

Separation of powder mixtures during nonelectrostatic and electrostatic coating

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Abstract—Powder separation causes uneven flavor and color on coated food products. Understanding the basics behind separation is needed to decrease the separation. Four commonly used powders (NaCl, starch, protein, sugar) and six powder mixtures of pairs of those powders were coated nonelectrostatically and electrostatically on targets. Separation was found in most mixtures, especially the mixtures with NaCl. Individual coating characteristics and interactions between powders caused separation during mixture coating. During nonelectrostatic coating, the difference in individual targeting loss primarily caused separation, particular in the mixture with NaCl which had greater targeting loss compared with other powders. Interactions in the mixtures reduced the separation by decreasing the difference in targeting loss of the mixtures with NaCl and decreasing of difference in adhesion loss of the mixture of starch, protein, sugar. During electrostatic coating, the biggest cause of separation of the mixture with NaCl was interactions in the mixtures which increased the difference between targeting losses of the mixtures. Electrostatic coating generally decreased separation in the mixtures of starch, protein and sugar by decreasing the difference in individual adhesion loss.

I. INTRODUCTION

Powder coating is used to apply food powder ingredients such as seasonings to create flavor and color variety in the food products. Powders are typically dispersed from the powder hopper aerodynamically, sometimes gravitationally, and deposits onto the food surface. During the coating process, some powders are lost with the air as dust and some powder, even already deposited on the food, slides off the food surface because of the poor adhesion. These losses cause problems in coating processing. To ensure that an adequate amount is on the food products, an excess amount of powder is used and consequently causes a higher processing cost. The lost powder may remain suspend in the air and causes respiratory distress to the operators after long periods of continuously breathing. Waste powder requires a higher labor to clean [1]. Besides the losses, uneven distribution of powder on the coated foods causing uneven flavor and color on the coated products which is undesired for food industry [1].

Electrostatic powder coating has been widely used in the automotive and painting industry for several decades before it was introduced to the food industry. Several studies

have proved that electrostatic coating offers superior coating performance than conventional coating. After powders are dispensed into the coating chamber where a corona zone is produced, the powders are charged and seek the nearest ground, which is the food products, by electrostatic force described in Coulomb's law [2, 3]. Combination of gravitational force and electrostatic force causes more powder to deposit on the food products, resulting in a reduction of dust and a decrease of overuse. Less labor is needed to clean the processing line because of less powder waste. Uneven distribution of flavor and color are also solved by electrostatic coating. Since powders after pass through the corona zone are similar in charge, they repel each and are evenly dispersed across the area of the food products.

Physical properties were found by several researches to have a significant impact on the coating performance. Large particles coat more efficiently than small particles in non-electrostatic coating [4, 5, 6]. For electrostatic coating, small particles coat more efficiently than large particles [4, 7, 8], however, when the size increases until it reaches a certain size where gravitational force overcomes electrostatic force, large particles show better coating efficiency than small particles [9, 10]. Powders with high ability to flow produce better coating efficiency than cohesive powder for nonelectrostatic coating [4, 5, 7]. For electrostatic coating, some studies found cohesive powders coat effectively over free flowing powders [4, 7] while one study found the opposite [5]. The greater the chargeability, the better transfer efficiency when using electrostatic coating [7, 8, 11]. Increase in particle density increases improvement in both nonelectrostatic and electrostatic coating transfer efficiency [4, 8].

The other important issue in food powder coating is separation of powder in a mixture during coating. Powders used in coating typically consist of a mixture of powders with different physical properties [12]. After coating, the ratio of powders coated on the food is changed from the original ratio. This is undesirable because uneven appearance and distribution of flavors occur on the products. A difference in particle size of the powders in the mixture causes separation during mixture coating [13, 14, 15]. Individual characteristics of powders and interactions during coating cause the powders to be different in targeting loss and adhesion loss. When mixtures containing different size powders (44 μm and 256 μm NaCl, 64 μm and 191 μm starch) were coated nonelectrostatically, greater targeting loss of small powder than large powder both in individual and mixture coating caused the powders separate. Using electrostatic coating increased the difference in adhesion loss of powders in mixture [15].

