Gas-Specific Cold Plasma Optimization to Eliminate Powder Hang-Up Points in Food Packaging Equipment

Vianca Tashiguano, Katherine Sofia Sierra, and Telah Black
Auburn University

1. Executive Summary

Dry powder processing systems, including milk powder production, present a persistent hygienic design challenge due to powder retention in geometrically complex areas such as pipe elbows, flanges, gasket interfaces, and dead legs. Conventional dry-cleaning methods, such as compressed air, vacuuming, vibration, and product purges, often fail to achieve complete removal of adhered residues. These retained powders may serve as harborage sites for pathogens such as Salmonella spp. and Cronobacter sakazakii, which are capable of surviving extended periods in low-moisture environments and pose significant public health risks when reintroduced into finished product streams.

This proposal presents an innovative air plasma–assisted dry sanitation strategy designed to enhance cleanability and microbial control within sanitary piping systems. The concept integrates engineered turbulent airflow with plasma-generated reactive oxygen and nitrogen species (RONS) to achieve dual functionality: mechanical powder detachment and microbial inactivation. Flow modelling of a representative 4-inch sanitary pipeline demonstrates that turbulent velocities (10–25 m/s) can generate measurable wall shear stress to promote residue removal, while plasma activation introduces reactive species that may reduce electrostatic adhesion forces and decrease microbial load in non-line-of-sight regions.

The system is designed for integration into scheduled dry-cleaning cycles at critical control points, including dryer discharge, silo transitions, and pre-packaging sections. By maintaining a fully dry process and avoiding liquid chemicals, the approach remains compatible with low-moisture production constraints and 3-A hygienic design principles. Preliminary economic analysis suggests feasible installation costs and potential reductions in labor requirements and contamination risk.

Although further pilot-scale validation is required, this concept establishes a technically grounded and scalable pathway toward transforming conventional dry cleaning into an active, science-driven hygienic intervention for powder processing facilities.

2. Background and Problem Context

Dry powder production facilities, including those manufacturing milk powders, infant formulas, dietary supplements, and other low-moisture ingredients, face a persistent hygienic design challenge: achieving complete removal of product residues from food contact surfaces without introducing moisture. Unlike wet-processing systems, dry operations rely on cleaning strategies such as compressed air, vacuum systems, mechanical vibration, and product purges. While these methods reduce visible accumulation, they frequently fail to eliminate powder trapped in geometrically complex or poorly accessible areas. These microenvironments allow residual material to remain despite routine dry cleaning, creating persistent niches within the processing system.

From a hygienic design perspective, incomplete powder removal is not simply a housekeeping issue; it is a food safety hazard. Low-moisture foods are often perceived as inherently safe because bacterial growth is limited at low water activity. However, this perception is misleading. Several pathogenic microorganisms are capable of surviving extended periods in dry environments, maintaining viability under hot and desiccated conditions typical of powder facilities. Among the most significant are *Salmonella* and *Cronobacter sakazakii*. These organisms can persist in residual powder deposits and await the introduction of moisture through condensation events, wet cleaning procedures, product rehydration, or human consumption to resume metabolic activity and potentially proliferate.

According to the Centers for Disease Control and Prevention (CDC, 2024), *Salmonella* causes approximately 1.35 million infections annually in the United States. The organism is well documented for its ability to survive in low-moisture foods and dry processing environments for weeks to months. Recent outbreak investigations further illustrate this risk: an ongoing outbreak of *Salmonella* infections has been linked to moringa leaf powder used in dietary supplements, demonstrating that shelf-stable dry products remain capable of transmitting foodborne illness when contamination occurs. In 2014, the U.S. Food and Drug Administration conducted a sampling assignment to determine the prevalence of *Cronobacter spp*. and *Salmonella* in facilities manufacturing milk powder. *Cronobacter* was detected in 38 of 55 facilities (69%), indicating widespread environmental presence in dry-processing plants. This high detection rate demonstrates that pathogen persistence in powder environments is common and represents a systemic risk rather than an isolated occurrence (Hayman et al., 2020)

Cronobacter sakazakii has emerged as a critical pathogen associated with neonatal infections. Between 2021 and 2022, *Cronobacter* contamination in infant formula was linked to multiple illnesses in the United States, including two infant deaths, and contributed to large-scale product recalls and formula shortages worldwide. *Cronobacter* infections reported fatality rates ranging from 40% to 80% in cases of invasive disease.

