

Whey Protein–Starch Coating to Improve Flowability and Reduce Powder Build-Up in Food Powder Processing Systems

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Objective:

To apply a whey protein–starch–based matrix as a coating for food-powder packaging and processing equipment to improve powder flowability, reduce interior surface powder accumulation, and enhance overall equipment sanitation.

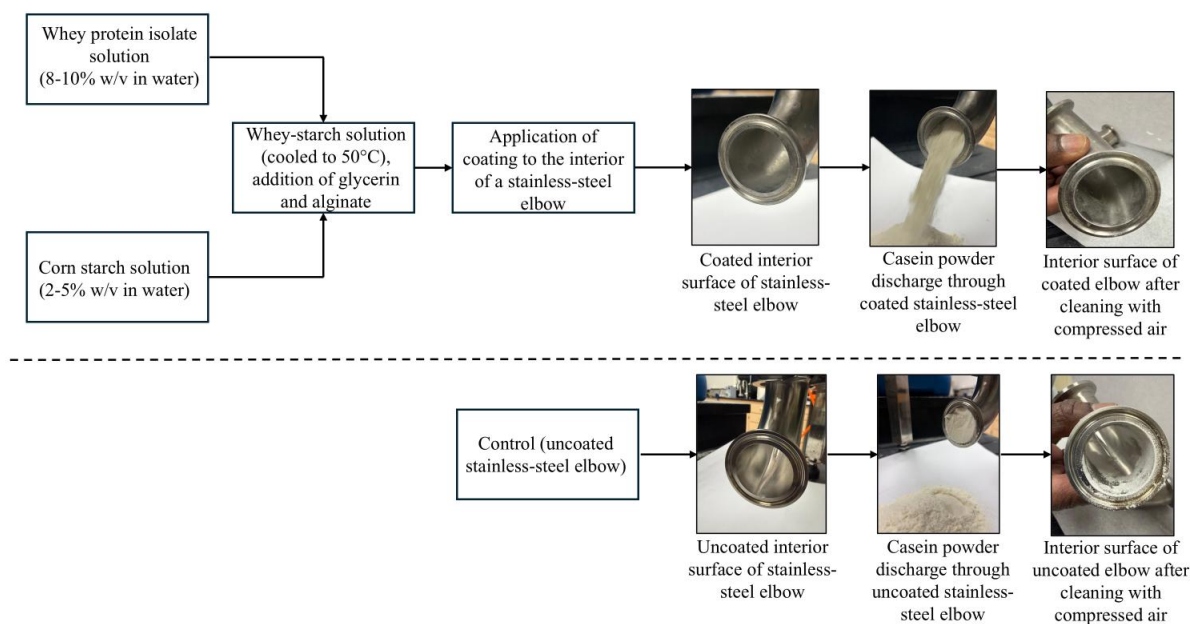


Figure 1. Illustration of the proof-of-concept study for whey protein–starch coating designed to improve flowability and reduce powder build-up in food powder processing systems.

1. Basis and justification for the proposed proof-of-concept study

We have developed a whey-protein–starch–based matrix as a coating for food-powder packaging and processing equipment to improve powder flowability, reduce interior surface powder accumulation, and enhance overall equipment sanitation. The whey-protein–starch coating is formulated to form a thin, continuous, and uniform layer on interior stainless-steel surfaces, including pipelines, storage vessels, sifters, cyclone dryers, hammer mills, and selected packaging components. The coating on the interior surface is engineered to improve powder flowability and minimize unwanted buildup, and it functions solely as a surface modification of interior components without altering or compromising the structural elements or geometric configuration of the processing system.

Our approach is aligned with the **3-A Sanitary Standard for General Requirements (ANSI/3-A 00-01-2018)**. The 3-A framework **defines** cleanability as the suitability of materials, design, and

fabrication to ensure that equipment can be freed of soil (C4) and includes specific provisions for coatings and surface treatments (C35 and E3). In accordance with these principles, the coating is formulated from food-grade, nontoxic materials intended for product-contact surfaces and designed to be removable under appropriate cleaning conditions. For example, the food grade whey-protein–starch–based coating solution can be pumped through the targeted pipeline sections or components, allowing it to cover all interior surfaces. Forced heated air can then be supplied to dry the coating and ensure proper adhesion to the stainless-steel surfaces. This approach is intended to prevent surface discontinuities and promote a uniform internal coating, helping ensure that the coating does not interfere with hygienic design and sanitation requirements. The coating will remain fully inspectable either visually or with a micro-camera when needed, and it will not interfere with Clean-in-Place (CIP) capability where applicable.