When mixtures of similar size but different densities and compositions were nonelectrostatically coated, the fine mixture showed separation while little separation occurred in the coarse mixture [16]. In the fine mixture, the separation is because the high density powders have significantly higher individual targeting loss and mixture adhesion loss than the low density powders. During electrostatic coating, the high density powder has significantly greater individual adhesion loss than low density powder in both the fine and coarse powder mixtures, resulting in the separation.

Despite several studies on the effect of physical properties affecting coating efficiency, there is limited information on how the physical properties of powders and use of electrostatic coating impact mixture separation. Thus the objective of this study was to determine the major cause of separation in mixture coating, when mixtures of powder with similar

size (36-48 μm) were coated nonelectrostatically and electrostatically. The amount of powder coated on the target, targeting loss and adhesion loss of individual powders and mixtures were determined.

II. MATERIALS AND METHODS

A. Powder sample

Food powders tested in this study included potato starch (AVEBE American Inc., Princeton, NJ), NaCl (325 Extra Fine Salt, Morton International, Inc., Chicago, IL, U.S.A.), soy protein (ADM, IL, U.S.A.) and powdered sugar (Dixie Crystal, TX, U.S.A.). 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 measured. Because water activity of the powder has been reported to affect the coating efficiency, all powders were equilibrated for 7 d at 20-25 °C and stored over saturated magnesium chloride solution (32.8% relative humidity) in sealed desiccators until used.

B. Coating conditions

An electrostatic powder coating machine (Terronics Development Corp., Elwood, IN, U.S.A.) was used to coat the food powders on nine 15 cm x 10 cm aluminum sheets (Figure 1). No voltage was applied for nonelectrostatic coating and -25kV was used for electrostatic coating. An air compressor (5.0 hp, 15.0 gallon tank, Model WL650AJ, Campbell Hausfeld, OH, U.S.A.) was used to supply airflow to drive the powder through the coating chamber. All experiments were carried out at an air velocity of 3.3 m/s, 30-35% relative humidity and at 20-25°C.

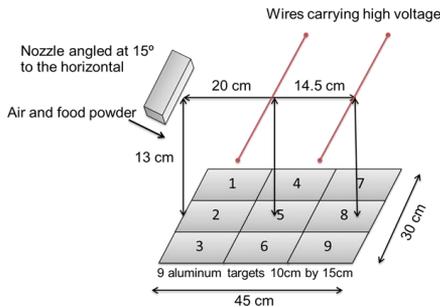


Fig. 1. Target setup reference

C. Powder property determinations

Angle of repose was used to measure the flowability of the powders. It was determined by the modified fixed base method using a 2.81 cm diameter and 1.22 cm high petri-dish. Powder was sifted with a powder sifter through a funnel with its tip 11 cm from the top edge of the petri-dish. The maximum peak height of the powder prior to collapse was measured by a caliper and recorded. The arctangent of the peak height over the radius gives the angle of repose.

Resistivity of the powders was measured using a powder resistivity test cell. The powder test cell was filled with 5 cm³ of the powder. Air was dispelled by tapping the cell for 5 sec. Voltage (125 V) was applied to the cell via a high voltage supply unit. The current value was read from the electrometer when there was no change over a 15 sec period. Resistivity was calculated using: $(K \cdot I)/V$, where K represents the cell constant (0.014), I represents electrical current (A) and V represents the voltage applied (volt).

Bulk density was determined by sifting the powder (120±10 g) into a 250 ml graduated cylinder. The powders in the cylinder were weighed; their weights and volumes were recorded. Bulk density was calculated by dividing powder weight (g) by powder volume (cm³).

D. Determination of deposited powder

Both individual powders and powder mixtures were coated in order to determine if there are any interactions between the two powders during mixture coating. To calculate the targeting loss and adhesion loss, 20.000±0.002 g of individual powder or a mixture of the two powders in a 1:1 ratio were coated nonelectrostatically and electrostatically on unoiled and oiled targets. For the oiled target, approximately 1 g vegetable oil (Kroger Pure Vegetable Oil, Cincinnati OH, U.S.A.) was applied on each aluminum target. After coating, the mass of the individual or mixture of powder on each location was measured and used to calculate the percent targeting loss and adhesion loss. For the powder mixture, the targets were weighed and the deposited powder was rinsed off the target by deionized water. The weight of the solution was recorded in order to calculate the concentration of each powder in the mixture. The solution was filtered through filter paper (No.5 filter paper Whatman, UK) to remove the water-insoluble materials: starch, oil and insoluble protein which interfere with the NaCl reading, UV absorbance and the brix reading.

