Effect of Particle Size and Composition Differences in a Mixture during Nonelectrostatic and Electrostatic coating

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***Abstract* - Many foods, especially snack foods, have powdered seasonings in order to enhance their flavor and increase product variety. Seasonings are generally a mixture of powders but most studies in food powder coating have used only one powder. The objective of this study was to determine the effect of being in a mixture on transfer efficiency, separation and dustiness during nonelectrostatic and electrostatic coating. Fine (51-63 µm) and coarse (244-367 µm) NaCl, KCl, sugar, rice starch and whey protein powders were mixed. The mixtures were coated on a target at 0 and -25 kV at 30-35% relative humidity. During both nonelectrostatic and electrostatic coating, being in a mixture decreased or did not change the transfer efficiency of fine powders, compared to when they were coated individually. Transfer efficiency of coarse powders was generally not affected by being in a mixture during nonelectrostatic or electrostatic coating. Total transfer efficiency of most mixtures did not change when comparing the powders coated individually and as a mixture during either nonelectrostatic or electrostatic coating. Effect of being in a mixture on separation was dependent on the exact powder. In all but one case, being in a mixture has no effect on dustiness during either nonelectrostatic or electrostatic coating. Only in the protein mixture did the amount of dust decrease when coating the mixture nonelectrostatically.**

I. INTRODUCTION

Many foods, especially snack foods, have powdered seasonings in order to enhance their flavor and increase product variety. Seasoning is usually a mixture of at least two powder ingredients. This is because of the unique function of each ingredient. Most commonly used ingredients are salt, filler such as maltodextrin and corn flour, dairy powders such as cheese powders and sour cream powders, dehydrated vegetable powders, spices, compounded flavors, flavor enhancers, sweeteners, acids, color, processing aids such as vegetable oil silicon dioxide, and antioxidants [1]. In spite of the high frequency of use, research related to coating characteristics when the mixture is coated is still limited.

Particle size has a huge impact on coating characteristics. When powder is coated individually, finer powders have lower transfer efficiency than coarser particles [2, 3, 4]. The fine powders tend to remain in the air that passes out of the coating system with the air flow, creating more dust, while coarse powders with a higher mass dominated by gravitational force fall onto the target resulting in less coating loss [2, 5, 6]. When a mixture containing difference sizes of powders is coated, midair collision between fine and coarse powder decreases the velocity of coarse particles and increases the velocity of fine particles. Consequently, more coarse powders and fewer fine powders land on the targets. This correspondingly causes powder separation [7, 8, 9].

Separation is one of the undesirable characteristics found during powder coating. It causes uneven distribution of flavor and appearance on the finished products. Seasonings typically are mixtures. The difference in physical properties of powders such as particle size, and interaction between the powders during coating leads to a change in the ratio of powders from the original [9, 11]. Since there is a higher gravitational force on coarse powder and due to the change in velocity after collision, coarse powders are more often found on the product than fine powders after coating the mixture [9]. Using a similar size powder may decrease separation during coating of mixtures [10]. Density and composition also contribute to separation of mixtures [11]. During coating of a mixture of powders of different composition, particle size plays a primary role in the separation if the powders are fine. While in a mixture of coarse powders, density plays more of a role than particle size on the separation. Individual targeting loss is the greatest cause of separation. When coating a mixture containing two different fine powders, the targeting loss of the mixture was observed to be higher than the targeting loss of a mixture of two different coarse powders. Targeting loss of powders increases by 15% when particle size decreases from 75 to 25 µm, but only a 5% increase is observed when particle size increases from 225 to 175 µm [4]. Consequently, the smaller the powders in the mixture are, the larger the magnitude of the separation is [11]. Powders with high density have less loss than powders with low density, leading to a greater concentration of high density powders than low density powders on the final product after coating [11]. Density plays a significant role in mixtures containing NaCl. NaCl has a high intrinsic density. When mixing fine NaCl with other fine powders, NaCl collides and scatters away the other powder it is mixed with [10]. However, this phenomena results in a decrease in separation because it decreases the difference in losses between NaCl and other powders.

Most powders used for coating are very small and cause dust during coating. Dust is undesirable because it causes powder waste, overuse of powders, additional time and cost for cleaning, and respiratory distress to the employees. Several physical properties affect dustiness [2, 12]. With increasing particle size and density, dustiness decreases [2, 12]. As the powder becomes more cohesive, dustiness decreases [12]. Although there are no studies on the effect of food powder mixtures on dustiness, electrostatic coating is generally known to be efficient in reducing dust during powder coating [2, 12, 13].

