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Effect of tube wall material on electrostatic separation of plant raw-materials

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Abstract
The influence of charging tube materials and diameter on the separation efficiencies of a gluten-starch model mixture and lupine flour was studied. Offline analysis of tribo-charging with different tube materials showed that gluten takes a positive and starch a negative charge. However, the charge of the mixture was found not equal to the sum of the charge of the individual components and measured charges could not be related to the triboelectric series. During electrostatic separation significant protein enrichment was observed for both plant raw-materials. For the model mixture differences in protein, enrichment were observed between tube materials, but this was not the case for lupine flour. The lupine protein content increased from 37 to 65 g/100 g dry flour. Concluding, electrostatic separation needs to be evaluated during separation experiments, as particle-particle interactions dominate the charging process and thus separation of mixtures.

Practical applications: The combination of dry milling and electrostatic separation is investigated as a sustainable and mild route for protein fractionation. The results of this study showed that offline charging tube experiments could not predict separation performance of for example finely milled lupin flours. Instead, performance should be directly assessed during separation experiments, which is explained as charging is rather related to differences in material or triboelectric charging properties between powder particles than to charging tube wall properties. The results of this study benefit development of new applications for electrostatic separation.

1 | INTRODUCTION

The growing world population leads to a rapidly increasing demand for protein, while the potential of our planet to produce foods may well decline due to changes in the global climate (Asseng et al., 2015). Therefore, the current plant protein production needs to become more efficient. This can be done by shifting to more plant-based diets and by developing more efficient protein isolation routes (Aiking, 2011). Traditional wet protein isolation processes generally aim at high purity (> 90% protein) and are intensive in their use of water and energy. However, the native functional properties of proteins are often lost due to harsh processing conditions. Dry fractionation, which involves the combination of dry milling and dry separation, is proposed as a sustainable and mild route for protein fractionation. Dry fractionation provides less pure but highly functional protein-rich ingredients (Schutyser, Pelgrom, Van der Goot, & Boom, 2015), which has been demonstrated for various seeds of cereals and pulses (Schutyser & Van der Goot, 2011). The first step of

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this solid separation process is ultrafine milling of the seeds into a flour (Basset, Kedidi, & Barakat, 2016). In starch-rich legumes, the starch granules are liberated from the protein/fiber matrix as it is ground into small powder particles. Subsequent dry separation is often carried out using sieving or air classification depending on the differences in size and density of the particles (Lammi et al., 2018). A more recent dry separation technique introduced for food ingredients is electrostatic separation, which separates particles based on their triboelectric charging properties (Wang, Zhao, De Wit, Boom, & Schutyser, 2016). Studies demonstrated electrostatic separation for the protein enrichment of navy bean, rapeseed, lupine, and soybean (Basset et al., 2016; Tabtabaei, Vitelli, Rajabzadeh, & Legge, 2017; Wang et al., 2016; Xing, de Wit, Kyriakopoulou, Boom, & Schutyser, 2018). A large proportion of protein in lupin and soybeans is stored as protein bodies, which can be enriched during dry separation. Protein bodies were found positively charged and could be collected on the ground electrode (GE) as a protein enriched fraction, while fibers charged negatively and could be collected on the positive electrode (PE) as a protein depleted fraction (Xing et al., 2018). Provided that the ideal protein-enriched fraction only contains detached protein bodies, the theoretical limit for protein enrichment with dry fractionation is equal to the protein content of the protein bodies ($73 \sim 80$ g/100 g) (Wang et al., 2016). Process optimization is required to achieve protein enrichment as close as possible to this limit.

Triboelectric charging of materials is an often observed, but poorly understood phenomenon (Lacks & Shinbrot, 2019). When two materials are brought into contact, charge transfer induces a positive charge on one material and a negative charge on the other. The transferred charge can be either an electron, an ion, or very small material fragments (Lacks & Shinbrot, 2019). Different mechanisms are described for charge transfer upon contact between metals, insulators, and their combinations. For metal–metal contact the transfer of charge by the exchange of electrons has been quantified using material-dependent work functions (Mirkowska, Kratzer, Teichert, & Flachberger, 2016). A metal with a higher work function is closer to the negative end of the so-called triboelectric series (Figure 1) and tends to be charged negatively when in friction with another metal with a lower work function (Kwetkus, 1998). For conductor-insulator and insulator–insulator contacts however the exact mechanisms of charge transfer are unknown, although multiple studies have tried to characterize and develop theories for tribo-charging between these materials (Mirkowska et al., 2016; Zhang, Chen, Jiang, Lim, & Soh, 2019). In practice, often triboelectric series are reported, but the

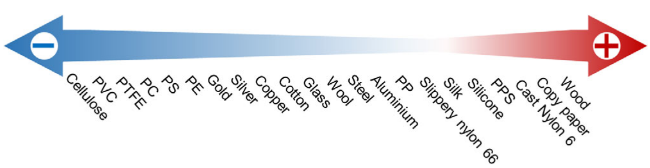

FIGURE 1 Triboelectric series of some common materials (Liu, Zheng, Yang, & Tao, 2018; Zou et al., 2019)

drawback is that the order of materials in the triboelectric series is not always reproducible since many additional factors influence the triboelectrification process. During triboelectric charging of mixed materials, both particle-particle and particle-wall may contribute to the overall tribo-charging of the particles.