Based on preliminary observations, the coating is expected to maintain its functional integrity under dry-powder processing conditions for approximately one week. After this period, it can be intentionally removed using standard alkaline cleaning procedures and subsequently reapplied as part of a scheduled sanitation or preventive-maintenance cycle. This periodic renewal strategy is designed to ensure consistent surface performance while maintaining effective sanitation.

Because the coating solution contains whey protein, which is classified as a milk allergen under the U.S. labeling regulations, its use is intended primarily for dairy-powder processing environments where milk is already a declared allergen. Therefore, the coating does not introduce a new allergen category into the system. In facilities that handle multiple product types, however, allergen verification testing will still be required. As an additional safeguard, amino acid composition analysis of the coating matrix and final products can be used to confirm whether any components of the coating matrix, particularly proteins, have migrated into the finished product.

From a regulatory perspective, coatings applied to food-contact equipment are classified as indirect food additives under the U.S. regulations. Commercial implementation of the proposed coating may therefore require submission of a Food Contact Substance Notification (FCN) to the U.S. Food and Drug Administration (FDA), including migration testing and toxicological safety evaluation for the intended conditions of use. At present, this work is presented as a proof-of-concept demonstration within the context of hygienic design innovation, and no FCN submission

has been initiated. Should commercial interest arise, regulatory compliance would be pursued through the appropriate FDA notification pathway prior to industrial application.

2. Background of Dry Powder Processing

Dry-powder processing systems used for products such as whey powder and infant formula often experience clogging or fouling at compressed surfaces, pipe elbows, flanges, and equipment dead zones. Extensive cleaning is required to remove accumulated material from these areas. When residues are not fully removed, sanitary conditions can be compromised, as microorganisms may grow on retained material (Koutsoumanis et al., 2024).

Current dry-cleaning approaches, such as forced air, vacuuming, vibration, and product purging, are often insufficient due to powder adhesion, electrostatic interactions, and the inherent roughness of conventional food-contact materials. Although wet cleaning is generally more effective, frequent use is undesirable in dry-powder facilities because moisture introduces microbial risks and increases downtime (Frabetti et al., 2021; Klug et al., 2024). There is a critical need to improve powder flowability, reduce interior-surface powder accumulation, and enhance overall equipment sanitation without introducing water into the dry-powder processing industry (Karuppuchamy et al., 2024).

We propose a whey-protein–starch–based matrix as a coating for the interior surfaces of dry-powder processing equipment. Our proof-of-concept study demonstrated that this coating matrix can be applied to stainless-steel surfaces, particularly components such as pipe elbows, to improve powder flowability and reduce interior-surface powder accumulation.

Protein-based films and biopolymer coatings have been widely investigated for edible packaging and barrier applications; however, limited information exists regarding their potential use as hygienically compatible surface modifications to mitigate powder accumulation in dry powder processing equipment. In particular, the application of whey protein-starch matrices as functional coatings for stainless-steel surfaces in powder handling systems remains underexplored.

3. Materials and Methods

3.1. Preparation of the coating solution and its application onto the stainless-steel surface of a conical tank's elbow fitting

Whey protein isolate (8% w/v) was dissolved in distilled water and allowed to hydrate under continuous stirring. The solution was subsequently heated to 80 °C for 20 min to induce protein denaturation and promote network formation. In parallel, corn starch (2% w/v) was dispersed in distilled water and heated to its gelatinization temperature (75 °C) under continuous agitation to prevent clumping and ensure homogeneous gelatinization. The gelatinized starch dispersion was then combined with the denatured whey protein solution under controlled mixing conditions to form a homogeneous biopolymer matrix. Upon cooling to approximately 50 °C, glycerin was incorporated at 50% of the total polymer weight to function as a plasticizer and enhance film flexibility. Sodium alginate was subsequently added at concentrations ranging from 2% (w/v) and thoroughly dispersed to improve film-forming properties, viscosity, and structural integrity of the coating matrix. For laboratory-scale evaluation, the resulting coating solution was applied by spraying onto the stainless-steel surface of a conical tank's elbow fitting (**Figure 2**). The coated elbow was dried with hot air at 50 °C until a uniform and continuous coating formed on the interior surface.

