3-A 2026 Student Hygienic Design Proposal

Dry-to-Safe: Moisture-Free Powder Removal for Pathogen-Safe Processing

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Summary of Proposed Solution

Our proposed solution aims to combine the use of a surface-engineered static-dissipating coating material for stainless steel surfaces with the use of forced air at elevated temperatures (45 or 90 °C) and low humidity (≤ 30% RH) during processing and cleaning. The combined effect of the proposed solutions will significantly reduce powder retention and improve the removal of residual powder from equipment surfaces during cleaning operations.

Background

Mechanisms of powder accumulation

Low moisture environments, such as dry powder processing systems (flour milling, infant formula, protein powders), are often subjected to persistent powder accumulation due to three primary mechanisms:

Triboelectric charging:

When powders collide with equipment walls, chutes, or impact bends, charge transfer between particles and surfaces occurs. Most powder processing units employ pneumatic conveying (especially through bends), which creates frequent particle-wall and particle-particle impacts that steadily build up net charge due to electron, ion, or material transfer at the interface (Conway & Ghori, 2018). The triboelectric charge generation and interactions with steel are depicted in **Figure 1**. Fine powders tend to reach a higher specific charge because they experience a higher collision frequency and have a higher specific surface area. Charge dissipation is relatively slower when powders and surfaces behave as insulators at the interface, even if the steel beneath is conductive. Charged particles are captured by the wall via electrostatic forces (including image-charge attraction) and by adhesion to existing insulating deposits, so initial dusting promotes further dust accumulation. This is often the case with infant formula, where the median particle size D_{50} is in the range of 119-133 um (**Figures 2 and 3**) (Bettersize Instruments Ltd., 2021). Protein powders are reported to be cohesive, with particle sizes similar to wheat gluten (240.1 µm), while soy (263.1 µm) and pea (261.6 µm) (Nkurikiye et al., 2025) (**Figure 4**).

Vander Waals adhesion:

In the absence of electrostatic charging, fine powders can adhere to equipment surfaces because intermolecular forces such as van der Waals interactions become dominant at small length scales (Frabetti et al., 2021). This adhesion becomes more pronounced as particle size decreases because gravitational force scales with particle volume, while surface forces scale with contact area. In addition, low relative humidity (RH) can further aggravate handling by promoting dustiness and electrostatic issues because moisture increases surface conductivity and accelerates charge dissipation. However, low RH slows down charge decay and allows charge to persist (Li et al., 2004).

Glass transition and caking

The composition of food also influences retention. Amorphous components in food powders can undergo a water-plasticization-induced glass transition. As water activity increases (and/or temperature rises), the glass transition temperature (T_g) decreases. When the actual temperature exceeds T_g ($T - T_g > 0$), the material transitions into a rubbery state, reducing viscosity and increasing molecular mobility. In this rubbery state, particle surfaces can deform and flow, promoting the formation of viscous-capillary bridges at particle-particle and particle-wall contacts. These bridges increase powder cohesiveness, accelerate caking, and contribute to wall fouling.

<u>Proposed Solution # 1 (Modified Surface Coating)</u>

Rationale for Coating Design and Material Selection

Base Resin

The matrix material selected for this system is a food-equipment-compatible polyester or epoxy-polyester hybrid thermoset powder-coating resin.

Mechanical Durability and Abrasion Resistance

Dry powders such as wheat flour and pea protein possess mild abrasive characteristics that progressively induce micro-scratching on untreated stainless-steel surfaces. Micro-scratches increase effective surface roughness and create mechanical anchoring sites for fine particles. Thermoset polyester and epoxy-polyester coatings, upon curing, form a crosslinked polymer network characterized by hardness, improved scratch resistance, resistance to microfracture propagation, and stable surface integrity on repeated mechanical contact. This ensures the formation of new retention sites.

Chemical and Environmental Stability

Although dry processing facilities limit the use of wet sanitation, alkaline-based cleaning agents, mild alkaline detergents, and intermittent wet cleaning cycles may be employed. Under such conditions, the polyester and hybrid thermosets exhibit good hydrolytic resistance, are stable at moderate pH, and show minimal swelling relative to thermoplastic films. *This ensures coating integrity under sanitization.*

Smooth Film Formation, Surface Continuity, and Thermosets

Powder coatings are applied as dry particulates and, upon thermal curing (typically 180-200 °C), they melt, flow, and level to form continuous, non-porous films with reduced pinholes and surface defects and a controlled film thickness (typically 60-100 µm). This smooth, continuous surface minimizes microscale crevices and lowers opportunities for particle lodging, thereby improving cleanability and reducing sites for powder retention and fouling initiation. For hygienic powder-processing applications, thermoset coatings are generally preferred to thermoplastics because curing produces a crosslinked network with greater dimensional stability, resistance to softening or creep under frictional heating, and improved resistance to mechanical damage. In contrast, thermoplastics may undergo plastic deformation under moderate thermal and tribological stresses, increasing surface roughness over time and compromising cleanability by promoting particle adhesion and accumulation.