There are different methods to evaluate the charging behavior of powders (Zafar, Alfano, & Ghadiri, 2018). Often charge is measured of a single material with a Faraday cup, where charging is realized for example with a charging device. Disadvantage is that such a method is less suitable for particle mixtures of different materials, as not only contact occurs between particle and wall, but also between particles. Alternatively, charge may be determined after electrostatic separation of different fractions. Drawback is that these studies are time-consuming and more useful for analyzing the separation experiment rather than for characterization of the tribo-charging.

Electrostatic separation is already applied on an industrial scale for the beneficiation of minerals, fly ash, and recycling of plastics (Chen & Honaker, 2015; Felsing et al., 2018; Tabtabaei, Jafari, Rajabzadeh, & Legge, 2016a), while not yet for protein fractionation (Tabtabaei, Konakbayeva, Rajabzadeh, & Legge, 2019). Lab-scale tribo-electrostatic separators consist of a dosing system, a charging tube, and a separation chamber with an electric field. Materials to be separated are conveyed by air or inert gas via a charging tube and subsequently separated in an electric field (Song & Mehrani, 2017). Very few studies systematically investigated the influence of the tube material choice, diameter, and surface properties on the separation of food ingredients. Tabtabaei, Jafari, Rajabzadeh, and Legge (2016b) compared different charging materials, namely PTFE, PVC, Nylon, and copper, for the enrichment of navy bean flour. The chargeability, in that study, was determined by measuring the charge of navy bean flour in a Faraday cup acquired after shaking the flour in the different tubes. Based on the results, PTFE was selected as the tribo-charging material. With the PTFE tube, the protein content increased from 25 to 47%. In another study, Chen et al. (2014) compared different tube walls by dispersing and conveying wheat bran particles in PTFE, Nylon, and steel tubes and collecting those in a Faraday cup. They claimed that insulators (PTFE and Nylon) would be more suitable than stainless steel for separating aleurone from pericarp particles. In our previous study (Xing et al., 2018), significant legume protein enrichment was achieved by electrostatic separation with the use of aluminum and stainless steel charging materials. From the above, we conclude that previous studies came to different conclusions using approaches with tribo-charging measurements and/or electrostatic separation.

This study aims at the evaluation of methods to come at the best selection of charging tube wall material and studies the effect of tube wall material and tube on electrostatic separation for the protein enrichment of flours. A range of charging tube wall materials were investigated, both conductors and insulators. Tribo-charging measurements were carried out with pure wheat gluten, wheat starch, and lupine flour. The added value of tribo-charging measurement of pure components and their mixtures was discussed to predict the separation of particle mixtures during electrostatic separation. Finally,

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electrostatic separation experiments were performed on a gluten: starch model mixture and on lupine flour to find out the main contributing factors to protein enrichment.

2 | MATERIALS AND METHODS

2.1 | Materials

Wheat gluten and starch were obtained from Roquette (France) and Sigma-Aldrich, respectively, and were stored in tightly screw-capped polyethylene vessels at −20°C. Dry and dehulled lupine seeds were purchased from Frank Food Products (Twello, The Netherlands) and stored in tightly sealed polyethylene containers at 4°C.

2.2 | Preparation of model mixture

Gluten and wheat starch were mixed at a ratio of 1:1 with a food mixer (Bosch MUM5, Germany). The model mixture was left overnight before using.

2.3 | Preparation of lupine flour

Lupine flour was prepared by a two-step procedure. First, dry lupine seeds were coarsely milled into lupine grits with a pin mill (LV 15 M, Condux-Werk, Germany). Then, the lupine grits were further milled into fine lupine flour with an impact mill (ZPS50, Hosokawa-Alpine, Augsburg, Germany) at ambient temperature. Classifier wheel speed was set at 2500 rpm, impact milling speed was 8,000 rpm and the airflow was 80 m^3/h (Wang et al., 2016). The prepared lupine flour was stored in sealed plastics bags in the freezer at −20°C.