Electrostatic coating was widely used in other industries such as the automotive and painting industries for several years before it was introduced into the food industry. Several studies have proven that electrostatic coating offers superior coating performance over traditional coating. During electrostatic coating, powders pass through the corona discharge area, where the intense voltage gradient ionizes the air around the negative electrode, and are charged by negative ions. The charged powders are accelerated by electrostatic force described in Coulomb's law to deposit onto the nearest grounded target [14]. Gravitational force, which depends on the powder mass, and electrostatic force cause powders to deposit on food products, resulting in an increase in transfer efficiency [3, 4, 13] and a reduction of dust [2, 12, 13]. Even though electrostatic coating is more efficient than nonelectrostatic coating in individual coating, it increases separation when mixtures are coated [7]. In a mixture of coarse and fine powders, differences in adhesion loss increases the separation. Fine powders with a higher charge adhere well on the target and increase the adhesion loss of coarse powders by creating a charge layer and repelling the incoming coarse powders. In a mixture with similar size powders, using electrostatic coating decreased separation by decreasing targeting loss and adhesion loss of powders in the mixture [10, 11].

In previous work, nonelectrostatic and electrostatic coating of six difference mixtures from five commonly used powders with similar size were carried out and produced a significant difference on the target due to separation of the mixture [10]. Although the effect of size on a mixture during coating has been studied, the number of mixtures tested in that research was limited [7]. Additionally, there is a lack of knowledge on dustiness when coating the mixture. In our work, five mixtures of the most commonly used powders were coated to determine the effect of being in a mixture on the transfer efficiency, dustiness and separation. Physical properties of the powder which are generally known to govern the coating performance and interactions between powders were used to explain the differences when coating powder individually and when mixtures were coated.

II. MATERIALS AND METHODS

A. Powder samples

Mixtures used in this study were mixtures of two powders with the same composition but different in particle size: fine and coarse powders. The fine powders were NaCl (325 Extra fine salt, Morton International Inc., Chicago, IL), KCl (Fisher Scientific, Fair Lawn, NJ), powdered sugar (Dixie Crystal, Sugar Land, TX), rice starch (National starch and chemical Ltd., Thailand) and whey protein isolate (Proliant, Iso-Chill 9000, Ames, Iowa). Among these five powders, KCl, rice starch and whey protein were ground using an ultra-centrifugal mill (ZM100, RETSCH GmbH & Co.KG, Clifton, NJ) three times at 18,000 rpm to reduce particle size. The coarse powders were NaCl (Alberger flake salt, Cargill Inc., Minneapolis, MN), KCl (Sigma-Aldrich, St. Louis, MO), granulated sugar (Domino, Yonkers, NY), rice starch and instantized whey protein isolate (Proliant, Iso-Chill 9010, Ames, Iowa). Mean diameters of the powders were measured using the Malvern Mastersizer (X standard bench, Malvern Instrument Ltd., Worcestershire, U.K.). The volume mean diameter D[4,3] of each powder was reported. Because water activity of the powder has been shown to affect the coating efficiency, the powders were equilibrated over saturated magnesium chloride solution (32.8% relative humidity) in sealed desiccators until used. The mixtures were 20g of the fine powder mixed with 20 g of the coarse powder. Forty grams of each powder were used for individual coating.

B. Coating process

An electrostatic powder-coating machine (Terronics Development Corp., Elwood, IN) was used to coat the food powders on an aluminum tray (Fig. 1). A previous study [10] found that targeting loss is the main factor in powder loss during coating and there was little effect of adhesion loss. Thus this study focused only on the targeting loss. Adhesion loss was prevented from occurring by using a tray with a 2 cm height edge as a target.

No voltage was applied for nonelectrostatic coating and −25 kV was used for electrostatic coating. An air compressor (Hitachi EC79, Hitachi Koki Co., Ltd., Tokyo, Japan) was used to supply airflow to drive the powder through the coating chamber. All experiments were carried out at 30–35% relative humidity and 20–25°C. Either individual powders or mixtures (40 g) were blown through the coating chamber at an air velocity of 3.3 m/s. A vibratory feeder (Syntron Magnetic Feeder, Model FTO-C, FMC Corporation, Homer City, PA, U.S.A.) was used to control the consistency of powder feeding.