Static-Dissipative Mechanism through Percolation-based Conductivity

The proposed coating incorporates a controlled conductive additive system to impart static-dissipative behaviour rather than full electrical conductivity. A target surface resistivity of 10^6-10^9 Ω/sq was selected to enable controlled charge dissipation during powder handling, thereby limiting electrostatic charge accumulation and reducing the likelihood of electrostatic discharge while avoiding the behaviour of highly conductive surfaces. We propose increasing electrical functionality through a percolation-based mechanism in which the additive concentration exceeds the critical percolation threshold required to form continuous or semi-continuous conductive pathways within the polymer matrix. Candidate approaches include low-loading carbon-based fillers, commercial static-dissipative powder coating formulations, and engineered intrinsically conductive polymer systems. Additive loading must be optimized to preserve both coating performance and hygienic surface characteristics. Excessive loading may increase surface heterogeneity or cause filler protrusion, thereby increasing roughness and promoting mechanical anchoring of powder particles. Accordingly, formulation design should balance electrostatic charge dissipation with surface smoothness, coating adhesion, and mechanical integrity. The objective is therefore not maximum conductivity but control charge bleed while maintaining hygienic surface morphology. A flowchart for the production and application of the proposed coating is shown below

Powder Release Function

In addition to triboelectric charging and electrostatics, fine powders can adhere to surfaces through van der Waals forces and mechanical interlocking. We aim to address this through our coating. The coating design integrates surface chemistry selection that lowers the effective surface energy relative to bare stainless steel, together with cure optimization to promote surface levelling and the formation of a smooth, continuous film with minimal porosity and micro-defects. Reducing both surface energy and surface roughness decreases the effective interfacial contact area, lowers the magnitude of adhesive force, and reduces the likelihood of particle smearing and persistent film formation on process-contact surfaces. For highly cohesive powders such as infant formula and pea protein, which are characterized by high specific surface area and strong interparticle attractions, even modest reductions in particle-surface adhesion may substantially decrease dust-film persistence and surface fouling.

Table 1: Comparison of adhesion mechanisms between bare stainless steel and SE-SDS coating

Adhesion mechanism	Bare stainless steel	SE-SDS coating
Electrostatic attraction	High	Reduced (controlled dissipation)
Mechanical anchoring	Moderate (increases with wear)	Reduced (smooth film)
Van der Waals adhesion	Moderate	Reduced (lower interfacial energy)
Net residue retention	High	Lower

<u>Proposed Solution # 2 (Conveyance / Removal)</u>

In addition to SE-SDS coating, we also propose the use of forced-air at elevated temperatures (45 ˚C during processing and 90 ˚C during cleaning) and reduced humidity (≤ 30% RH) during processing (i.e., pneumatic conveying and mixing) and cleaning operations (i.e., purging) to aid the removal of residual powder after processing. The warm air can be generated using a dedicated compressed-air line connected to powder-handling equipment, such as bins, conveyance lines, receivers, and packaging systems. The heating action can be provided by a sanitary electric or steam coil heater designed for food-contact surfaces, equipped with temperature and flow control systems. The generated air will be passed through a HEPA filter (0.3 µm) prior to entering process equipment surfaces to minimize the introduction of airborne microbial contaminants into the system. During processing, the temperature of the warm air used can be limited to ≤ 45 °C to minimize heat-related quality deterioration to the product being processed. During cleaning operations, the temperature can be increased further to ≥ 90 °C (recirculated for 3 h) to maximize the drying effect and improve the removal of residual powder in process equipment during cleaning.

Theoretical Basis

The difficulty of completely removing powdered ingredients stems from their flowability issues. Powder flow is the ability of granular solids to move during processing and handling, and it is typically regarded as a multivariate phenomenon (Rosentrater et al., 2006). This characteristic is typically affected by inherent powder characteristics such as its composition and particle properties. Environmental conditions such as temperature and relative humidity also play a major role in the flowability of powdered ingredients. In general, given that powder characteristics remain the same, the use of elevated temperatures and lower humidity values typically improves the flowability of powdered ingredients (Rivera et al.,2023). This phenomenon is mostly related to changes in the powder's moisture content as moisture is removed by contact with warm/dry air. Crouter & Briens (2013) reported that lower moisture contents in various pharmaceutical powders tend to improve flowability. Moisture tends to decrease powder flowability by increasing interparticle contact, leading to higher cohesiveness, clumping, caking, and clogging (Teunou & Fitzpatrick, 1999; Rivera et al., 2025). Although other components of powdered ingredients (protein and fat) affect flowability, introducing a solution that can influence powder moisture is a more flexible solution. It can be applied virtually to any granulated material to improve flowability, without altering its major components or the resulting end-use quality.

Experimental Basis for the Proposed Solution

In our experiment, we used soft wheat flour as a medium to demonstrate the basis for this solution. We used soft wheat flour (SW) because it is known to have poorer flowability due to its high cohesiveness and rougher particle surfaces. Hence, it can be viewed as a “worstcase" scenario for improving the flowability of powdered ingredients via the proposed solution. The proximate composition of SWs used are protein – 10.7 to 11.0%, fat – 0.4 to 0.5%, and carbohydrates – 77.2 to 78.0%. The compositional variations within the samples are not significant enough to account for the observed differences in the experiments, which suggests that the observed differences are likely due to moisture changes caused by the exposure treatments. The SW samples were spread thinly in aluminum trays and placed in controlled humidity chambers set at different temperatures (45 and 90 °C) and %RH (30 and 50%RH) combinations. The control treatment is the unexposed SW sample. This experiment was done to mimic the conditions proposed on using forced air to improve residual powder removal. The exposure time was set at 3 h to mimic potential drying times in powder processing. **Figure 5** shows the effect of the exposure conditions on the moisture content of the soft wheat flour used. Overall, the results show that elevated temperatures reduced moisture content in all exposed SW samples relative to the control. In addition, the higher humidity (50% RH) slightly lessens the extent of moisture removal from the samples as they had higher MC values than the exposed samples at 30% RH.