The protein content of all mixture containing protein was determined using UV absorption. The absorbance of the mixture solutions were measured at 280 nm with a UV-Visible spectrophotometer (UV2450, Shimadzu, Japan). The amount of starch, NaCl or sugar in the mixture with protein was calculated by subtracting the protein content from the total mixed powder content after coating. The NaCl concentration of the mixture between NaCl and starch or sugar was determined using a salt analyzer (Newport M-10 Digital Salt Analyzer, Santa Ana, CA, U.S.A.). The amount of starch or sugar in the mixture with NaCl was calculated by subtracting the NaCl content from the total mixed powder content after coating. Sugar concentration in the mixture of sugar and starch was measured using a digital refractometer (Mark II, ABB, Reichert, NY, U.S.A.). The amount of starch was calculated by subtracting the sugar content from the total mixed powder content after coating.

E. Targeting loss and adhesion loss determination

Targeting loss and adhesion loss of the mixture were calculated. Targeting loss is a loss of powder to the environment occurring during the targeting step. It also includes the powder that missed the target. Targeting loss was calculated by the total mass of the powder fed into the system minus the powder deposited on the oiled target. Adhesion loss occurs after powders are already deposited on the targets. Not all deposited powder stays on the target, some powders roll off of the targets due to their poor adhesion. Adhesion loss was calculated by total loss of powder on unoiled targets minus the targeting loss.

F. Statistical analysis

For statistical analysis, one-way ANOVA with Tukey method for means was performed. Independent two tailed, two-sample T-test with unequal variance was performed to determine significant differences between the amounts of powders on the targets, and also to compare the means for the actual amount and the predicted amount of the powder on the targets. A p-value of 0.05 indicates a significant difference between the two groups.

III. RESULTS AND DISCUSSION

A. Separation in the mixtures

Mixtures of two powders in equal percentage were coated onto nine targets. The amount of each powder deposited on the target surfaces was measured to determine the occurrence of separation. On each location, separation is said to occur when the deposited amount of each of the two powders is significantly different. During both nonelectrostatic and electrostatic coating, most mixtures showed separation in at least half of the locations (Table 1). Only the mixture of protein and sugar showed little to no separation. Separation during coating of the mixture is caused by the difference in individual coating performance of each powder and/or interaction between powders during coating. Separation may be caused by the difference in coating performance of each individual powder that caused different amounts to be deposited in each location. In addition, during coating of a mixture, collisions between the powders may cause their coating performance to be different from when they are coated individually, thus interactions may also be important.

TABLE 1: NUMBER OF LOCATIONS (OUT OF NINE) WHERE SEPARATION OCCURRED IN THE MIXTURE (Mix.), AND WHERE PREDICTED TO OCCUR BASED ON COATING OF INDIVIDUAL POWDERS (Ind.). (SEPARATION IS DEFINED AS A SIGNIFICANT DIFFERENCE BETWEEN THE AMOUNTS OF EACH POWDER ON A LOCATION.)

Mixture	Nonelectrostatic coating				Electrostatic coating			
	Oiled target (Targeting loss)		Unoiled target (Targeting loss + Adhesion loss)		Oiled target (Targeting loss)		Unoiled target (Targeting loss + Adhesion loss)	
	Mix.	Ind.	Mix.	Ind.	Mix.	Ind.	Mix.	Ind.
NaCl /Starch	6	7	5	9	8	5	6	9
NaCl/Protein	4	9	9	8	5	4	9	6
NaCl/Sugar	6	7	4	6	7	8	6	8
Starch/Protein	7	5	6	8	4	4	2	6
Starch/Sugar	1	4	6	8	1	6	8	8
Protein/Sugar	2	5	0	8	0	6	0	6