2.4 | Electrostatic separator with varying charging tube configurations

A custom-built electrostatic separator was used for the separation experiments (Figure 2). The set-up was previously described in detail (Xing et al., 2018). The flour was entrained by a nitrogen gas flow which flowed through a charging tube. Upon exiting the charging tube, the entrained particles were exposed to an electric field that was applied between two vertically positioned electrodes at a distance of 10 cm. One electrode was grounded and the other had a positive voltage. Both electrodes were equipped with a PTFE conveying belt and brushes to continuously remove deposited powder from the electrodes. The conveying belts were driven by an electric motor, and brushes and powder collector boxes were placed at the bottom of the electrodes.

Charging tubes of varying materials (aluminum, stainless steel, Nylon 6, and polytetrafluoroethylene/PTFE), diameters, and surface properties were used as listed in Table 2. This choice was based on their use in previous studies, but also for their different positions in the triboelectric series (Chen et al., 2014; Tabtabaei et al., 2016b; Wang, de Wit, Schutyser, & Boom, 2014). Different tube diameters were selected to vary the gas flow velocity. A corrugated tube was made to examine the effect of increased convection near the wall: the inner diameter of this tube was 12 with 1 mm milled grooves, where the distance between two grooves was 2 mm.

For separation experiments with mixtures of wheat and gluten a feed sample of 25 g powder was used. For lupine flour, a feed sample of 50 g was used as starting material. The solids feed rate was controlled at 0.5 kg/h by a screw-feeding system. The nitrogen gas flow rate was always fixed at 50 L/min and the voltage applied to the positive electrode was 20,000 V. The corresponding electrical field strength was 200,000 V/m. After each separation run, four fractions were obtained. The fraction obtained from the ground electrode was

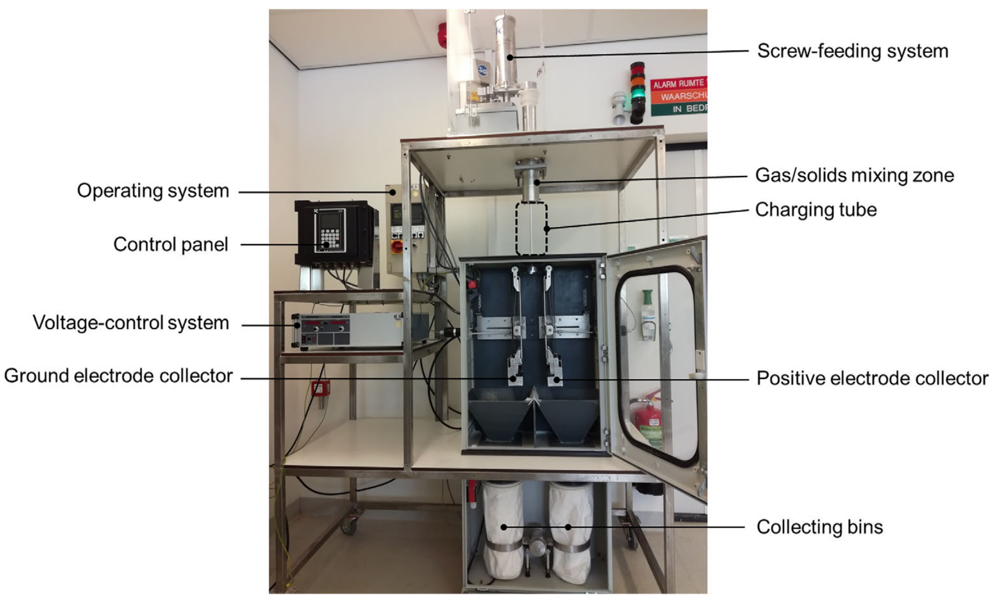


FIGURE 2 The custom-built electrostatic separator. Main parts of the separator are indicated in the picture

labeled "GE" and the fraction collected from the positive electrode was labeled "PE". Fractions collected from the filter bags installed below the separation chamber were referred to as "GC" and "PC," respectively. The separation experiments were carried out in duplicate. Protein enrichment was defined as the ratio of the difference between the protein content of the fraction collected at the ground electrode and the original material divided by the protein content of the original material.

2.5 | Tribo-charging measurements of particles with varying tube wall materials

Following the method from Tabtabaei et al. (2016b), the charge of pure gluten and wheat starch upon tribo-charging was measured in a dedicated system with the same tubes (Figure 2). This system consisted of: (a) the charging tube (b) a vibrator (HS 250, IKA, Germany), (c) a Faraday cup, and (d) an electrometer (Model 6215, Keithley Instruments, Inc.). For each experiment, the charging tube was filled with ~0.5 g powder and horizontally fixed on the shaker (Figure 3a). Subsequently, the shaker was activated in the direction parallel to the longitudinal axis of the charging tube, with the highest speed for 1 min. The charged powder was then transferred into a Faraday cup and the charge was measured with the electrometer. The result was expressed as the charge-to-mass ratio (μC/kg). The experiment was repeated for three times and the average values were calculated. Powders tested were gluten, starch, and a 1:1 mixture of both.