The flow indicators for the SW samples were measured using their compressibility indices. In addition, their dynamic (stability and variable flow rate, aeration) and shear (shear cell and wall friction) characteristics were measured using the standard FT4 Powder Rheometer (Freeman Tech, UK). Bian et al. (2014) provided more details on these tests. The compressibility indices (%CI) of the exposed SW samples are shown in **Figure 6**. %CI values are used as preliminary indicators of the flowability of granulated materials and are calculated from the percentage difference between their tapped and bulk densities. Higher values (> 15%) tend to indicate poor flowability. Overall, the results show that exposed SW (regardless of conditions) yielded lower %CI values than the control. The trend indicates improved flowability for the exposed SW samples relative to the control.

The dynamic flow properties of the SW samples were measured under non-aerated and aerated flow conditions. Under non-aerated flow (stability and variable flow rate), the ease of flowability of the SW powders was indicated by their basic flowability energy (BFE). The BFE value is regarded as the energy required to establish a consistent flow pattern in a loosely packed powder under confined conditions. In practice, this can be used as a predictor of powder flowability during conveying and mixing operations, such as those in powder blending and equipment cleaning. The BFE values of the exposed SW samples are shown in **Figure 7.** The results also indicate that the exposure of the SW samples to elevated temperatures and lower humidity (30% RH) resulted in lower BFE values. This trend indicates that exposure improved the flowability of the SW samples, which translates into easier removal of residual powder from equipment during cleaning operations. The flow rate index (FRI) and stability index (SI) of all SW samples ranged from 0.9 to 1.1; both values indicate that the exposure treatment did not influence the flow stability of SW under stable and dynamic flow rates.

Aside from the non-aerated flow, the flowability of the SW samples was also measured under aerated flow. In practice, the observations from this test can be used to predict powder flowability in processes such as pneumatic conveying, air purging, or any processes that use air as a flowability aid. The aeration characteristics of the SW samples are shown in **Figure 8**. For all samples, the total energy values decreased with increasing air velocity, indicating improved flowability with aeration. Among the samples, the use of 30% RH with 45 or 90 °C resulted in the lowest total energy required among the treatments. In addition, both treatments also had the highest aeration ratio (AR) values at 8.1 to 10.76 among other samples (3.71 – 6.22). This shows that exposure of the SW samples at both temperatures with 30% RH increases the positive impact of aeration on flowability.

The shear properties of the SW samples were also measured. Compared to the dynamic flow properties, shear properties describe how easily a powder can be made to flow after being compacted. In practice, this is relevant to powder handling processes such as bin/hopper discharge, screw feeding, filling, and compression. In cleaning, this can be used to indirectly determine how easy it is to dislodge compacted, accumulated powder masses on equipment surfaces during purging. The shear cell properties (cohesion) indicate how much force is needed to break apart a compacted powder to initiate flow. The cohesion values of the exposed SW samples are shown in **Figure 9**. The results show that the cohesion of the SW flours decreased post-exposure relative to the control.

The wall friction angle (WFA) is another shear property that indicates the powder's sliding resistance to a specific surface. In this case, the testing was done against a stainless-steel surface, as it is the most common surface used in powder processing. The WFA values of the SW samples tested are shown in **Figure 10.** The results show that the WFA values of SW decreased after exposure, which indicates that the sliding resistance of the exposed SW flours against stainless steel is lower. In both shear cell and WFA testing, the trends indicate that exposure at elevated temperatures (45 or 90 °C) and low humidity (≤ 30% RH) will facilitate easier discharge and dislodgement of compacted SW flours during processing or cleaning.

Overall, the results of the experiment show that the use of forced air at elevated temperature (45 or 90 °C) and ≤30% RH can be a viable aid in cleaning residual powder from equipment surfaces. This is based on the virtue of improving the flowability of the powdered ingredient (in this case, SW). In addition, preventing moisture gain in the powdered ingredient with this solution will help prevent clumping, caking, and adherence to the equipment surface. Hence, the solution will enable easier removal of residual powder during air purging, vacuuming, or any other powder removal process.

Justification for Use in Practical Settings and Food Safety Considerations

The coating can be used in practice, as it is compatible with stainless-steel surfaces and helps minimize fouling on equipment. This can help minimize downtimes. From a food safety standpoint, SE-SDS coating is made of polyester and epoxy, polyester thermoset resins, which are recognized as food-contact materials by the FDA 21 CFR 175. 300 (Resinous and Polymeric Coatings) and, therefore, are regularly certified to NSF/ANSI 51 for food equipment materials. The smooth, non-porous, crosslinked film prevents the formation of micro-scratches and crevices, which are the main sources of pathogen sheltering (*Salmonella* and *Cronobacter*), especially when these pathogens are in a persistently dry environment. The coating eliminates the accumulation of insulating powder deposits that protect microorganisms from the next dry cleaning steps by dissipating triboelectric charge via a controlled percolation network (target surface resistivity 10^6-10^9 Ω/sq). All conductive additives (carbon-based fillers) will be chosen from the substances that comply with the FDA indirect food additive regulations (21 CFR 174, 178) and will be confirmed by extractive testing according to 21 CFR 175. 300(c) to ensure that migration into food is kept within the permitted limits. The coating will be taken for NSF/ANSI 51 certification, which is a test of cleanability, coating adhesion, abrasion resistance, and heat resistance that also complies with the main 3A SSI criteria that surfaces in contact with the product should be non-toxic, cleanable, inspectable, and capable of withstanding the conditions of intended use.