3.2. Gravitational-discharge (flowability test) of milk powder on coated stainless-steel surfaces

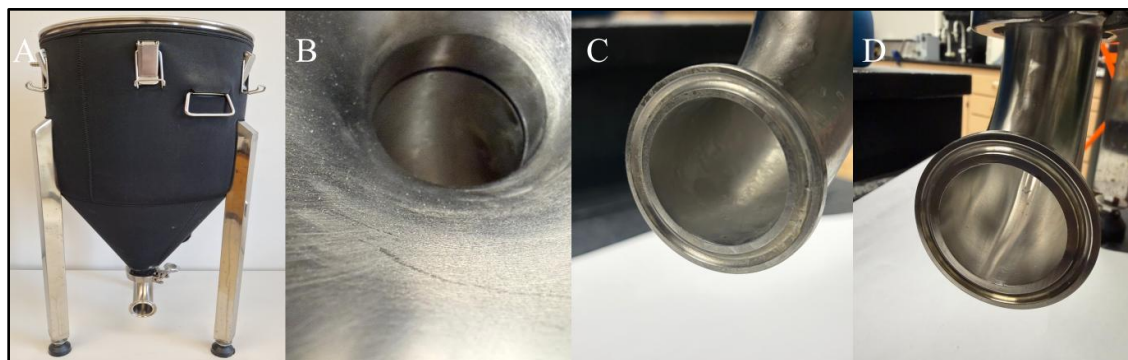


Figure 2. Conical stainless-steel discharge assembly with removable outlet elbow used to simulate dry-powder discharge conditions. A = Conical tank fitted with a 1.5-inch diameter stainless-steel outlet elbow, B = Interior view of the conical tank highlighting the discharge zone and outlet transition area, C = Interior surface of the elbow coated with whey protein–starch matrix, and D = uncoated elbow used as control.

As shown in **Figure 2**, a conical stainless-steel discharge assembly (A and B) equipped with a removable outlet elbow with coating (C) and without coating as control (D) was used to simulate powder discharge conditions representative of hopper transitions and gravity-driven outlet interfaces commonly found in dry powder processing systems.

The whey protein-starch coating was applied exclusively to the internal surface of the stainless-steel discharge elbow, while the remainder of the system remained uncoated. An uncoated stainless-steel elbow served as the control condition. A standardized mass of 1 kg of milk powder was introduced into the conical assembly and allowed discharge under gravity through the outlet elbow. Following powder discharge, compressed air at 40 psi was applied for 10 sec to simulate industrial dry-cleaning practices commonly used in low-moisture facilities. Residual powder accumulation was assessed through visual inspection and photographic documentation, with particular focus on the internal curvature and flange transition of the outlet elbow.

3.3. Removal of the coating from the stainless-steel surface of a conical tank's elbow fitting and cleaning-validation assessment

The removability of the whey protein–starch–alginate coating was evaluated to verify its compatibility with hygienic processing and Clean-In-Place (CIP) requirements. Stainless-steel elbow sections, previously coated and dried as described in Section 3.1, were subjected to a laboratory-scale cleaning protocol designed to simulate industrial alkaline CIP conditions. The coated elbow was rinsed with an alkaline aqueous solution (0.1 M NaOH, approximately pH 13) at 40 °C. The cleaning solution was circulated through the elbow section for 15 min to ensure full internal surface contact. Following alkaline washing, the system was thoroughly rinsed with distilled water to remove residual cleaning solution and solubilized coating material. After cleaning, excess of water was removed from the elbow and visually inspected to assess the presence of any remaining coating. Removal was considered complete when no visible film, residues, or surface irregularities attributable to the coating were observed on the stainless-steel surface.