Taken together, this data reveals a critical gap in current dry-cleaning strategies. Therefore, improving the ability to achieve near-complete powder removal through dry methods is not only an operational efficiency objective but fundamentally imperative for food safety.

In this challenge competition, we proposed pump air through the air-cold plasma machine so that the air becomes plasma-activated and can pass through the system. This allows contact with areas that workers cannot reach and clean. Cold plasma is the fourth state of matter that physicists have been able to generate at room temperature. It is essentially a gas energized by an electric field, which partially ionizes the gas and produces reactive oxygen and nitrogen species (RONS), including atomic oxygen, atomic nitrogen, hydroxyl radicals, hydrogen peroxide, and others. After contact with particles and bacteria, these reactive species revert to their stable forms, leaving no chemical residues.

The ions and reactive species generated in air plasma can alter the electrostatic forces on the particles, reduce the attachment force, and facilitate their removal. The air plasma can also kill *Salmonella, Cronobacter*, and other pathogenic bacteria. That is why our technology can improve sanitization in dry environments.

3. Objectives

Develop and validate an air plasma–assisted sanitation approach integrated into powder processing equipment to enhance particulate detachment from low-access geometries, such as pipe elbows, weld seams, gasket interfaces, dead legs, and crevices.

Reduction of *Salmonella* and *Cronobacter sakazakii* in pipelines and equipment using air plasma technology, strengthening preventive controls under Food Safety Modernization Act (FSMA) compliant food safety management systems.

4. Proposed Hygienic Design Solution

Dairy products spoil quickly; however, converting milk into powder extends its shelf life. In powdered form, milk can be stored for approximately one year at ambient temperature without significant degradation in quality. Milk powder production begins with the reception and bulk storage of raw milk, followed by separation and standardization to achieve the desired fat content. The milk is then preheated and pasteurized, typically at 75-120°C, to destroy microorganisms, inactivate enzymes, and improve heat stability. After thermal treatment, the milk undergoes multi-effect vacuum evaporation, increasing total solids from approximately 9–13% to 45–52%, removing more than 85% of the water and reducing the energy required for drying. The concentrated milk is atomized into fine droplets in a spray dryer, where hot air rapidly removes the remaining moisture, producing powder with approximately 6% moisture content. The powder is separated from exhaust air using cyclones and then undergoes secondary drying in fluidized beds to reach a final moisture content of 2–4%. Following drying, the powder is transported via pneumatic conveying systems to intermediate storage hoppers and then to the packaging line, where it is filled into bags or cans, ready for shipment to retailers' centers for human consumption (Figure 1).