For practical reasons, thermoset powder coatings are typically applied and cured (180-200 °C) using standard electrostatic spray and thermal curing methods that are commercially available through coating service vendors. Since the coating is applied to fabricated stainless steel parts before equipment assembly, it can be used for both retrofit and new build installations of bins, hoppers, conveyance lines, receivers, and packaging system components. Film thickness is controllable (60-100 μm), and the cured surface can be finished to meet or exceed the 3A surface roughness requirement of Ra ≤0.8 m (32 μin). The highly crosslinked polymer network is very stable; thus, it does not soften, creep, or scuff even when continuously rubbed with powder. This way, the surface maintains its integrity for a long time during production campaigns, thereby reducing maintenance frequency.

From an economic perspective, the SE-SDS coating provides a solution to powder hang-up, based on electrostatic adhesion, van der Waals attraction, and mechanical anchoring, rather than relying solely on increased cleaning action. Less residue retention is one of the direct results of shorter cleaning cycle times and less labor required during dry cleaning drives (air purging, vacuuming, product scouring). Based on the current industry approach, a production line might be shut down for cleaning for several days or even weeks to create a clean break between production runs. Any deed of a few days to recover from the lost production time and sanitation labor can be very helpful, especially if the residue stillness is considerably reduced. In addition, the risk of the coating causing a recall as a result of contamination events is lowered by the coating that has been applied. The costs of recall (which include disposal, investigation, and brand damage) far outweigh the one-time capital cost of coating application. Overall, the reduction in cleaning time, labor costs, and contamination risk leads to a good return on investment in surface engineering.

From a quality standpoint, the use of forced air can be practical, as the flexibility in temperature and humidity levels is unlikely to cause any quality deterioration in the powdered ingredient being processed. The proposed processing temperatures are expected to have minimal effect on product quality, as heat damage is unlikely at ≤ 45 °C. In terms of food safety, the use of heated air (positive pressure) and HEPA filters is a good deterrent in preventing the entry of airborne contamination into the equipment during processing and cleaning operations. In addition, the heater to be used will be "food grade" in that it uses stainless steel materials, is non-porous, and is not coated with heat-labile coatings, with food-contact-safe gaskets. A critical parameter for this would be humidity as it could introduce moisture (via condensation) if left uncontrolled. To address this, desiccants will be used with the air supply to reduce dew point, and humidity sensors will also be used to make sure the %RH values fall ≤ 30% RH. Process equipment will also be heated by introducing heated air, which can help prevent condensation. As for its economic benefits, both solutions (coating and forced air) make the removal of residual powder easier, which translates to lower labour and shorter operation times, potentially cheaper than the utility costs of using heated air.