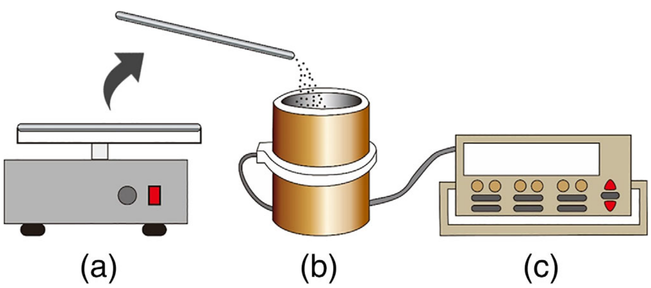


FIGURE 3 The charging measurement system: a vibrator with charging tubes fixed on it (a), a Faraday cup (b) connected with an electrometer (c)

2.6 | Analyses of plant raw-materials

2.6.1 | Compositional analysis

The oil, ash, and moisture contents of gluten, starch, and lupine flours were determined by methods AACC 30-25.01 (1999), AACC 08-01 (1983), and AACC 44-15.02 (1999), respectively. The protein content was determined with the Dumas combustion method (FlashEA 1112 series, Thermo Scientific, Breda, The Netherlands). A nitrogen conversion factor of N × 6.25 was used for calculating the protein content (Wang et al., 2016) Table 1.

2.6.2 | Scanning electron microscopy

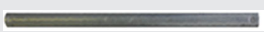
Scanning electron microscopy (Phenom G2 Pure, Phenom World BV, The Netherlands) was used to visualize the morphology of the wheat starch, gluten, and lupine flour particles. All the powder samples were imaged without any pre-treatment. Carbon tabs (SPI Supplies/Structure Probe Inc., West Chester, PA) were used to fix the samples on 12.7 mm aluminum pin mounts (JEOL Europe BV, the Netherlands). The acceleration voltage was set at 5,000 V.

TABLE 1 Compositions of wheat gluten, wheat starch, and lupine flour

	Protein (g/100 g)	Carbohydrate[a] (g/100 g)	Oil (g/100 g)	Ash (g/100 g)
Gluten	77.9 ± 0.1	19.1 ± 0.0	2.2 ± 0.1	0.8 ± 0.0
Starch	0.8 ± 0.3	98.9 ± 0.0	0.1 ± 0.0	0.2 ± 0.1
Lupine flour	37.2 ± 1.2	55.9 ± 0.3	5.6 ± 0.1	3.0 ± 0.3

[a]Calculated by difference.

TABLE 2 The configurations of the charging tubes used in this study

No.	Tube	Material	Shape	Length (mm)	Inner diameter (mmm)	Inner surface condition
1		Stainless steel	Straight	296	8	Smooth
2		Stainless steel	Straight	296	13	Smooth
3		Stainless steel	Straight	296	13	Corrugated
4		Aluminum	Straight	296	8	Smooth
5		Nylon 6	Straight	296	8	Smooth
6		PTFE	Straight	296	8	Smooth

2.6.3 | Particle size distribution

The particle size distribution of wheat gluten, starch, and lupine flour was analyzed with a Mastersizer-3000 (Malvern Instrument Ltd., Worcestershire, UK) equipped with a module for dry powder dispersion (Aero S, UK). A dispersion pressure of 2 bar was applied and the median for a volume distribution (Dv50) was calculated according to the Fraunhofer light scattering theory.

2.7 | Statistical analysis

Data were analyzed by analysis of variance (one-way ANOVA) using SPSS statistics Version 22.0 (IBM, Armonk, NY). Variances within a group were analyzed using least-significant difference multiple comparison analysis (LSD Duncan). Differences at a level of 95% ($p < .05$) were considered significant. Average values ± *SD* are reported for duplicate experiments.

3 | RESULTS AND DISCUSSION

3.1 | Offline analysis of tribo-charging

In this study, wheat gluten and starch were used as model powders to examine the effect of tube wall material on tribo-charging. Half a gram of pure gluten, pure starch, or their 1:1 mixture was loaded and shaken in charging tubes made from stainless steel, aluminum, Nylon, and PTFE, respectively (Table 2. No. 1, 4, 5, 6). The tribo-charging in the different tubes was evaluated by analysis of the charge to mass ratio for gluten, starch, and the model mixture using a Faraday cup (Figure 4).

