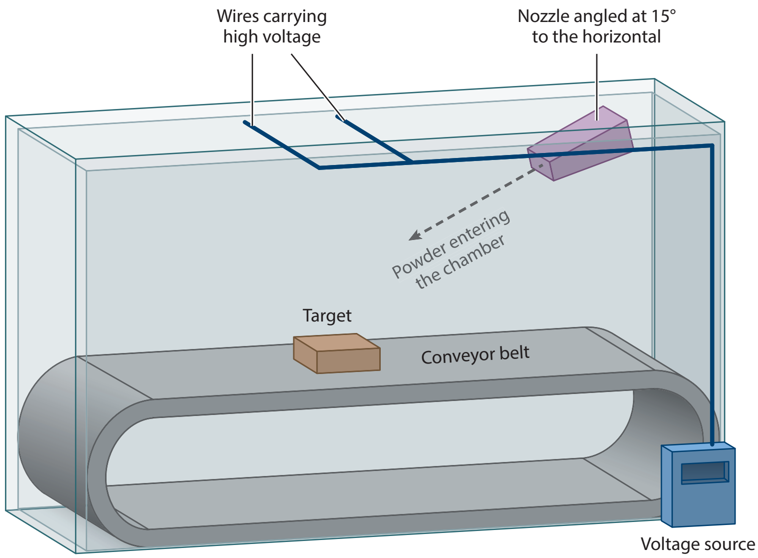

Figure 1

An electrostatic conveyor belt coating system. Powder enters the chamber from the nozzle to land on the target. The voltage source provides high voltage to the wires, creating the electrostatic field in the coating chamber.

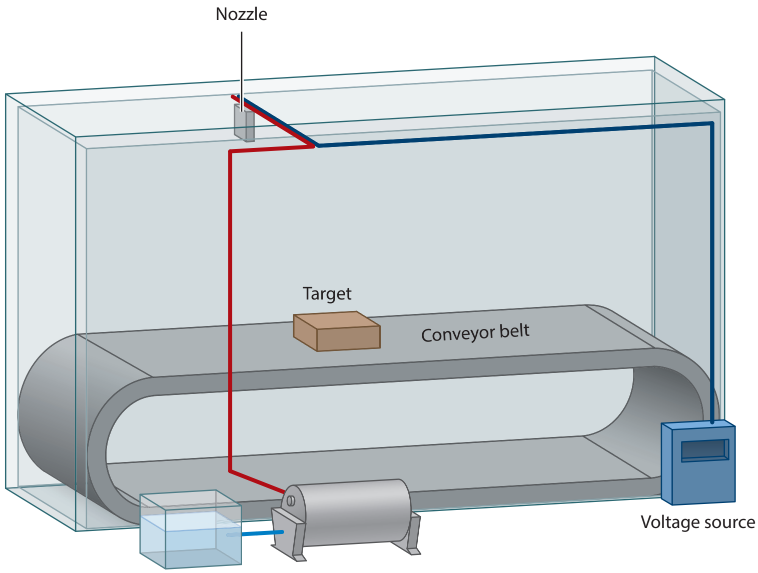

Figure 2

A liquid electrostatic coating system. Liquid is pumped to the nozzle before entering the chamber and landing onto the target. The voltage source provides the current to the nozzle.

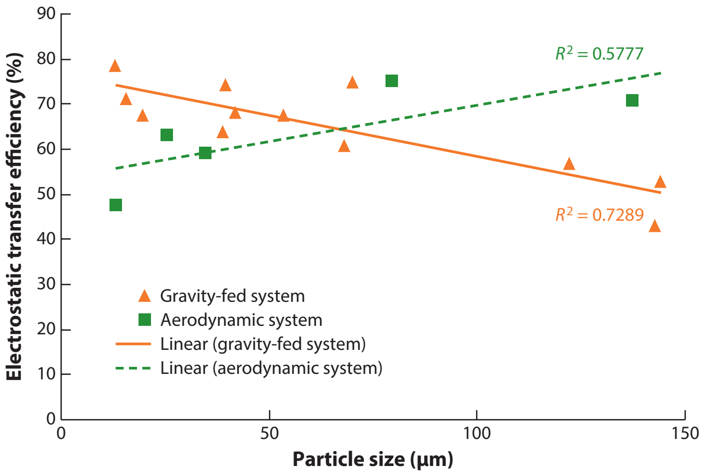

Figure 3

Effect of powder particle size on electrostatic transfer efficiency in a gravity-fed system and an aerodynamic system. Data from Biehl & Barringer 2003, Mayr & Barringer 2006.