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Figures

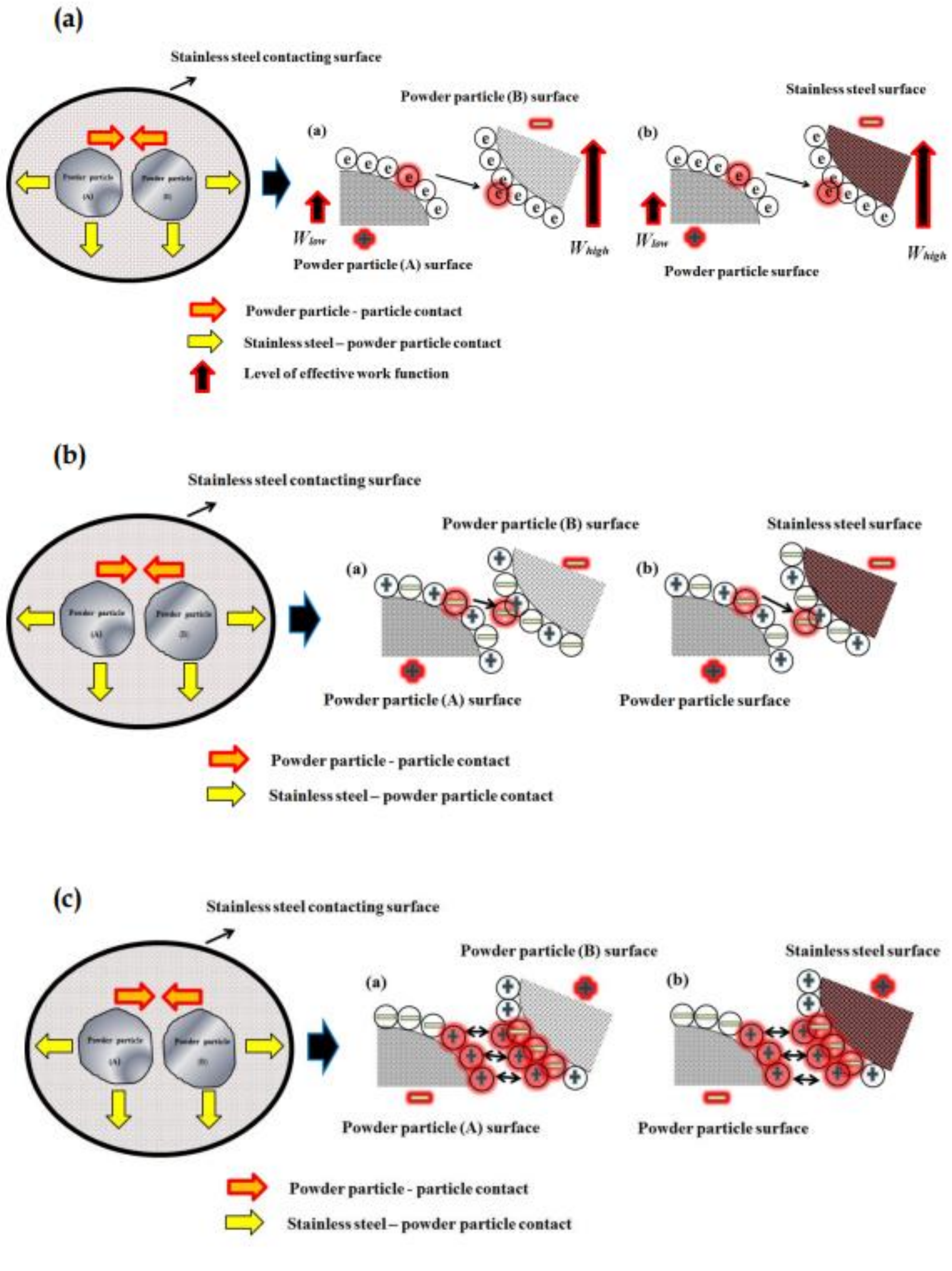

Figure 4. Schematic illustration of (a) electron transfer (b) ion transfer and (c) material transfer theory of triboelectric charge generation.

Figure 1: Triboelectric charge generation by a. electron transfer; b. ion transfer and c. theory of triboelectric charge generation [source: Conway & Ghori (2018)].

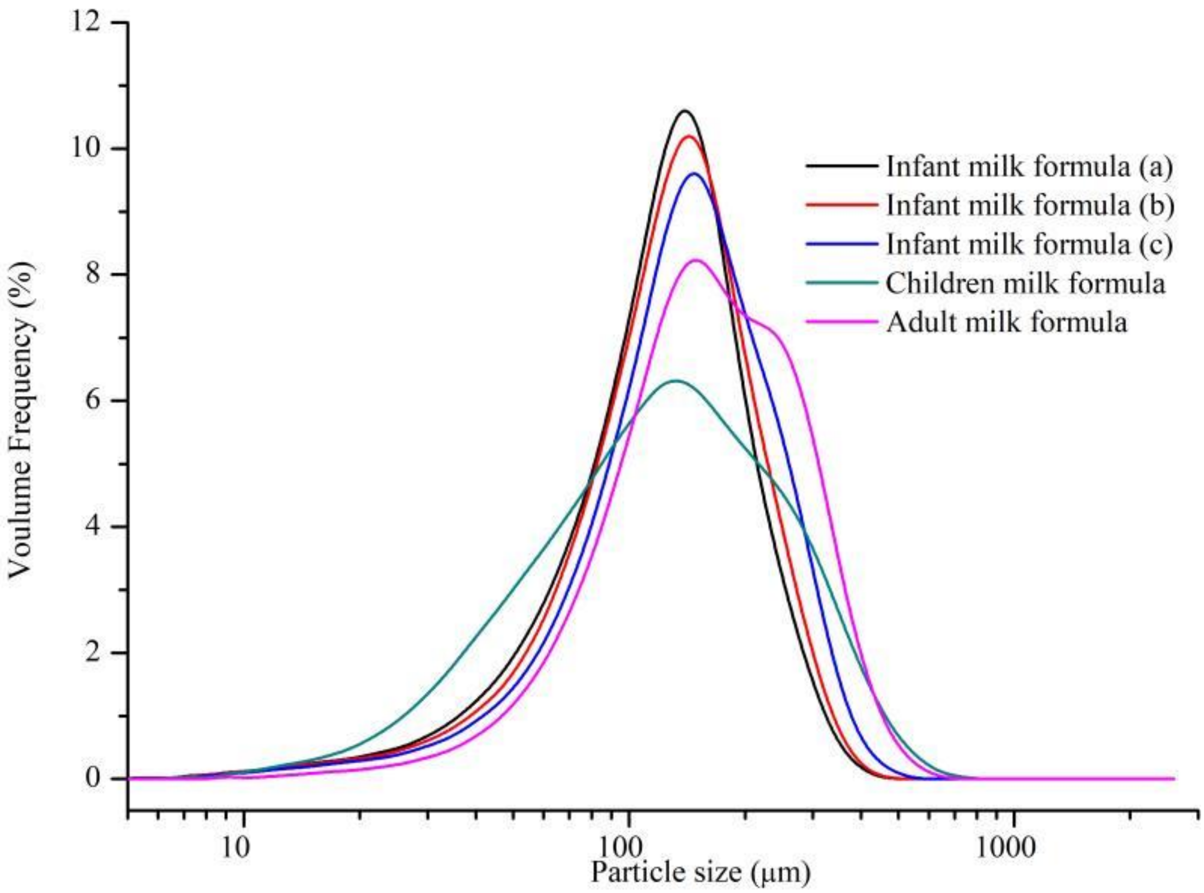

Figure 2: Milk powder particle size distribution [source: Bettersize Instruments Ltd. (2021)].