4. Results and Discussion

4.1. Gravitational-discharge performance (flowability test) of milk powder on coated stainless-steel surfaces

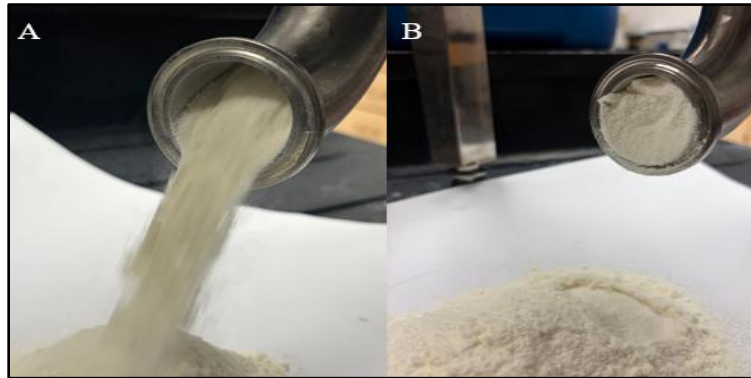


Figure 3. Flow discharge of casein powder through the coated elbow and the uncoated elbow. A = Interior surface of the elbow coated with whey protein–starch matrix, and B = Uncoated elbow used as control.

The coated elbow exhibited improved gravitational discharge without clogging (**Figure 3**), whereas the uncoated elbow showed noticeable clogging. The coated elbow showed noticeably lower residual powder accumulation after compressed-air application compared with the uncoated stainless-steel elbow, which retained a smaller amount of powder along the internal curvature and near the flange interface (**Figure 4**).



Figure 4. Residual after compressed air application of the coated elbow and the uncoated elbow. A = Interior surface of the elbow coated with whey protein–starch matrix, and B = Uncoated elbow used as control.

In contrast, the uncoated elbow exhibited a substantial amount of milk-powder buildup. These observations indicate that localized surface modification using a whey-protein–starch coating at critical transition points, such as elbows, can enhance powder-release efficiency.

The improved powder discharge observed on coated surfaces can be attributed to modifications in surface-particle interactions induced by the whey protein-starch matrix. Powder adhesion to stainless steel is governed by a combination of van der Waals forces, electrostatic interactions, and mechanical interlocking associated with surface roughness and surface energy. Studies have shown that coating can alter surface free energy and frictional behavior, thereby reducing cohesive and adhesive interactions between particles and contact surfaces (Frabetti et al., 2021). The incorporation of polysaccharides such as starch and alginate into protein-based matrices has been shown to improve film uniformity, reduce particle-surface friction, and consequently promote better powder flowability. (Jafari et al., 2020).

4.2. Removal of the coating from the stainless-steel surface of a conical tank’s elbow fitting and cleaning-validation assessment

The whey protein-starch-based coating was completely removed under the applied alkaline washing conditions. After 15 min of circulation with 0.1 M NaOH at 40 °C, followed by water rinsing, no visible coating residues were observed on the internal surface of the stainless-steel elbow. The metallic surface appearance after cleaning was consistent with that of untreated stainless steel. No persistent film fragments or surface irregularities associated with the applied coating were detected. These results indicated that the coating could be effectively removed using standard alkaline washing conditions commonly employed in food processing environments.

5. Conclusions

This proof-of-concept study demonstrated that a whey protein–starch polymer coating can be successfully applied to stainless-steel surfaces and can enhance dry powder release, reduce clogging, and minimize powder build-up within dry powder food processing systems. The coating formed a continuous, uniform film on the internal surface of the stainless-steel elbow and demonstrated improved powder-discharge behavior under simulated processing conditions

compared with the uncoated control. Cleaning validation confirmed that the coating could be fully removed using standard alkaline wash conditions. The absence of visible residues after cleaning indicated that the coating was compatible with hygienic processing and sanitation requirements. Overall, the results suggest that the coating can be used to modify stainless-steel surfaces to reduce powder accumulation in dry-processing environments. Further quantitative evaluation under industrial-scale conditions is needed to validate long-term performance and durability.

Food-based coatings used on equipment surfaces are regulated by the FDA as indirect food additives. If this coating were to advance toward commercial application, it may require a Food Contact Substance Notification (FCN) submission. An FCN is a mandatory pre-market notification that demonstrates the safety of a new substance intended for use in food packaging or food-processing equipment, followed by a 120-day FDA review period.

Future work should include rapid allergen-detection testing on coated surfaces to confirm the absence of detectable milk proteins after application and cleaning, as well as verification that no residual coating remains under dynamic CIP conditions.

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