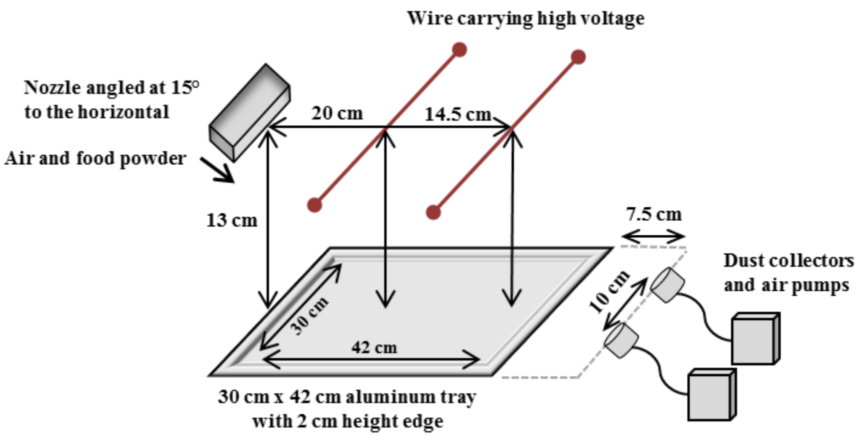

Fig. 1. Coating setup

C. Dustiness

During coating, dust was collected by a dust collector consisting of a cassette, cellulose support pad, 5.0 µm polyvinyl chloride filter (SKC Inc., Eighty Four, PA) and air sampling pump (Gillian Model HFS 513A, Sensidyne, Clearwater, FL). The pumps were operated at 4 liters per minute. Dust was collected from two different locations at the outlet of coating chamber for the entire coating time (3.30 m) (Fig. 1). The reported amount of dust for each replicate was a summation of the dust amounts from these two locations.

D. Determination of the amount of powder in a mixture after coating

In order to identify how much fine and coarse powders were in the deposited mixture, the cutoff (particle size used to differentiate fine powder from coarse powder) was determinezd using the Malvern Mastersizer. Fine and coarse powders were individually measured to determine their particle size distribution. The cut off particle size was selected to produce the least overlap or error of percent fine and coarse powders when coating individually. To ensure that the selected cutoff also works for a mixture, the cutoff was tested with mixtures of known concentration. The errors produced by using the cut off were 0-10%.

E. Separation

Separation was determined by dividing transfer efficiency of fine powders by transfer efficiency of coarse powders. If no separation occurs, the result is equal to one. Less than one indicated the occurrence of separation and a higher percent of coarse powders than fine powders in the deposited powders. Conversely, greater than one indicated the occurrence of separation and a higher percent of fine powder than coarse powders.

F. Statistical analysis

Independent two tailed T-test with unequal variance and one-way analysis of variance ANOVA with post-hoc analysis using Tukey's test were performed. A p-value of 0.05 was used to indicate significantly different results.

III. RESULTS AND DISCUSSION

A. Transfer efficiency

During nonelectrostatic coating, being in a mixture decreased or did not change the transfer efficiency of fine powders, compared to when they were coated individually (Fig. 2). The transfer efficiency of the fine powders in the NaCl and KCl mixtures decreased significantly when they were coated as a mixture, as expected. According to momentum conservation, when a small object collides with a large object, the velocity of the small object increases and the velocity of the large object decreases. Fine NaCl and KCl collided with the coarse powders in the mixture during coating. These fine powders were scattered at a higher velocity and thus missed the target, resulting in a decrease in the deposited fine powder after coating. A decrease in fine powders after coating a mixture was also observed by others [7]. However, being in a mixture had no effect on transfer efficiency of fine powders in the sugar and starch mixtures. Density may explain why fine sugar and starch acted differently from the fine NaCl and KCl. The bulk density of NaCl and KCl is significantly higher than the other powders (Table 1). High density powders are subjected to greater change in velocity when collisions occur than low density powders. Surprisingly, transfer efficiency of fine proteins in a mixture increased instead of decreasing when compared to individual coating. This indicates that there was an interaction between fine and coarse powders. The coarse protein used in this study was an instantized whey protein. It was agglomerated to improve dispersability, making it very porous. During mixing, fine powders may have been trapped or bound to the coarse powders, resulting in less fine protein being lost during the targeting step. Consequently, transfer efficiency of fine protein increased.