2.1.1. Particle size. Performance can be either directly or inversely proportional to the powder particle size, depending on the particle size range used and other specifics of the system. With smaller particles, electrostatic force dominates, and the smaller the particle, the greater the charge-to-mass ratio of the particle and the more efficient the coating. With large powders, gravitational force dominates, and the larger the powder, the more efficient the coating. The specifics of the coating system determine the particle size range at which each force dominates. For example, the electrostatic transfer efficiency increased with a decrease in particle size from 145 to 13 µm in a gravity-fed curtain dispensing system, where electrostatic force guided the powder to the target (**Figure 3**) (Biehl & Barringer 2003). However, in a pneumatically fed system, electrostatic transfer efficiency increased with increasing particle size, as the gravitational force aided in guiding the powder to the target (**Figure 3**) (Mayr & Barringer 2006). If enough sizes are tested, it is possible to determine the particle size needed for gravitational, as opposed to electrostatic, force to dominate (Ratanatriwong & Barringer 2007).

2.1.2. Powder density. Powder density can affect transfer efficiency during coating (Biehl & Barringer 2003). In computer simulations, electrostatic transfer efficiency increased by 10% for small powders, as particle density increased from 1,200 to 2,200 km/m^3. Powders with lower density have lower mass and inertia and are more likely to remain in the air as dust than more dense powders of the same particle size (Yousuf & Barringer 2007). Experimentally, electrostatic transfer efficiency increased only 4%, as powder density increased from 1,600 to 2,200 kg/m^3 (Biehl & Barringer 2003). Most food powders fall within a small range of densities; thus, density generally has an insignificant influence during electrostatic coating when compared to particle size or other factors (Biehl & Barringer 2004).

2.1.3. Powder flowability. The flowability of powder, which determines how a powder flows under specific conditions, is a significant factor in predicting how evenly and efficiently the powder coats onto a target (Biehl & Barringer 2003). Flow characteristics of a powder depend on the chemical composition of the powder, as well as particle size and shape (Dhanalakshmi et al. 2011). The methods used to measure powder flowability include flow index, angle of repose, cohesion, and the Hausner ratio.

Powders can be categorized by their flowability into three categories, free-flowing, cohesive, and nonflowing. During coating, free-flowing powders usually produce the most even coating and greatest transfer efficiency, given that cohesive powders tend to adhere to each other and clump, resulting in uneven coating on a target (Amefia et al. 2006, Biehl & Barringer 2004, Ratanatriwong & Barringer 2007).

2.1.4. Powder charge and resistivity. The charge produced on a particle influences particle velocity, transfer efficiency, adhesion, and coating thickness during electrostatic coating (Masui & Murata 1982). As the particle size decreases, the charge-to-mass ratio increases and produces a greater radial trajectory, resulting in more even and uniform dispersion (Ali et al. 2000). Singh et al. (1978) showed that the minimum charge-to-mass ratio for producing good adhesion on the target was 0.2 μC/g. Powders with higher charge-to-mass ratios produce higher electrostatic transfer efficiency, given they have higher attraction to the target (Biehl & Barringer 2003, Mazumder et al. 1997).