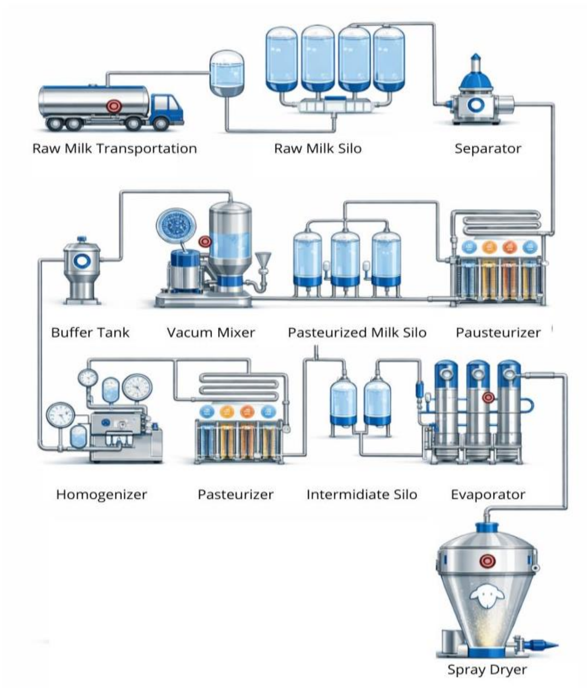

Figure 1. Graphical representation of the standard milk powder production process.

The proposed air plasma cleaning system (Figure 2) shall be designed to effectively remove and loosen adhered dry milk powder residues from critical harborage locations within processing equipment, which may include elbows, tees, reducers, valve seats, or crevices associated with O-rings, gaskets, and mechanical joints where product accumulation commonly occurs. The system shall be capable of reaching non-line-of-sight regions to the greatest extent feasible through directed airflow and plasma delivery, ensuring treatment of geometrically complex internal surfaces such as pipe corners and recessed areas. The intervention must operate entirely as a dry-cleaning method, without water or liquid chemicals, to maintain compatibility with dry milk powder processing environments and prevent moisture-related product caking or microbial growth. In addition, the system should provide repeatable and controlled plasma treatment with defined operating parameters, including exposure time (depending on the size of the pipes and processing plants), plasma power (50W), and airflow (depending on the inch ID pipe, but let's say 4-inch pipe for this proposal), to ensure consistent coverage and cleaning performance. Integrated controls and safety interlocks shall be included to regulate plasma power and airflow rates.