During electrostatic coating, being in a mixture was similar to the effect found during nonelectrostatic coating: being in a mixture decreased or did not change the transfer efficiency of fine powders, when compared to individual coating (Fig. 2). The transfer efficiency of fine KCl again decreased in the mixture. Transfer efficiency of fine NaCl was expected to decrease. However, being in a mixture did not change the transfer efficiency, compared to individual coating. This could be due to electrostatic force being dominant over the force driving the scattering, resulting in the fine NaCl powders, which should have been scattered when they were in the mixture, depositing on the target instead. The transfer efficiency of all fine powders increased when coated electrostatically (Fig. 2). The increase in transfer efficiency of fine powders when using electrostatic coating created an equal transfer efficiency between fine and coarse powders in the sugar and starch mixtures. So that, being in the mixture had no effect on transfer efficiency. Transfer efficiency of fine proteins increased when they were coated as a mixture. This may also be attributed to the trapping or binding of fine proteins by or with coarse proteins.

Transfer efficiency of coarse powders was generally not affected by being in a mixture during nonelectrostatic coating (Fig. 2). During individual coating, more coarse powders deposited onto the target than fine powders due to the higher gravitational force on coarse powders than fine powders (Fig. 2). Only KCl showed no difference in the transfer efficiency between the coarse and fine powder. When the mixtures were coated, transfer efficiencies of coarse NaCl, sugar and starch were not significantly different from individual coating. This was mainly because individual transfer efficiency of these coarse powders was so high, that the changes were not significantly different. Transfer efficiency of coarse KCl powders in the mixture increased as expected. Due to the momentum conservation, the velocity of large objects colliding with small objects decreased. This may contribute to a decrease in targeting loss of the coarse KCl powders during coating. Transfer efficiency of coarse protein powders in the mixture decreased when compared to individual coating. This decrease could be attributed to the collision between the coarse proteins and the coarse proteins that trapped the fine proteins inside or bound with the fine proteins. Due to the collision, the coarse proteins without fine proteins trapped or bound with may be scattered, resulting in a decrease in transfer efficiency of coarse protein.

During electrostatic coating, the effect of being in a mixture on transfer efficiency of coarse powders was similar to nonelectrostatic coating; being in a mixture increased or did not change the transfer efficiency of coarse powders, compared to when they were coated individually (Fig. 2). Transfer efficiency of coarse KCl powders in the mixture increased, while transfer efficiency of coarse sugar and coarse starch did not change when compared to when they were coated individually. However, during electrostatic coating the difference between the transfer efficiency of coarse powder when coated individually and as the mixture was higher than when coated during nonelectrostatic coating. Transfer efficiency of coarse protein in the mixture decreased when compared to individual coating. This result was also found in nonelectrostatic coating.