The amount of charge on the powder is affected by the powder resistivity, which affects how quickly a powder particle picks up charge in the air, or loses the charge once on a target. Powders can be categorized into three different resistivity ranges: below 10^{10} Ωm, between 10^{10} and 10^{13} Ωm, and above 10^{13} Ωm (Bailey 1998). Powders with resistivity below 10^{10} Ωm, for example salts, are conductors that pick up charge quickly in the air, and lose their charge quickly when in contact with the target. The powders in this range are not always suitable coating materials (Luo et al. 2008). Powders with resistivity between 10^{10} and 10^{13} Ωm, which include most food powders, have a short charge decay time and poor adhesion (Bailey 1998, Luo et al. 2008). The behavior of these powders is hard to predict because good charging and adhesion depend on specific powder and target properties (Sumonsiri & Barringer 2010). Powders with resistivity above 10^{13} Ωm, for example cocoa powder, are insulators and have a slow charge decay time, resulting in poor charging but good adhesion when in contact with a target surface (Bailey 1998, Sumonsiri & Barringer 2010).

During charging, more charge is deposited on the powder particles with lower resistivity, which is a desirable characteristic. However, after landing on a target, a slower charge decay, which can be found in powders with higher resistivity, is desirable, given that this produces better adhesion force between powder particles and the target surface (Hughes 1997). During electrostatic coating of food powders from all three resistivity ranges, powders with higher resistivity produced better transfer efficiency and adhesion (Halim & Barringer 2007). Powder resistivity is also dependent on relative humidity. As the relative humidity increases, powder resistivity decreases, resulting in lower electrostatic adhesion (Xu & Barringer 2008).

2.2. Separation of Food Powder Mixtures During Electrostatic Coating

Differences in particle size (Somboonvechakarn & Barringer 2009, Wang et al. 2005, Ye & Domnick 2003), density (Somboonvechakarn & Barringer 2011, Yousuf & Barringer 2007), and particle surface charge (Yousuf & Barringer 2007) cause separation of the different powders in a food powder mixture during coating. This separation is not desirable in powder coating due to the uneven appearance and distribution of flavors produced on the target. During electrostatic coating, using particles with the same size produces less separation because small powders have greater charge-to-mass ratios and so land closer to the nozzle, whereas large powders develop lower charge-to-mass ratios and so deposit further away from the nozzle (Somboonvechakarn & Barringer 2009). This can be seen theoretically as well as experimentally (Yousuf & Barringer 2007). Powders with

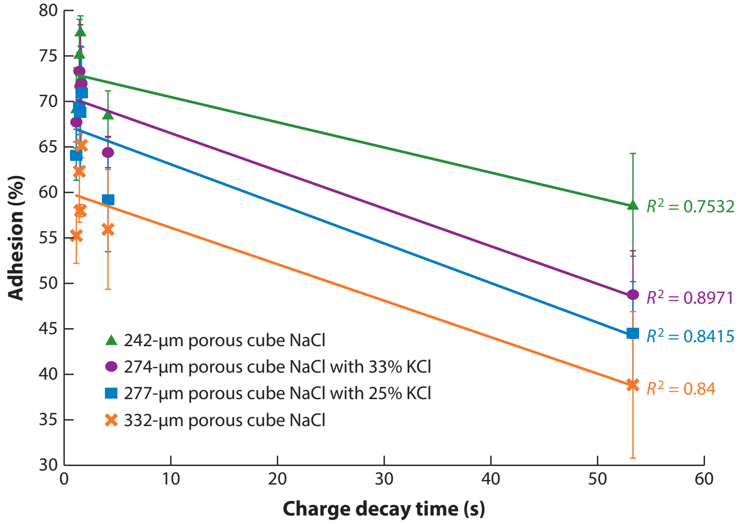

Figure 4

Effect of target charge decay time on adhesion during electrostatic coating of NaCl with different particle sizes and composition ($n = 3$, R^2 = correlate coefficient, error bars = standard deviation). Data from Sumonsiri & Barringer (2011).

different density also cause separation, given that high-density powders are more affected by gravity and have greater adhesion loss than low-density powders (Somboonvechakarn & Barringer 2011).