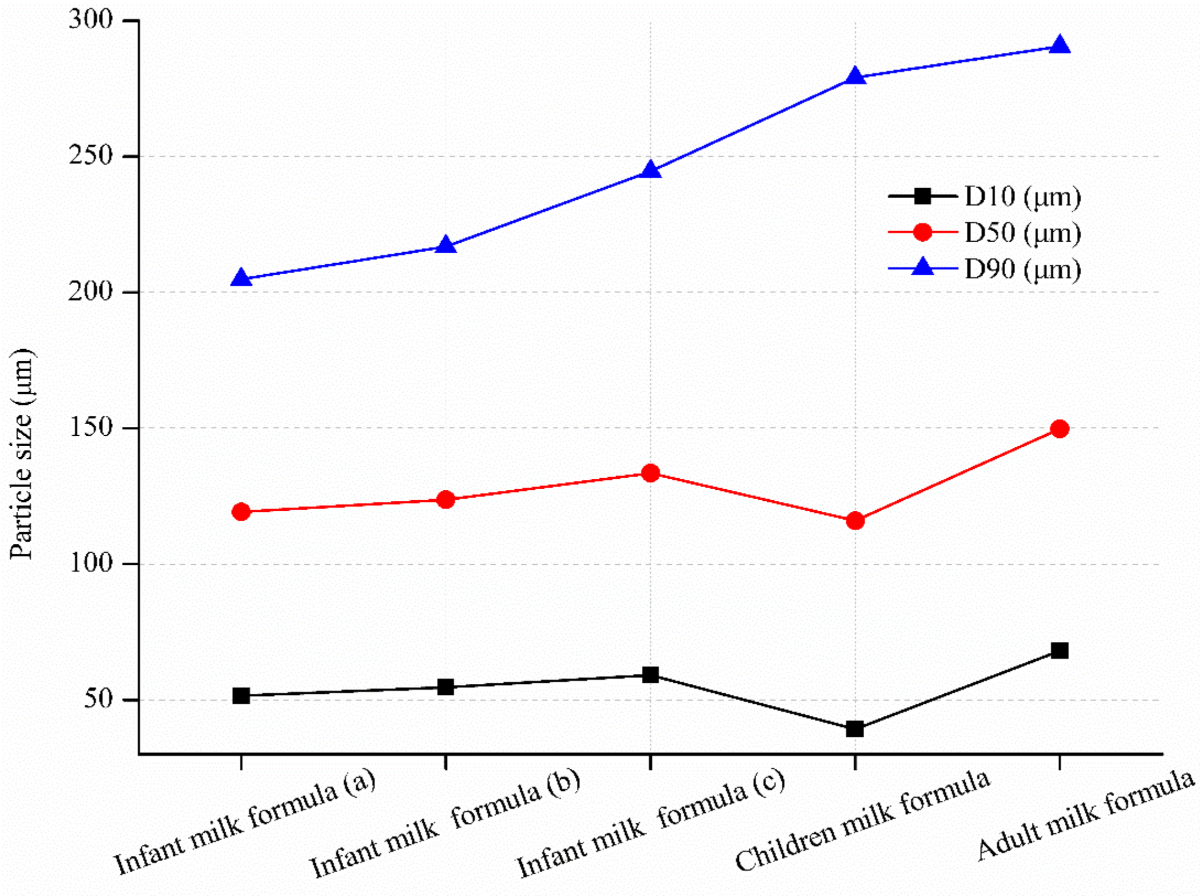

Figure 3: The particle size distribution of infant formula [source: Bettersize Instruments Ltd. (2021)].

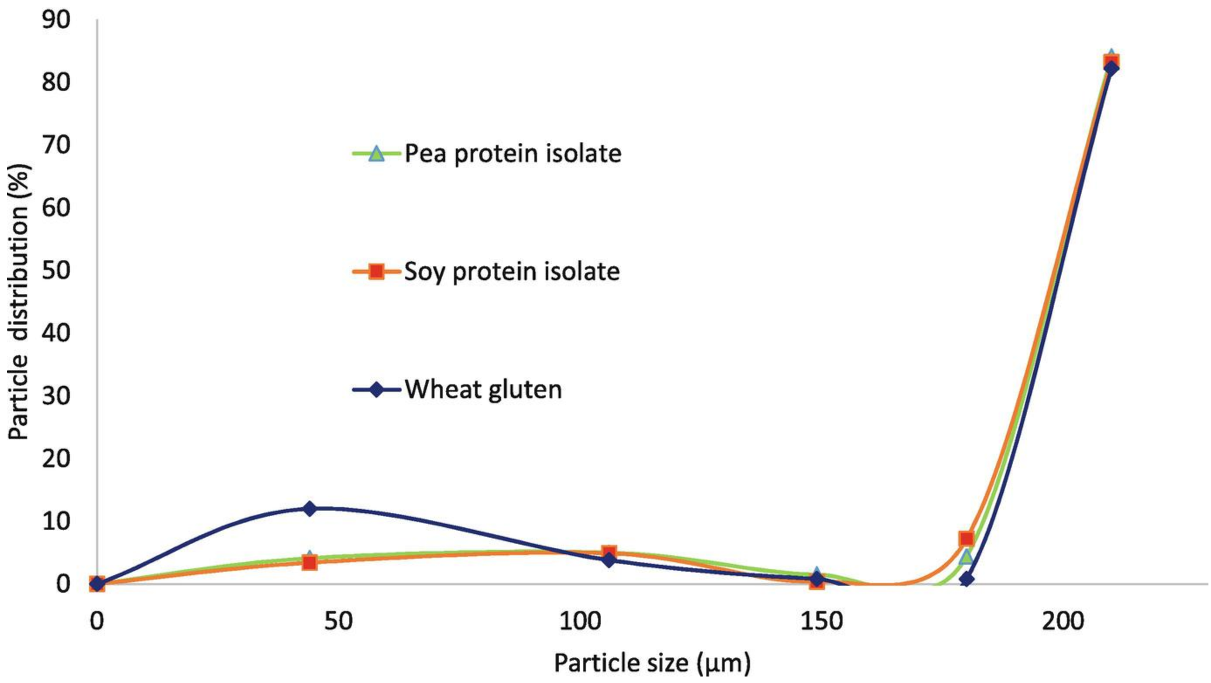

Figure 4: Particle size distribution of protein powders [Nkurikiye et al. (2025)].