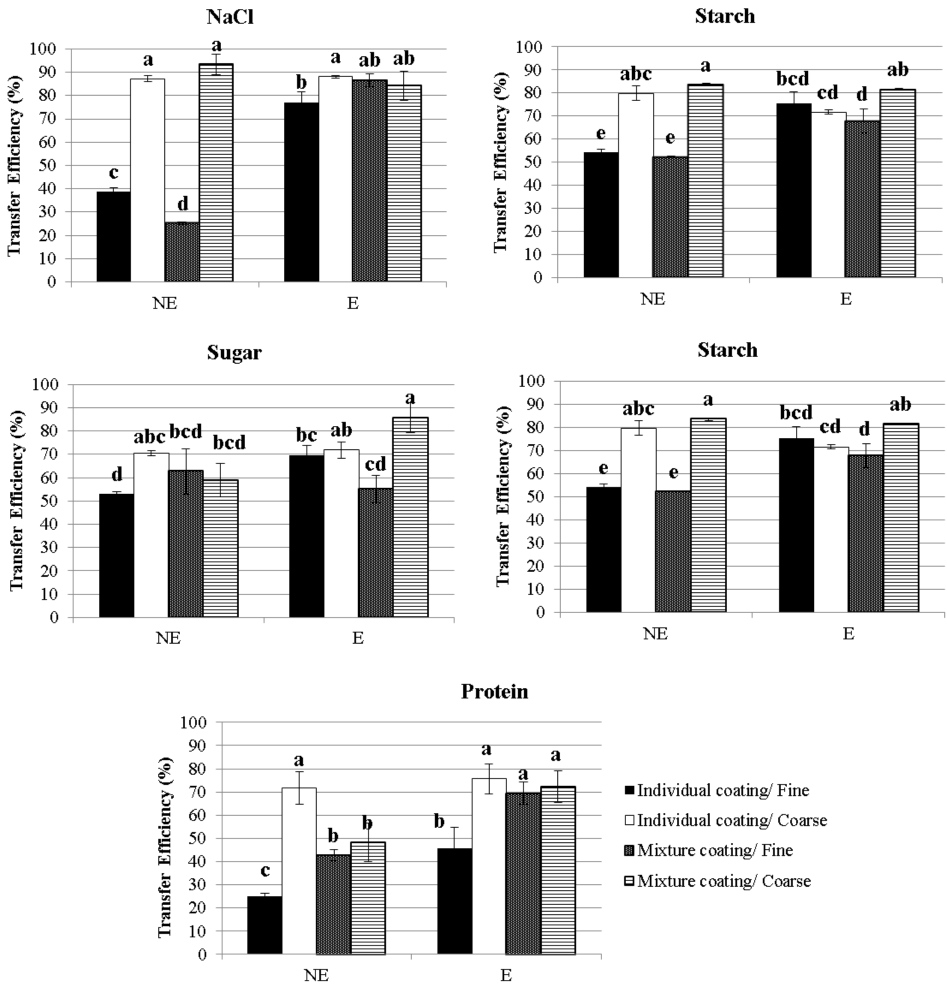

Fig. 2. Transfer efficiency of the mixtures containing different size powders during nonelectrostatic coating (NE) and electrostatic coating (E) ([a]Samples with different letters in each graph are significantly different).

TABLE 1: PHYSICAL PROPERTIES OF NaCl, KCl, SUGAR, STARCH AND PROTEIN

Property	Particle size (μm)		Flowability (Degree)		Bulk Density (g/cm^3)		Resistivity ($x10^5 \Omega m$)	
Powder	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
NaCl	58.21^{d}	278.59^{b}	55.09^{c}	48.61^{d}	1.08^{b}	1.17^{a}	0.655^{b}	140^{b}
KCl	59.92^{d}	366.52^{a}	65.80^{b}	48.00^{d}	1.15^{a}	1.07^{b}	350^{b}	3570^{b}
Sugar	56.09^{d}	357.22^{a}	70.34^{a}	45.87^{d}	0.74^{d}	0.96^{c}	241000^{b}	6140000^{a}
Starch	62.02^{d}	244.30^{c}	52.95^{c}	46.80^{d}	0.66^{e}	0.55^{f}	17100^{b}	40500^{b}
Protein	51.75^{d}	249.89^{c}	54.96^{c}	53.05^{c}	0.59^{f}	0.43^{g}	0.573^{b}	2460^{b}

[a]Samples in the same category of physical property with different letters are significantly different.

Total transfer efficiency of most mixtures did not change when comparing between coating the powders individually and as a mixture during either nonelectrostatic or electrostatic coating (Fig. 3). Being in a mixture significantly changed transfer efficiency of some fine and coarse powders; however, by decreasing the coarse powder and increasing the fine powders. This consequently caused no difference in total transfer efficiency. Protein mixture was the only mixture whose total transfer efficiency was affected by being in a mixture. Being in a mixture increased the total transfer efficiency of the protein mixture by 10%. This increase is mainly due to an increase of transfer efficiency of fine protein powder when the mixture was coated electrostatically (Fig. 2). Using electrostatic coating was the largest effect on total transfer efficiency in most mixtures. Only the protein produced an increase in total transfer efficiency when in a mixture.