To determine if the differences between the coating profiles of individual powders caused separation in coating of the mixture, each powder was coated individually and the amounts on the targets were compared. A significant difference in the amount between two powders when they are coated individually predicts that separation will occur during

coating of the mixture. A difference in predicted amount was found in at least four out of the nine locations in all pairs of powders based on the individual coating (Table 1). This indicates that the difference in individual coating characteristics of powders was a major cause of separation in the mixtures. However, the interactions between the powders during coating also affect separation. Comparing the amount predicted to be on a location based on individual coating, to the actual amount when the mixture is coated, indicates how much interaction occurs. Interactions decreased separation in most mixtures.

During coating, both targeting loss and adhesion loss occurs. Targeting loss is a loss of powder during application, including the powder lost with the air as dust and powder deposited beyond the target. Adhesion loss describes the loss of powder that deposits on to the target but falls off because of poor adhesion between the powder and the target. In this study, oil was applied on one set of target surfaces to eliminate adhesion loss. Thus, the oiled targets measure only the targeting loss while unoiled targets measures both targeting loss and adhesion loss.

B. Nonelectrostatic coating of the mixtures with NaCl

When NaCl was one of the powders in the mixture, there were a greater number of locations both where separation actually occurred and where it was predicted to occur, than with the other powder mixtures (Table 1). NaCl had much higher individual targeting loss (72%) than protein, sugar and starch, whose targeting loss values were similar to each other (44-50%) (Fig. 3). The difference in targeting loss between NaCl and the other powders caused many locations to have separation. The high targeting loss of NaCl is possibly caused by the poor tribocharging ability of NaCl. During coating, the powders flow through the hopper tube, colliding with the pipe wall causing charge exchange to occur between the powders and the pipe wall, known as triboelectric charging [3]. NaCl is an electrolyte and has the lowest resistivity among the powders, therefore it quickly loses its charge while powders with high resistivity hold this charge and seek the nearest target by Coulombic force (Table 2). Others have also observed that NaCl has small tribocharging value and poor tribocharging ability [9, 17].

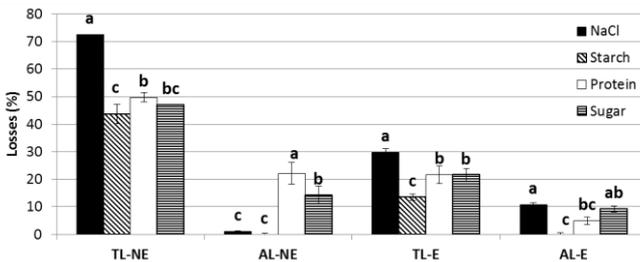


Fig. 3. Targeting loss (TL) and adhesion loss (AL) of powders when coated individually nonelectrostatically (NE) and electrostatically (E) (^asamples with different letter are significantly different between the powders in the same treatment).

TABLE 2: PHYSICAL PROPERTIES OF POTATO STARCH, EXTRA FINE NaCl, SOY PROTEIN AND SUGAR

Properties	NaCl	Starch	Protein	Sugar
Flowability (degree)	41.09 ^b	40.48 ^b	62.41 ^a	63.91 ^a
Bulk Density (g/cm ³)	2.04 ^a	2.15 ^a	1.68 ^c	1.87 ^b
Resistivity (x10 ⁵ Ωm)	9 ^d	9000 ^c	89000 ^b	150000 ^a

^a Samples in the same row with different letters are significantly different.

Interaction between powders in the mixture decreased the separation (Table 1). In the mixture, the targeting loss of NaCl did not change, while the targeting loss of the powders it was paired with increased comparing to when they were coated individually (Fig. 4). During coating, NaCl, which has a high intrinsic density (2.20 g/cm³), collides with and scatters the powders it is paired with, which have lower intrinsic density (starch 1.51 g/cm³, protein 1.31 g/cm³, sugar 1.63 g/cm³) [4]. This interaction greatly decreased the difference in losses between NaCl and the other powders and caused less separation than was predicted based on individual coating (Fig. 5).