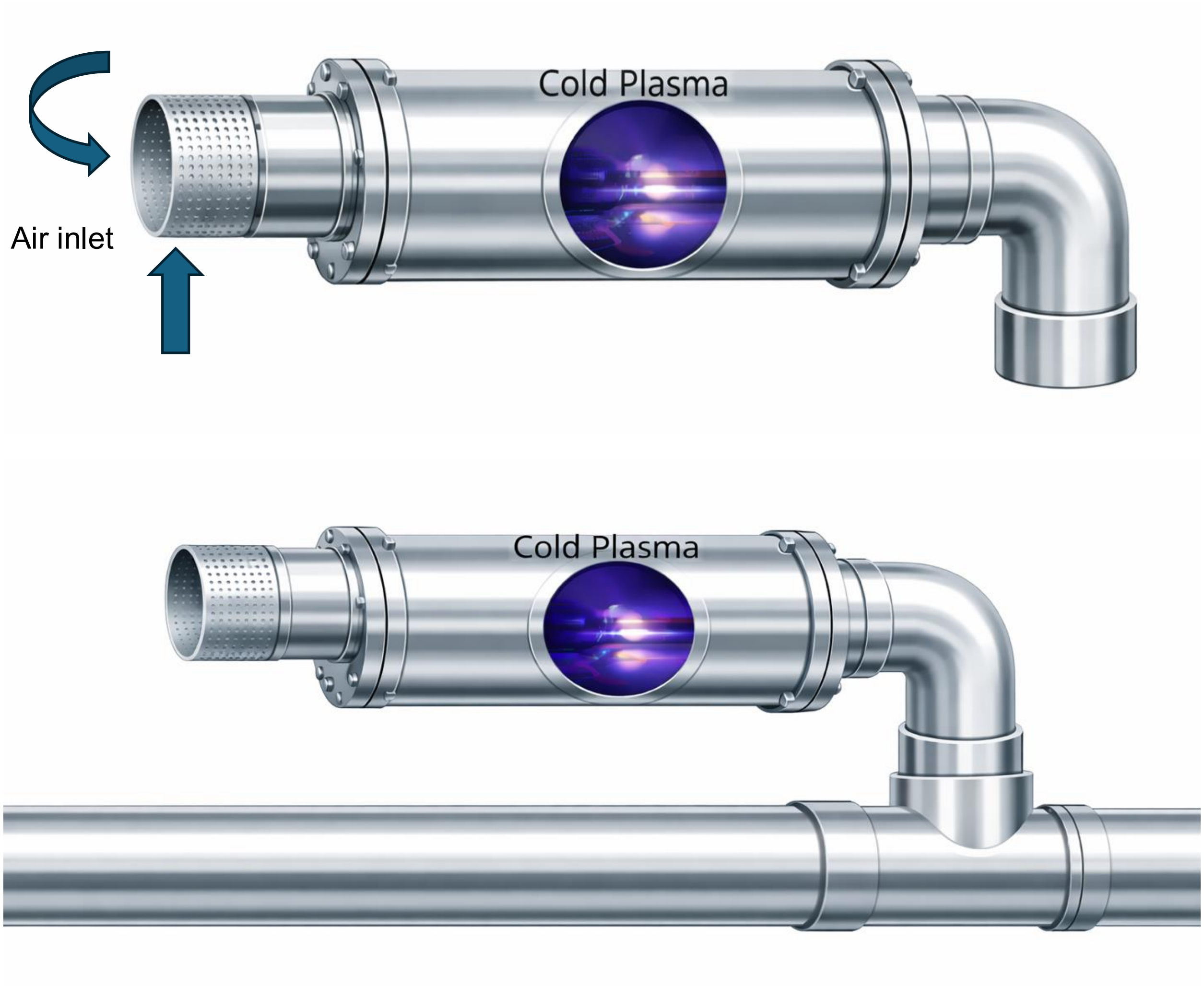

Figure 2. Schematic representation of the atmospheric air plasma unit (Size will depend on the size of the processing plant)

This air plasma unit is recommended to be installed in line, using T tubes for better adaptation in the pipelines. The unit contains filters to prevent the incoming milk powder particles from entering the air.

The locations selected for the atmospheric cold plasma integration inline were chosen based on the critical control points and contamination risks that are most likely to occur during dry processing. We focused on transition points, including the discharge before the spray dryer, after the fluid bed, after the storage silo and right before packaging pipes. These areas experience changes in airflow direction and velocity, which increase electrostatic charge and make fine milk powder more likely to adhere to stainless steel surfaces, but with the air plasma, particles will reduce the attachment force, and facilitate their removal, thus improving the food safety.

In addition, we considered that the facility may operate with two different packaging systems, can filling (Figure 3) and bag filling (Figure 4), so positioning the plasma upstream ensures that both lines receive treated powder without requiring separate intervention at each packaging machine. This approach allows effective control while maintaining the integrity of the dry process and minimizing modifications to existing equipment.

4.1 Cold plasma integration scenarios

The cold plasma system can be installed in different ways depending on the manufacturer's needs, the size of the operation, the level of risk, and even the available budget. In our proposal, plasma is not used during production but is part of the dry sanitization step. The units would operate during scheduled cleaning times or between production runs, treating equipment surfaces and internal conveying sections where powder residue may still remain after standard dry cleaning.

If only one plasma unit is used, the most practical location would be just before the packaging equipment. This area often has powder buildup and is the last point before the product enters bags or cans. During sanitization, the plasma would treat the inside of the conveying line and the filler inlet, helping reduce microbial presence and lower the electrostatic charge that causes powder to stick.

With two plasma units, one could be installed near the dryer discharge or fluid bed outlet, and the second before packaging. This setup allows treatment of both an upstream residue-prone area and the final packaging transition point. It is especially useful in facilities that run both bag-filling and can-filling.

If three or four units are installed, they would be placed at key transition points: at the cyclone discharge, near the storage silo or silo outlet, and just before packaging. This setup provides broader coverage of the dry system, focusing on areas where powder tends to accumulate due to flow changes and electrostatic effects. It offers the most complete level of protection and may be better suited for high-sensitivity products or facilities with long production cycles.