2.3. Effect of Target Surface Characteristics on Electrostatic Coating Performance

During electrostatic coating, coating performance is also dependent on target surface properties (Bailey 1998), including roughness, resistivity, and oil content. The target roughness influences the adhesion between the powder particle and the target surface. The adhesion significantly increases when the roughness of the target surface decreases because there is more contact area; thus, there is greater van de Waals force between the particle and the target (Podczeck 1998). A target surface with lower resistivity produces better attraction between the powder and target due to greater charge flow from the ground (Sims et al. 2000). As resistivity decreases, charge decay time decreases and adhesion between salt particles and the target surface increases (Sumonsiri & Barringer 2011) (**Figure 4**). In addition to roughness and target resistivity, adhesion is dependent on the oil content on a target surface, given that the high capillary forces from a surface with high oil content dominate over the other adhesion forces. However, lower adhesion between powders and the target surface can be produced due to the high resistivity of oil, which can result in charge building up on the target surface (Buck & Barringer 2007).

2.4. Wraparound Effect During Electrostatic Food Powder Coating

Under suitable conditions, powders will coat down the sides of a thick target and produce a wraparound effect due to the effect of electrostatics on the particle trajectory (Bailey 1998). The wraparound effect can be measured by the percent side coverage on a thick target (Sumonsiri & Barringer 2010, 2011). In electrostatic coating, the percent side coverage increases as powder particle size decreases, cohesiveness of the powder increases, and powder resistivity increases

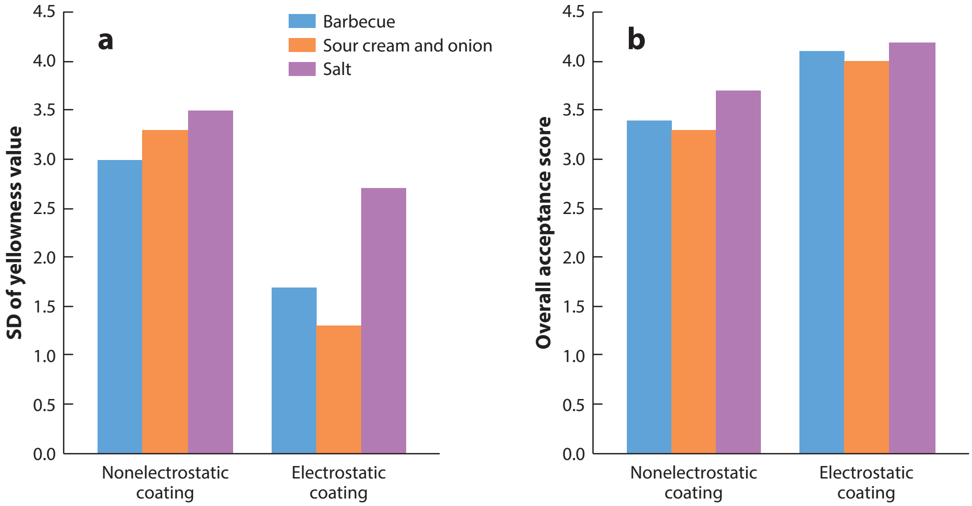

Figure 5

(*a*) Standard deviation (SD) of the yellowness and (*b*) overall acceptance of fried banana chips after nonelectrostatic and electrostatic coating with the seasonings barbecue, sour cream and onion, and salt. A lower SD indicates more even coating, whereas a higher acceptance score indicates greater liking from the consumer. Data from Ratanatriwong et al. (2009).

(Sumonsiri & Barringer 2010). Targets with higher water activity, lower resistivity, and shorter charge decay time produce better percent side coverage (Sumonsiri & Barringer 2011).