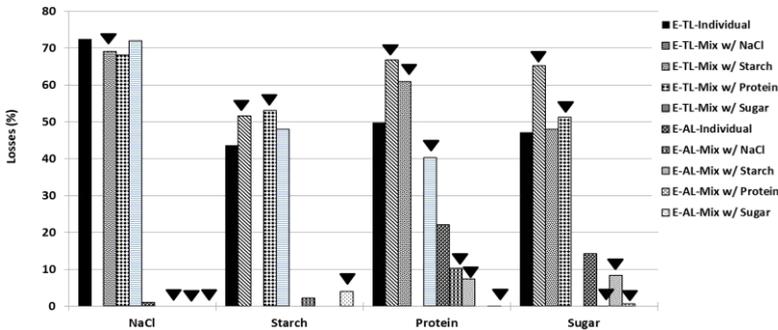


Fig. 4. Nonelectrostatic coating: targeting loss (TL) and adhesion loss (AL) of the powder coated individually and in a mixture. (Samples with a triangle on top are mixtures significantly different from individual coating.)

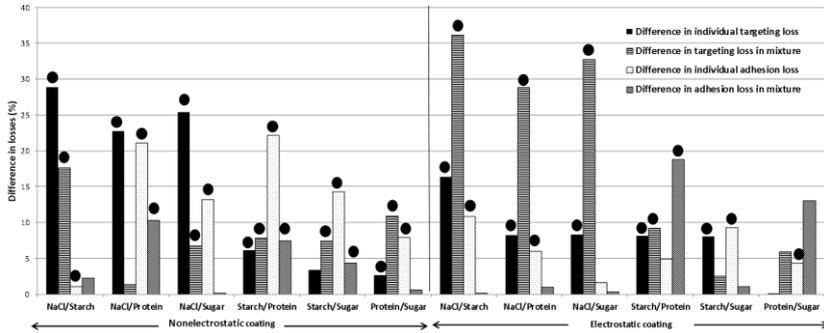


Fig. 5. Difference in losses in each mixture with two powders of similar size. (A solid circle on top shows significant difference between the losses.)

Individual adhesion loss predicted separation, but interactions greatly decreased the difference. (Table 1, Fig. 5). In individual coating, adhesion loss did not have a marked effect on the separation. Adhesion loss of NaCl was very small; 1% when it was coated individually and 0% when it was coated as a mixture. Any change in adhesion loss of the powders that NaCl mixed with, affected the separation. Only for NaCl-protein, there was much change in separation (Table 1). When the NaCl-protein was coated, interaction decreased the adhesion loss of protein (Fig. 4), resulting in an increase of the separation (Table 1).

C. Nonelectrostatic coating of the mixtures with starch, protein and sugar

Most mixtures with starch, protein and sugar showed separation but it was less than for the mixtures with NaCl (Table 1). The protein-sugar mixture showed no separation. The greatest factor causing separation was the individual targeting loss. Individual targeting loss of these three powders were nearly the same (44-50%) (Fig. 3), however separation was predicted to occur at least 4 locations in these mixtures (Table 1). This can be explained by the difference in trajectory of the powders during the coating. Trajectory of a particle is dependent on particle mass and external force. During nonelectrostatic coating, aerodynamic force was applied as an external force. The difference in mass among the powders caused the difference trajectory and difference pattern of powder distribution (Fig. 6). Six out of nine locations were found significant difference in the amount of coated powder on the oiled target. This led the separation predicted to occur when their mixtures were coated. Thus, difference in trajectory of powder is one of sources causes the separation. When the mixtures were coated, decreases in the separation were found in the mixtures with sugar, comparing to the separation in individual coating (Table 1). Targeting loss of sugar slightly increased when it was in the mixtures. Starch did not change its targeting loss from the individual coating while targeting loss of protein significantly decreased when they were in the mixture with sugar.