The results showed that gluten charged positively, and starch charged negatively with all charging materials (Figure 4a,b). The observed charge polarity was expected and has been related earlier to the surface properties of both components (Tabtabaei et al., 2016b). The measured net charge of the model mixture (Figure 4c) was positive and close to the measured charge of the pure gluten, suggesting that gluten dominates the charging of the mixture despite the 1:1 ratio and the larger particle size of gluten. It can be observed from Figure 5a that gluten particles had an irregular shape and rough surface, while starch particles were oval and smooth. The particle size distribution curves (Figure 5c) showed that starch particles were smaller than the gluten particles (65 μm), having an average size of 15 μm.

By comparing the measured and the calculated charge from the measurements with the pure components, it could be concluded that the charge of the mixture was not simply the sum of the charge of the two different particles (Figure 4c). This finding is in agreement with Wang, de Wit, Boom, and Schutyser (2015) who conducted online charging measurements of 1:1 gluten-starch mixture in an aluminum tube. Their measured value was positive, while the calculated value was negative.

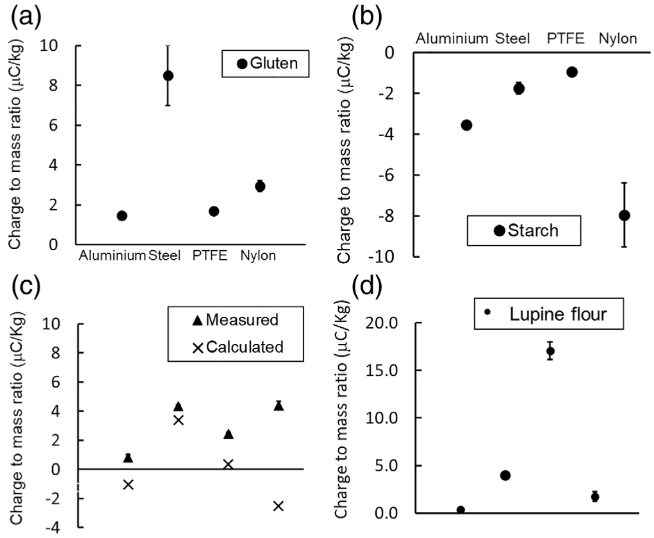


FIGURE 4 Tribo-charging measurements of wheat gluten (a), wheat starch (b) gluten and starch 1:1 model mixture (c) and lupine flour (d) after contact with aluminum (Tube No. 4), stainless steel (Tube No. 1), PTFE (Tube No. 6) and Nylon (Tube No. 5), respectively. In Figure 4c, the calculated charge values of the mixture are calculated on the basis of the charges of the individual components multiplied with their mass fraction, from Figure 4a,b. Results are expressed as charge to mass ratio (μC/kg). The error bars represent *SD*

The different tube materials are expected to display different chargeability toward the same plant raw-materials. However, surprisingly gluten obtained the largest positive charge after contact with stainless steel compared with the other materials (Figure 4a). This was not expected nor in line with the triboelectric series, as materials should exchange more charge and thus become more strongly charged when the distance between two materials in the triboelectric series is larger. This observation demonstrates the limited value of the empirical triboelectric series, as besides the surface properties also the measurement conditions very much determine the charging (Chen et al., 2014). Specifically, different collision behavior may explain deviating charging behavior between off-line measurements (during which particles move due to horizontal vibration) and the online measurements (where particles are conveyed by a gas).

Starch obtained its largest negative charge after contact with Nylon compared to other materials (Figure 4b). It may be expected that conductors are more efficient in tribo-charging than insulators, due to their free moving electrons (Wu, Li, & Xu, 2013); with insulators, one would expect charge buildup, which influences the charging behavior (Mirkowska et al., 2016). Both conductor and insulator materials have been applied successfully in electrostatic separation (Tabtabaei et al., 2016a; Xing et al., 2018). However, in our study, it was observed that Nylon displayed better charging compared to aluminum when contacted with starch or gluten (Figure 4a,b).

Different charging results were obtained for lupine flour (Figure 4d), which may be expected as a result of the different composition of lupin flour, being a mixture of finely milled fibers and protein