2.5. Evenness and Consumer Acceptance in Electrostatic Food Powder Coating

The appearance and functionality of the coating are affected by the evenness of the coating process. More even coating on a food target produces better flavor distribution, resulting in better flavor intensity and release during consumption (Clark 1995, Seighman 2001). For colored seasoning or targets, the coating evenness can be determined using a color parameter, such as the yellowness to blueness on potato chips and banana chips (Ratanatriwong et al. 2003, 2009). Electrostatic coating of seasoning on potato chips produced more evenly colored products than those nonelectrostatically coated (**Figure 5**) (Ratanatriwong et al. 2003, 2009). French fries electrostatically coated with glucose or smoke extract produced more even color than those nonelectrostatically coated (Amefia et al. 2006). Meats with the same total amount of sodium erythorbate and/or glucono-delta-lactone electrostatically coated were redder in color that those nonelectrostatically coated because the more even coating produced more color formation (Barringer et al. 2005). Sensory evaluation showed that consumers preferred electrostatically coated foods over nonelectrostatically coated ones, e.g., for the flavor intensity and distribution of fried banana chips, especially when they were seasoned with barbecue or sour cream and onion (**Figure 5**) (Ratanatriwong et al. 2003, 2009).

3. ELECTROSTATIC LIQUID COATING

3.1. Liquid Coating in Snack and Confectionery Processing

Electrostatics can also be used in the application of liquids (**Figure 2**), known as electrohydrodynamic coating. This is one of the important emerging technologies for coating foods with oils, flavors, and emulsions (Abu-Ali & Barringer 2008). In this coating system, a liquid is dispersed into fine droplets, ranging between 0.1 and 1,000 μm, where the stream of liquid breaks into droplets because of the electrostatic force charging the surface of the liquid (Watanabe et al. 2003). The advantage of this system is the use of minimal energy to form very fine droplets that will not coalesce, given the electric charge of the same polarity on the droplets (Gorty & Barringer 2010, Liu 2000).

In electrostatic liquid coating, electrical forces are used to continually increase the surface energy and thus the surface area until there is an instability and disintegration of the liquid surface. The mother liquid forms filaments, which then atomizes into droplets. Individual small, highly charged droplets are composed of hundreds of molecules of mother liquid (Bailey 1974). During electrostatic coating, separation between like charges is maximized by spreading the electrical charges along the surface of the droplet, which creates repulsion between droplets. According to Coulomb's law, these repulsive forces are inversely proportional to the distance between charges but directly proportional to the number of available charges. When the number of charges on the surface of a liquid reaches Rayleigh's limit, the repulsive forces between the ions exceed the surface tension, and the liquid breaks into droplets. Coating occurs as these small, charged droplets are attracted to, and land on, a grounding target. For production of good atomization, an intense electrical field is required to produce optimal charge concentration on the liquid surface at the nozzle tip (Abu-Ali & Barringer 2005, 2008).

3.2. Factors Affecting Electrostatic Oil Spraying

The factors that play an important role in the performance of liquid electrostatic coating include applied voltage, electrical resistivity, and viscosity of the liquid (Abu-Ali & Barringer 2008). The electrical resistivity is the most important factor in coating effectiveness (Downer et al. 1993). The resistivity of food oils is relatively high, which causes difficulty with atomization during electrostatic coating. The electrostatic resistivity of the solution is dependent upon viscosity and temperature, as well as type and concentration of ions in the liquid (Adamczewski 1969). In one system, liquids with resistivity between 10^6 Ωm and 10^8 Ωm produce good atomization during electrostatic coating (Law 1984, Wilkerson & Gaultney 1989). As resistivity decreases, the droplet size of soybean oil decreases (Wilkerson & Gaultney 1989). In another system, liquids with resistivity below 10^5 Ωm or above 10^9 Ωm would not atomize (Abu-Ali & Barringer 2005). Low resistivity causes the applied charge to move too fast, bypassing atomization and moving back through the solution to ground out through the reservoir (Abu-Ali & Barringer 2008). When the resistivity increases above 3.7×10^8 Ωm, the droplet size significantly increases during confectionery coating using cocoa butter, cocoa butter equivalent, and lauric butter. The width of coating, which refers to the distance between the furthest drops on the right and left sides of the coating area, is also inversely proportional to the resistivity. Emulsifiers, such as lecithin, which is an ionic compound, can be used to decrease the resistivity of oils into the atomizable range. The resistivity of cocoa butter, cocoa butter equivalent, and lauric butter significantly decreases when lecithin is added (Marthina & Barringer 2012).