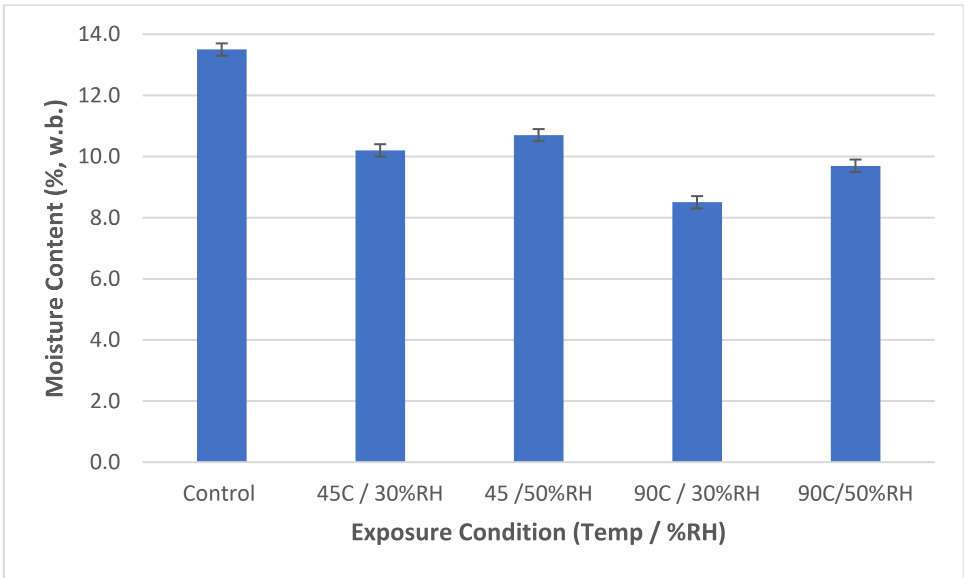

Figure 5. Moisture contents of exposed SW samples

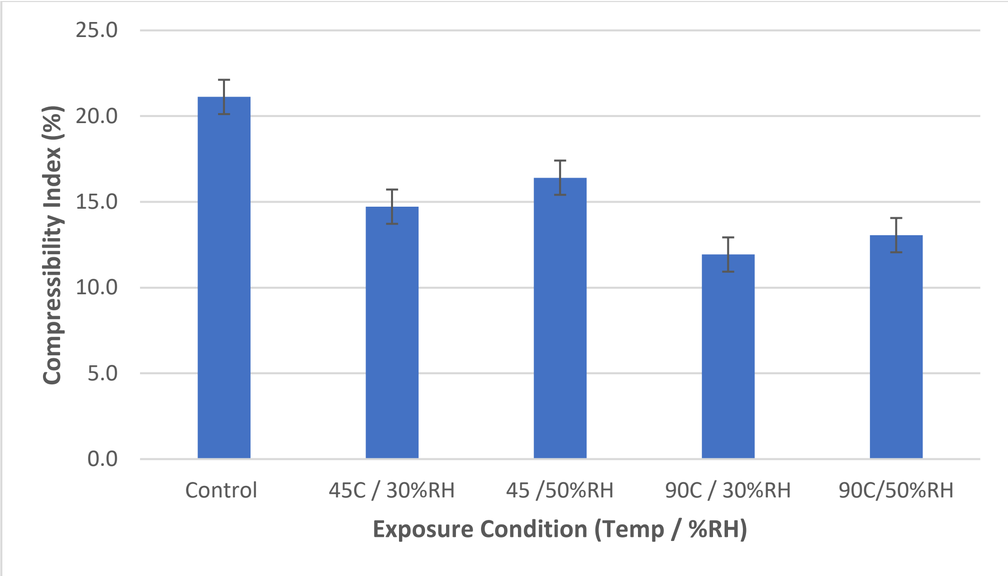

Figure 6. Compressibility indices of exposed SW samples

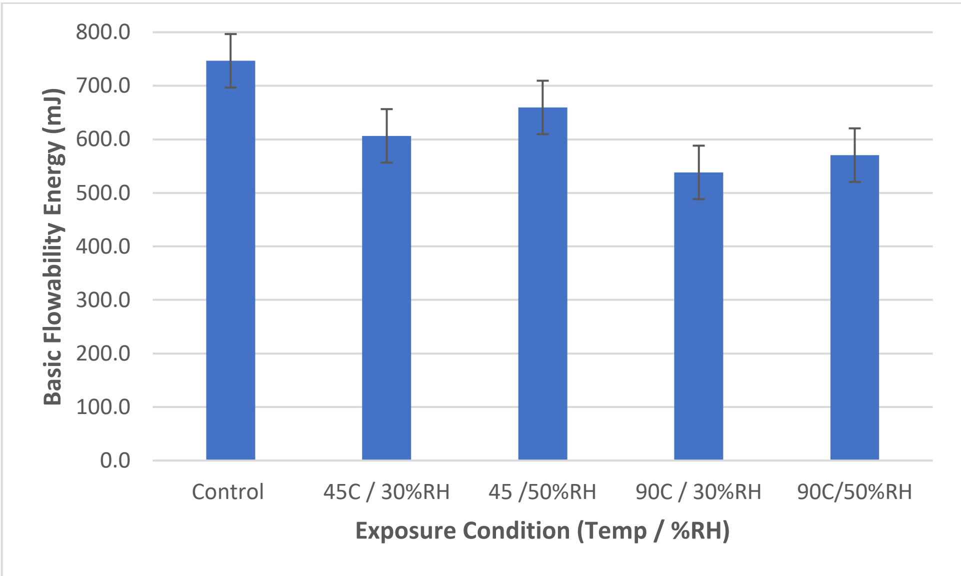

Figure 7. Basic flowability energy (BFE) indices of exposed SW samples

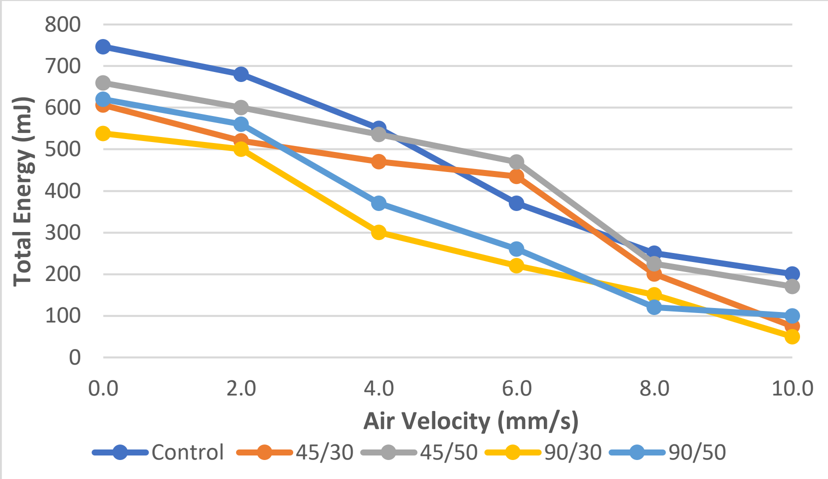