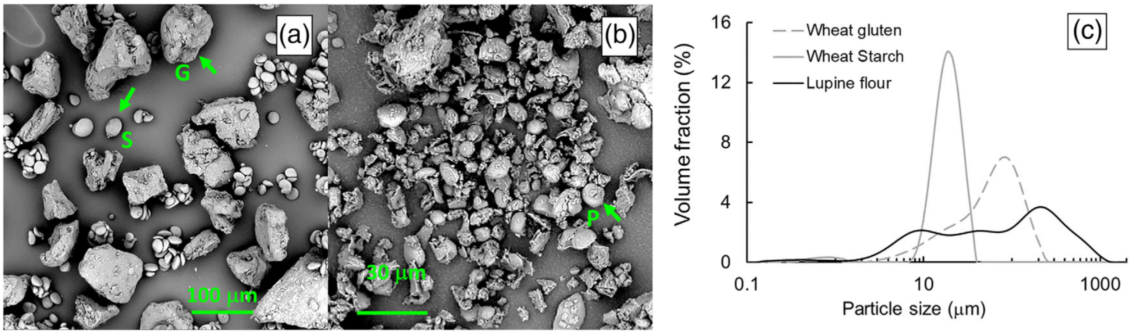


FIGURE 5 Scanning electron microscopy picture of gluten-starch mixture (a) and lupine flour (b). "S," "G," and "P" indicated by arrows represent starch granular, gluten particle and protein body, respectively. The particle size distribution curves of pure gluten, starch, and lupine flour are plotted together (c)

body fragments (Wang et al., 2016). The charge of lupine flour obtained after contact with the different tubes was positive. The observation that the net charge of lupine flour with PTFE is higher than with Nylon and with copper is in line with that of Tabtabaei et al. (2016b) for navy bean flour. However, because the charge of lupine flour is the sum of positively and negatively charged particles, it is impossible to draw conclusions on the chargeability of individual components and thus predict their separation performance.

Overall, the results indicated that it was not possible to directly relate the tribo-charging behavior of the studied materials to earlier reported triboelectric series. Moreover, one cannot directly predict the overall charge of mixtures of particles from the charge that the individual particles obtained when charged in isolation. Particle-particle interactions in mixtures have a large impact on the charging process. This conclusion is also in line with the study of Landauer, Aigner, Kuhn, and Foerst (2019) who observed that particle-particle collisions were crucial in separating whey protein-barley starch mixtures. As particle–particle interactions between the two materials to be separated is crucial for subsequent separation in the electric field, these interactions should be optimized in an electrostatic separation device. This may be achieved by increasing residence time, solids concentration, or even redesign of the charging part.

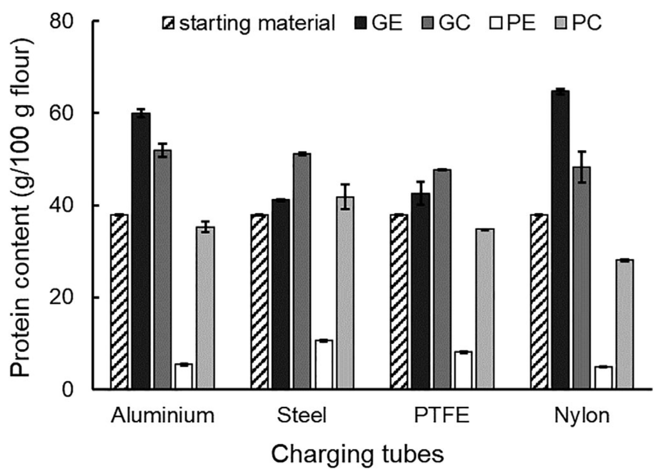


FIGURE 6 Electrostatic separation of gluten and starch mixture (1:1): protein content (g/100 g flour) of starting material and four fractions collected from ground electrode (GE), positive electrode (PE), ground collector (GC), and positive collector (PC). The error bars represent *SD*

3.2 | Separation performance of varying charging tubes

3.2.1 | Protein enrichment during experiments with model gluten-starch mixtures

The separation performance of four different charging tubes (Table 2. No. 1, 4, 5, 6) was first evaluated with the model mixture. The N_2 gas flow rate was 50 L/min, the voltage was 20,000 V and the feeding rate was 0.5 kg/h. The protein content of the starting material was 37.8 g/100 g flour and it can be observed from Figure 6 that protein enrichment was achieved with all the charging materials, whereas the protein content of the starch enriched fraction was significantly lower (p < .05). Significantly higher protein enrichment was observed for aluminum and Nylon tubes (p < .05), while the fractions obtained from the filter bags of all tubes showed similar compositions. Since the compositions of the latter fractions were not so far from the starting material, in practice they could be recycled. In another study using a mixture of whey protein and barley starch no difference between different tube wall materials (all insulators) were observed on electrostatic separation (Landauer et al., 2019). The high separation efficiency for Nylon (and also aluminum) can be derived from the increased protein content of the GE fraction (65 g/100 g flour and 60 g/100 g flour for Nylon and aluminum, respectively), which was close to the protein content of gluten. The enrichment decreased from Nylon, aluminum, PTFE to stainless steel. These results are probably related to the measured charge of starch particles (Figure 4b), which was highest for both Nylon and aluminum, but not to that of the gluten (Figure 4a), which obtained a very high charge after contact with steel. However, it seems impossible to select the best charging tube on basis of the tribo-charging measurements only.