The voltage applied during electrostatic liquid coating has the greatest effect on reproducibility of atomization (Abu-Ali & Barringer 2008). The optimal range of voltage for most reproducible results in one system was from 30 kV to 35 kV. When the voltage increases, the charge-to-mass ratio on droplets first increases and then decreases (Franz et al. 1987, Marchant & Green 1982). As the charge-to-mass ratio increases, there is more repulsion between droplets, resulting in more reproducible coating. The voltage also has a significant effect on the number of droplets and droplet size. As the voltage increases from 0 to 40 kV, both the droplet size and droplet size range

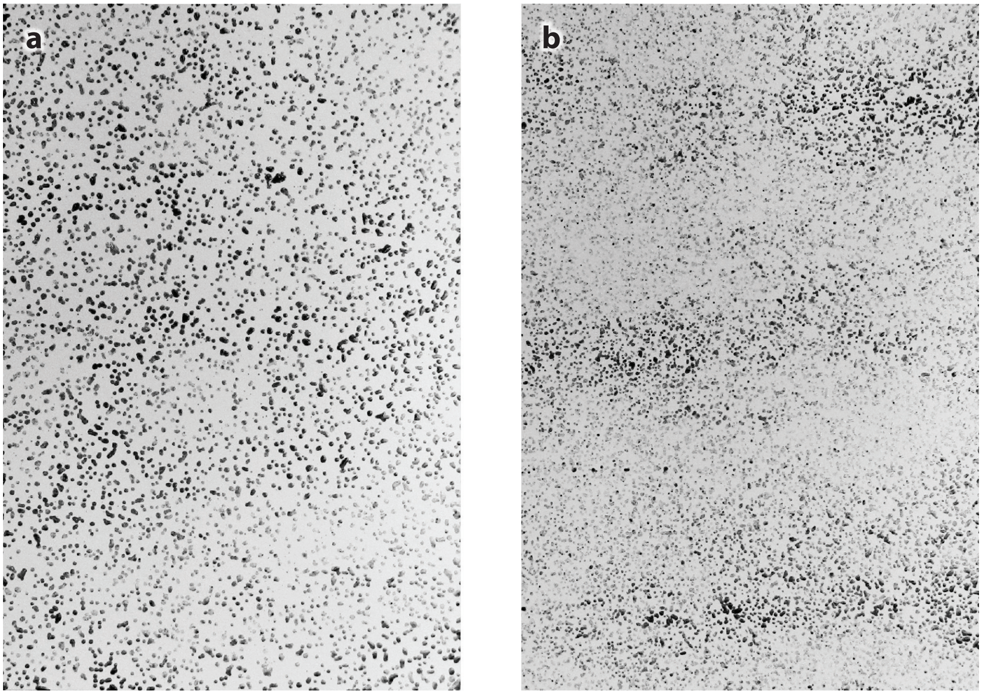

Figure 6

Oil-sensitive papers after electrostatic coating with 10% lecithin at (*a*) 25 kV and (*b*) 40 kV (Aykas & Barringer 2014).

of soybean oil decrease (**Figure 6**) (Aykas & Barringer 2014). Viscosity, interacted with voltage, has a significant effect on reproducibility of liquid electrostatic coating. Higher reproducibility can be obtained by using soybean oil with higher viscosity at intermediate voltage (Abu-Ali & Barringer 2008).

4. CONCLUSION

In both powder- and liquid-coating systems, electrostatics can be used to improve coating quality. These techniques show significant potential for food applications. There are several important factors that can influence the performance of electrostatic coating, including powder particle size, density, flowability, charge, resistivity, and target surface properties for food powder coating, as well as applied voltage, electrical resistivity, and viscosity of the liquid for liquid coating. Studying these parameters can help food processors to design the optimal coating systems needed to provide better coating quality for different foods.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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