Figure 8. Aeration characteristics of the exposed SW samples

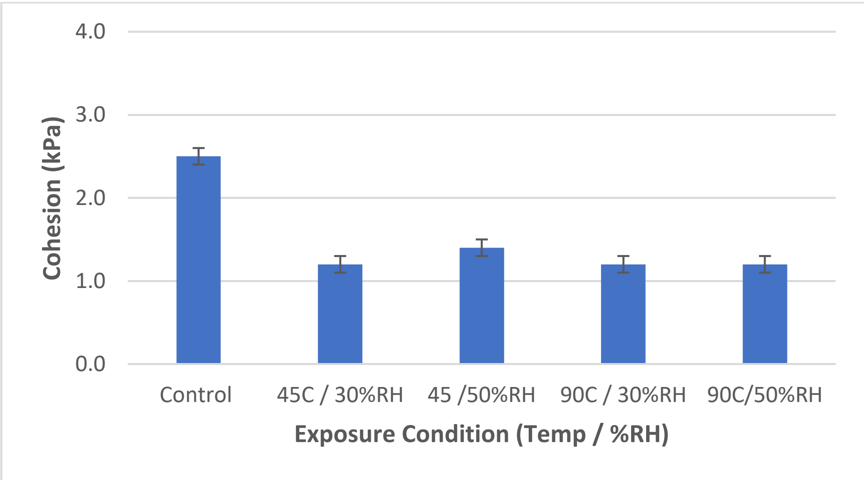

Figure 9. Cohesion of the exposed SW samples

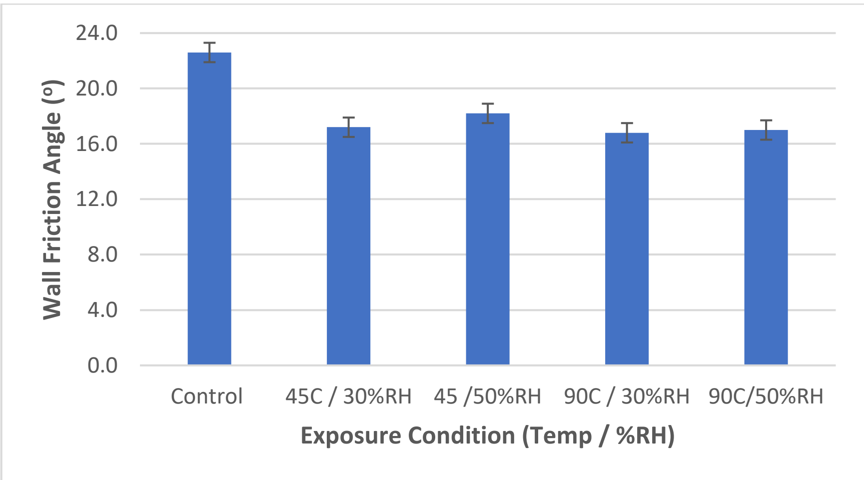

Figure 10. Wall friction angle of the exposed SW samples against stainless steel surfaces

Flowchart for coating preparation and application