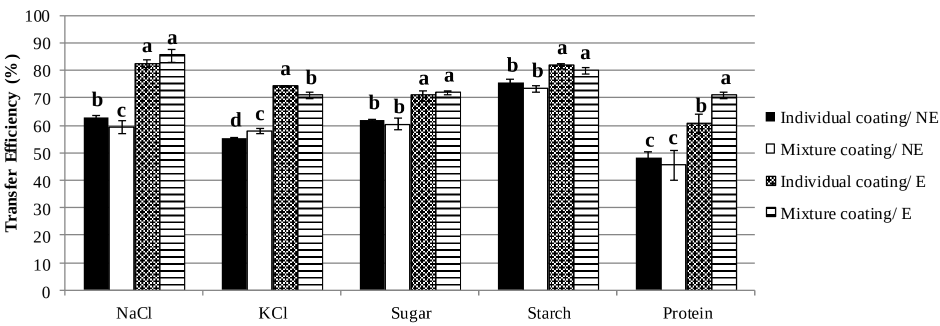

Fig. 3. Total Transfer efficiency of the mixtures containing different size powders during nonelectrostatic coating (NE) and electrostatic coating (E) ([a]Samples of the same powder type, with different letters are significantly different).

B. Separation

Separation is defined as a change in ratio of powder ingredients on the final product compared to the original ratio. This change negatively affects the flavor profile and frequently the appearance. During nonelectrostatic coating, the effect of being in a mixture was dependent on the type of powder (Fig. 4). The separation of the starch mixture did not change compared to when the powders were coated individually. This was not surprising because being in a mixture, the transfer efficiency of both fine and coarse powders did not change from when coated individually (Fig. 2). The separation of NaCl and KCl mixtures significantly increased (the separation values were further to 1) when they were coated as a mixture. While the separation of sugar and protein mixtures significantly decreased (the separation values were closer to 1) when they were coated as a mixture. The separation was promoted in the NaCl and KCl mixtures because when the mixtures were coated the fine NaCl and KCl had greater loss while the coarse KCl, which gravitationally deposited more fine powders in individual coating, deposited further more when they were coated as a mixture. Transfer efficiency of coarse NaCl in the mixture also was increased by the effect of being in a mixture. For the sugar and protein mixtures, being in the mixture significantly decreased the separation, although the changes in transfer efficiency of fine and coarse powders in the sugar mixture was not significantly different from those of individual coating (Fig. 2). However the changes decreased the difference between the transfer efficiency of fine and coarse sugar, resulting in a decrease of the separation. Similar to the sugar mixture, an increase on fine protein and a decrease of coarse protein in the mixture decreased the difference between the transfer efficiency of fine and coarse protein, resulting in a decrease of the separation.

During electrostatic coating, the separation was also dependent on the mixtures (Fig. 4). For the NaCl mixture, there was no difference between the separations occurring when coating the powders individually and occurring when coated as a mixture. Although the separation was found to be promoted by being in a mixture during nonelectrostatic coating, during electrostatic coating the transfer efficiency of fine NaCl increased, leading to a decrease in the difference between the transfer efficiency of fine and coarse NaCl. For the KCl and protein mixtures, being in a mixture decreased the separation while for sugar and starch mixtures, being in a mixture increased the separation. The effect of being in a mixture on separation during electrostatic coating mostly was opposite to the effect found during nonelectrostatic coating, except starch and protein mixtures.

The effect of using electrostatic coating compared to nonelectrostatic coating on the separation was dependent on the mixtures (Fig. 4). Using electrostatic coating decreased separation in NaCl and starch mixtures. Although after coating the mixture electrostatically, transfer efficiency of the coarse powders was still more than 50%, the transfer efficiency of fine powders increased, leading a decrease in separation. However, using electrostatic coating increased the separation in the sugar mixture. Mixtures of KCl and protein showed no significant effect of using electrostatic coating on separation.