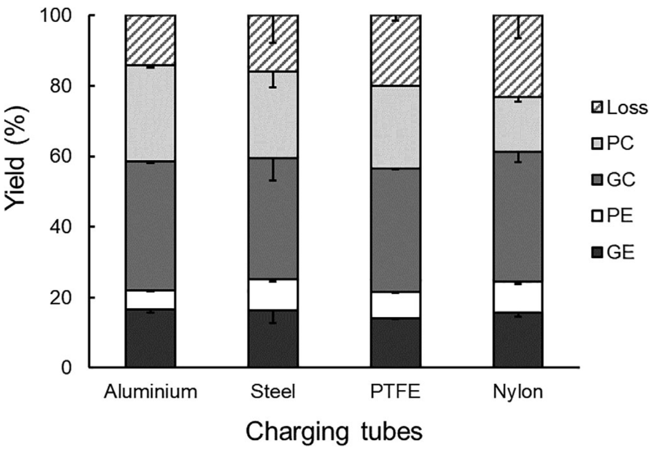


FIGURE 7 Electrostatic separation of model mixture with different charging tubes (8 mm of diameter): yield (g/100 g flour) of four fractions collected from ground electrode (GE), positive electrode (PE), ground collector (GC), and positive collector (PC). Weight of loss was calculated by difference. The error bars represent *SD*, only minus direction is shown

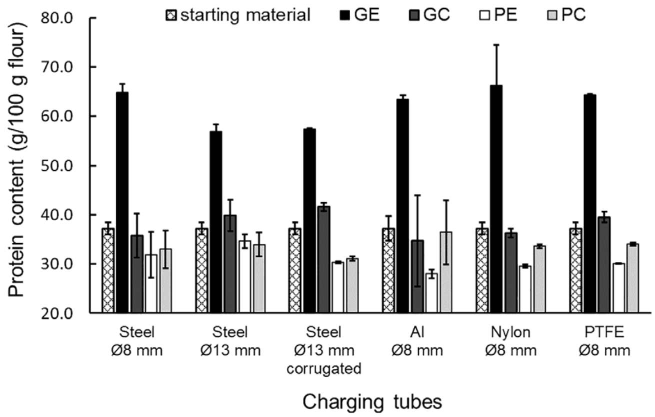


FIGURE 8 Electrostatic separation of lupine flour with different charging tubes: protein content (g/100 g flour) of starting material and four fractions collected from ground electrode (GE), positive electrode (PE), ground collector (GC), and positive collector (PC). The error bars represent *SD*

The yield of the protein-rich fraction is another important parameter to evaluate the separation performance. The yields of the four fractions are shown in Figure 7. The yields of the protein-rich fractions (GE) of the four-tube materials were similar ($p > .05$), also indicating a limited influence of the charging tube material on the yield. Some very fine material was not captured by either electrodes or filter bags, but was dispersed in the relative large separation chamber. This amount of lost material was relatively large, which was also partly related to the limited sample size used in this study.

3.2.2 | Lupine protein enrichment

To further investigate the effect of the charging process on the separation performance of plant raw-materials, tribo-electrostatic separation experiments were carried out with lupine flour using charging tubes of different materials and diameters (Table 2). The operating conditions were the same as that for separating model material: N_2 gas flow rate was 50 L/min, the voltage was 20,000 V and the feeding rate was 0.5 kg/h. The protein content of lupine flour and those of the different collected fractions are shown in Figure 8. The protein content of the GE fractions significantly increased compared to the starting material for all tube materials ($p < .05$). However, the PE fractions were not all significantly depleted in protein compared to the starting material ($p > .05$), indicating that the overall protein separation, relative to that obtained with the gluten-starch mixture, was much less. The earlier noted observation that the material on the PE electrode was only slightly depleted in protein suggests that the particles on the PE electrode were mostly composite particles containing both fiber and protein.

Despite that tubes were made of different materials, for all tubes with a diameter of 8 mm, the purity of the GE fraction was always in the range of 63 ~ 66 g/100 g and no significant differences ($p > .05$) were observed. This implies that the choice of tube material did not influence the electrostatic separation of lupine flour. This observation agrees with the conclusions from Landauer et al. (2019) who reported that the tube wall material had no influence on the tribo-electrostatic separation performance of small particles. This may indicate that inter-particle collisions are more important for the charging than the particle-wall collisions.