The difference in individual adhesion loss of the powders increased the number of locations where the separation was predicted to occur in these three mixtures (Fig. 3, Table 1). Individual adhesion loss of starch, protein and sugar were significantly different, causing separation. The difference in adhesion loss of these three powders was due to their flowability and resistivity. Protein and sugar are cohesive powders. They are likely to form

clumps and fall off the target [5]. There was no difference in individual adhesion loss between protein and sugar. But resistivity of sugar was almost twice higher than protein. This causes sugar held charge better than protein after tribocharging, resulting in a better adhering to the target and contributing less loss. In the mixture, adhesion loss decreased the separation in all mixtures, particularly in the mixture of protein and sugar, decreasing from 8 locations to zero locations (Table 1). Interaction during coating decreased the adhesion loss of protein (99%) and sugar (95%) when compared to the individual coating (Fig. 4). This caused no significant difference between their adhesion losses, reducing the separation (Fig. 5).

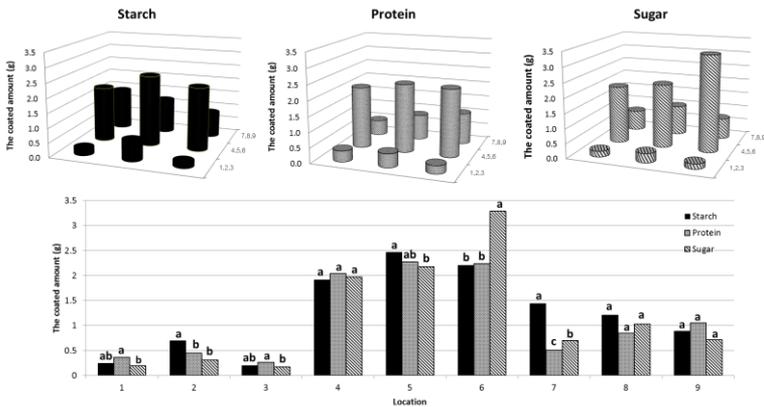


Fig. 6. Distribution of the powders nonelectrostatically coated individually onto the oiled targets. (^a Samples in the same location with different letters are significantly different.)

D. Electrostatic coating of the mixtures with NaCl

Using electrostatic coating, the mixtures with NaCl had increased separation when compared to nonelectrostatic coating (Table 1). The biggest cause of separation was interactions in the mixture which increased targeting loss, even though the individual coated predicted a decrease in separation. Targeting loss was still the greatest source of loss during electrostatic coating. However, the individual targeting loss of all powders during electrostatic coating was lower than in nonelectrostatic coating, (Fig. 3). The number of locations in which the separation was predicted to occur caused by individual targeting loss was less in electrostatic coating than nonelectrostatic coating (Table 1). This is because electrostatic coating decreased targeting loss of all powder, decreasing the difference in targeting loss between the powders and thus decreasing the separation, when compared to nonelectrostatic coating (Fig. 3, 5). The decrease in targeting loss during electrostatic coating is because charged powders did not remain suspended in the air but rather seek the nearest target by the force described in Coulomb’s law [3].

When the mixtures were coated, the separation increased in most mixtures compared to nonelectrostatic coating (Table 1). The interaction caused a change in targeting loss when compared to individual coating (Fig. 7). Interaction increased the targeting loss of NaCl when coated with sugar, while decreased the targeting loss of starch and largely increased

targeting loss of protein when coated with NaCl. All of these changes dramatically increased the difference between the targeting losses when compared to nonelectrostatic coating or even compared to individual coating during electrostatic coating (Fig. 5).

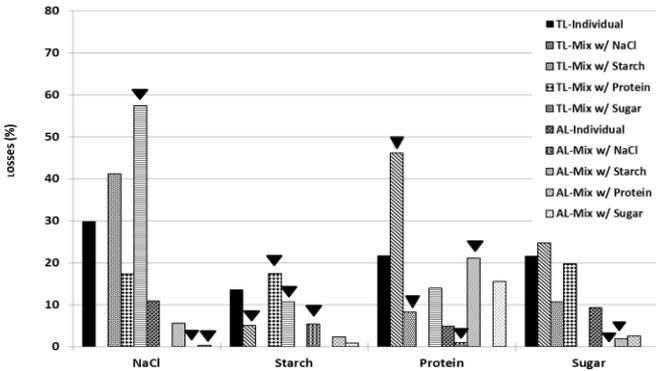


Fig. 7. Electrostatic coating: targeting loss (TL) and adhesion loss (AL) of the powder coated individually and in a mixture. (Samples with a triangle on top are mixtures significantly different from the individual coating.)