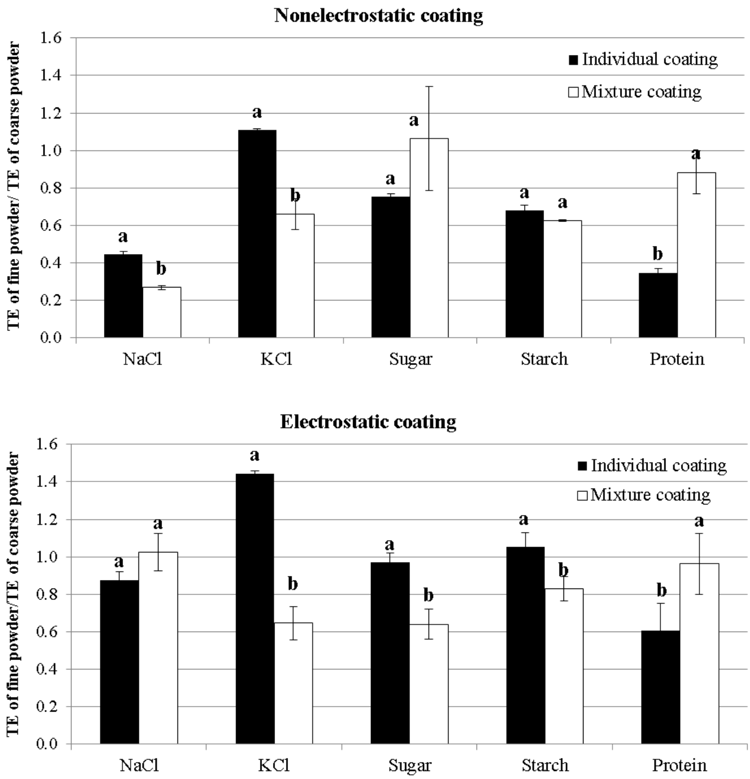

Fig. 4. Separation of fine and coarse powders in mixtures during nonelectrostatic and electrostatic coating. Samples that are equal to one mean no separation. ([a]Samples of the same powder with different letters are significantly different between individual and mixture coating).

C. Dustiness

In all but one case, being in a mixture had no effect on dustiness during either nonelectrostatic or electrostatic coatings (Fig. 5). Only in the protein mixture did the amount of dust decrease when coating the mixture nonelectrostatically. The coarse protein used in this study was an instantized whey protein. It was agglomerated to improve dispersability, making it very porous. During mixing, fine powders may have been trapped or bound to the coarse powders. As the fine powder is primarily responsible for dustiness, trapping the fine powder decreases the total amount of dust. Similarly, the transfer efficiency of fine powders increased when in a mixture (Fig. 2). Comparing between nonelectrostatic and electrostatic coating, electrostatic coating significantly decreased the dust in most mixtures.

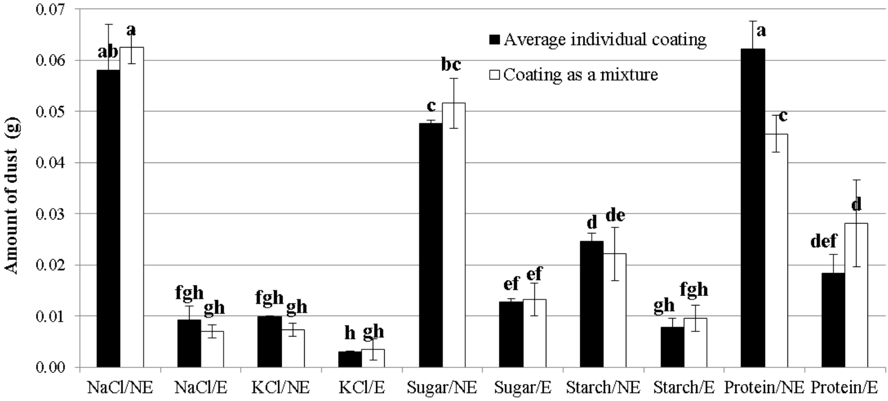

Fig. 5. Dust collected during nonelectrostatic coating (NE) and electrostatic coating (E) of the mixtures containing different size powders ([a]Samples with different letters are significantly different).

IV. CONCLUSION

Many foods, especially snack foods, have powdered seasonings in order to mainly enhance their flavor and possibly increase product variety. Seasoning is usually a mixture. Coating characteristics of a mixture differed from when a powder ingredient was coated. Being in a mixture decreased or did not change the transfer efficiency of fine powders, comparing to individual coating during both nonelectrostatic and electrostatic coating. Fine powders with high density were more affected by being in a mixture than low density fine powders. Collision and scattering were the primary reactions occurred and caused the changes during coating the mixtures. Transfer efficiency of coarse powders was generally not affected by being in a mixture during both nonelectrostatic and electrostatic coating. Protein acted differently from other powders. The difference reaction, possibly a trapping or binding between fine and coarse powders during coating, could be used to explain the difference. Total transfer efficiency of most mixtures did not change by the effect of being in a mixture during either nonelectrostatic or electrostatic coating. Effect of being in a mixture on separation was dependent on the exact powder. Using electrostatic coating can either decrease or increase the separation. Dustiness was generally not affected by being in a mixture. Only in the protein mixture did the amount of dust decrease when coating the mixture nonelectrostatically.

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