In contrast, the diameter of the tube showed a significant influence on the separation performance using similar gas flow rates (50 L/min) ($p < .05$). The GE fraction obtained with the stainless steel tube with a diameter of 8 mm showed significantly higher protein purity than that separated with the same material but with a diameter of 13 mm ($p < .05$). The gas velocities were 4.15 and 1.57 m/s, for the 8 and 13 mm tubes, respectively. Increasing the gas velocity leads to intensified collisions, more charge transfer, and thus better separation. A tube with a corrugated inner surface was constructed to enhance convection close to the wall and thus charging. However, after an initial improved separation performance, the improvement quickly diminished, probably due to the fouling of the corrugated surface (Figure 8).

For each separation experiment, a feed sample of 50 g of lupine flour was used as a starting material. The yields of four fractions were summarized and the weight of lost flour after each separation was calculated as the difference with the original amount. As shown in Figure 9, there was no significant difference between tube materials observed in terms of yield for the GE (8.8 ~ 12.2%) ($p > .05$). The yields of the fractions collected from the positive electrode and its filter bag (PE and PC) were higher than those from the negative electrode and its filter bag (GE and GC). The explanation for this is that the lupine flour has more fibers than protein, and protein bodies are only liberated to a certain degree from the fibrous matrix. Earlier research showed that collecting the fractions from the filter bag, subsequent milling and a second step of electrostatic separation can

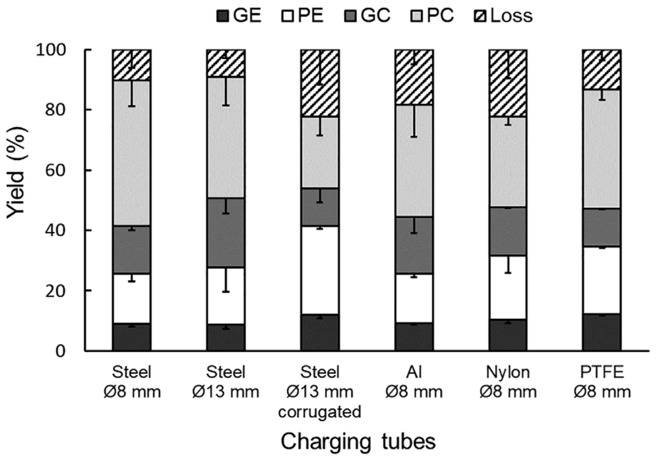


FIGURE 9 Electrostatic separation of lupine flour with different charging tubes: yield (g/100 g flour) of four fractions collected from ground electrode (GE), positive electrode (PE), ground collector (GC), and positive collector (PC). Weight of loss was calculated by difference. The error bars represent *SD*, only minus direction is shown

improve the purity and yield of the process (Wang et al., 2016). By calculating the mass balance, the protein content of the loss was in the range of 31.0 ~ 43.9%. It is possible to achieve higher protein recovery from the loss after scaling up.

The observation that the charging material does not have a systematic influence on the tribo-charging behavior, combined with the observation that an increase in flow rate significantly increases the charging efficiency ($p < .05$), leads to formulate the hypothesis that particle-particle collisions largely determine the charging. This would ultimately mean that the charging system should be optimized to maximize particle-particle collisions by introducing as much mixing as possible.

4 | CONCLUSIONS

Charging tubes made from stainless steel, aluminum, PTFE, and Nylon were used to charge pure gluten, wheat starch, their mixtures, and lupine flour. Wheat starch obtained a negative charge whereas gluten particles obtained a positive charge. Even the measured charge of the pure components could not be related to the triboelectric series. The charge of a gluten-starch mixture was also not simply the sum of the charge of the individual components, suggesting that particle-particle interactions have considerable influence on the charge of the mixture.

Electrostatic separation was then carried out using gluten-starch mixtures and lupine flour using again different tube wall materials. The protein enrichment for the model mixture appeared influenced by the wall material and seemed related to the measured starch charge. For lupine flour, the purity of the protein enriched fraction increased from 37 g/100 g flour to 65 g/100 g flour. Interestingly, the separation performance of the lupin flour was not related to the used tube material. Experiments with different tube diameters showed however a large influence of hydrodynamic conditions on the separation.

To conclude, particle-particle collisions are mostly responsible for the charging of mixtures. This conclusion explains why charging experiments with pure components do not predict the separation behavior during electrostatic separation, but also implies that redesigning the charging system to maximize particle-particle collisions, for example employing a fluidized bed rather than a charging tube, could lead to significantly better charging and thus separation.

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AUTHOR CONTRIBUTIONS

Qinhui Xing: Conceptualization; data curation; investigation; methodology; writing-original draft. **konstantina kyriakopoulou:** Supervision; writing-review and editing. **martin de Wit:** Investigation; resources. **Remko M. Boom:** Supervision; writing-review and editing. **Maarten A. I. Schutyser:** Conceptualization; project administration; supervision; writing-review and editing.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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