Individual adhesion loss increased the separation in electrostatic coating (Table 1). There was no difference in the number of location where the separation was predicted in the NaCl-sugar mixture because they have the same individual adhesion loss (Fig. 3). Generally, adhesion loss of the powders, except NaCl decreased when they were coated electrostatically. This is because when charged powder lands on the target and induces the target to create an image charge which is equal and opposite in polarity to the charged particle. This image charge attracts the charge powder with electrostatic force, resulting in a decrease in adhesion loss [2]. In the case of NaCl, its adhesion loss of NaCl increased 10 times compared to nonelectrostatic coating (Fig. 3). This might be due to a large decreasing of targeting loss, producing more chance for NaCl to have higher adhesion loss. In the mixture, no marked difference in the separation causing by the adhesion loss was observed between nonelectrostatic coating and electrostatic coating (Table 1). The interactions decreased the adhesion loss for all powders (Fig. 6). There was no significantly different between the adhesion losses of the powder for all mixtures (Fig. 5). This is similar to nonelectrostatic coating which the interactions significantly decreased the adhesion loss (Fig. 4). In the mixture, decreasing of adhesion loss to very low values by the interaction caused the adhesion loss have no effect on the separation.³

E. Electrostatic coating of the mixtures with starch, protein and sugar

For mixture of starch, protein and sugar, electrostatic coating generally decreased the separation when compared to nonelectrostatic coating (Table 1). The greatest factor decreasing separation was the decrease in individual adhesion loss with electrostatic coating. Individual targeting loss also was a great source of the separation in electrostatic coating. When compared electrostatic coating to nonelectrostatic coating, the number of location where the separation predicted to occur was not different. This might be because, the individual targeting loss of all powders decreased in a similar ratio with the electrostatic

coating (Fig. 3). In the mixture coating, targeting loss generally decreased the separation when compared to individual coating and nonelectrostatic coating (Table 1). Compared to individual coating, interaction did not make any change in the targeting loss of protein and sugar (Fig. 3). However, the targeting loss of starch increased when coated with protein and decreased when coated with sugar, consequently decreased the separation.

Individual adhesion loss considerably decreased the separation during electrostatic coating (Table 1). The adhesion loss of sugar and protein decreased from 22% to 5% and 14% to 9%, respectively while the targeting loss of starch was zero both in nonelectrostatic and electrostatic coating (Fig. 3). During electrostatic coating, charged powder lands on the target and induces the target to create an image charge which is equal and opposite in polarity to the charged particle. This image charge attracts the charge powder with electrostatic force, resulting in a decrease in adhesion loss [2]. Comparing to nonelectrostatic coating, the difference in individual adhesion loss of two powders for all mixtures decreased during electrostatic coating, causing less separation (Fig. 5). In the mixture coating, a similar trend was found as in nonelectrostatic coating which was adhesion loss decreased the separation in the starch-protein mixture but increased the separation in the starch-sugar mixture (Table 1). Interaction caused no change to adhesion loss of starch but significantly increased the adhesion loss of protein and decreased the adhesion loss of sugar (Fig. 7). Adhesion loss played no role on the separation of protein-sugar mixture. No separation in the mixture was a role of the targeting loss in the mixture.

IV. CONCLUSION

Individual coating characteristics and interactions between powders caused separation during mixture coating. During nonelectrostatic coating, the difference in individual targeting loss primarily caused separation, particular in the mixtures with NaCl which had greater targeting loss compared with other powders. Interactions in the mixtures reduced the separation by decreasing the difference in targeting loss of the mixtures with NaCl and decreasing of difference in adhesion loss of the mixtures of starch, protein, sugar. During electrostatic coating, the biggest cause of separation of the mixtures with NaCl was interactions in the mixtures which increased the difference between targeting losses of the mixtures. Electrostatic coating generally decreased separation in the mixtures of starch, protein and sugar by decreasing the difference in individual adhesion loss.

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