In terms of microbial performance, the air plasma system shall demonstrate a measurable reduction in microbial risk associated with dry milk powder residues. Based on prior laboratory studies and known RONS antimicrobial mechanisms, the system is designed to target a 2–7 $\log_{10}$ reduction, pending pilot-scale validation of selected microbial surrogates or relevant pathogens on dry milk residues present on stainless steel surfaces representative of processing equipment, including both flat coupons and pilot-scale pipe sections. This level of reduction will confirm the system's ability to not only remove product buildup but also reduce the microbial load associated with residual powders in harborage locations, thereby contributing to improved hygienic conditions and reduced risk of contamination during dry milk processing operations.

Figure 3. Standard milk powder production process with an integrated canning packaging line.

Figure 4. Standard milk powder production process with an integrated bag packaging line.

4.2 Flow Engineering Modelling (Estimation)

For a 4-inch ID sanitary pipe, turbulence begins at approximately 0.6 m/s ($Re \approx 4000$), so typical purge/cleaning velocities of 10–25 m/s remain fully turbulent and generate meaningful wall shear stress (≈0.3–1.5 Pa), supporting powder detachment in elbows, crevices, and gasket interfaces. These velocities correspond to approximately 172–429 CFM. Residence time scales inversely with velocity (e.g., 0.05–0.10 s per meter at 10–20 m/s), motivating a two-step sanitation cycle that combines a high-velocity scouring pulse for residue lift-off with a lower-velocity dwell phase to increase reactive species contact time for microbial inactivation. Pressure drop across 10 m of straight pipe is estimated at ~116–578 Pa (plus minor losses), which will be used to select a blower capable of delivering the target CFM at the required static pressure (Munson et al., 2017). All these numbers will depend on the length of the pipe and how big the processing plant is.

5. Justification

Air cold plasma is a technology developed by physicists, which can be used to eliminate harmful bacteria like LM on processing surfaces (Von & Schulz-Von, 2017). Cold Plasma is being investigated in different fields of medicine, biology, pharmaceuticals, agriculture, and food safety (Domonkos et al., 2021). Cold Plasma is created by applying electrical power to any novel gas to produce a mixture of ions, electrons, and neutrals (Von & Schulz-Von, 2017). They become partly or fully ionized. Cold Plasma generates a variety of reactive oxygen and nitrogen species (RONS), including hydroxyl radicals, superoxide anions, and singlet oxygen. These RONS can damage bacterial DNA, proteins, and lipids, leading to cell death (Khosravi et al., 2021).

This system would integrate a high-velocity air pump with plasma-generated ions, specifically reactive species (RONS), to facilitate the removal of residual milk powder particles from equipment surfaces while simultaneously inactivating bacteria trapped within these areas.

This technology is user-friendly, non-thermal, and non-chemical, offering a promising solution for the dry powder industry facing the concerns described above. Unlike conventional dry cleaning approaches, plasma treatment generates reactive species that actively inactivate microorganisms rather than relying solely on mechanical removal. By producing reactive ions within the system, we ensure microbial reduction directly at the surface level, which may enhance product safety, potentially extend shelf life, and reduce the likelihood of pathogen carryover into subsequent production batches.

In the following section, we present several projects conducted in our laboratory demonstrating the effectiveness of air plasma in reducing bacterial populations in dry foods and on food contact surfaces.

6. Previous Research Projects

6.1 Project 1: Application of Cold Plasma to Eliminate *Cronobacter sakazakii* in Full-Fat Milk Powder

A study was conducted in our lab, using cold plasma with argon gas to reduce the *Cronobacter sakazakii* in milk powder. The results showed that cold plasma was reduced by 1 log after 15 minutes of treatment. Results indicate that some pathogen cells are injured during the process

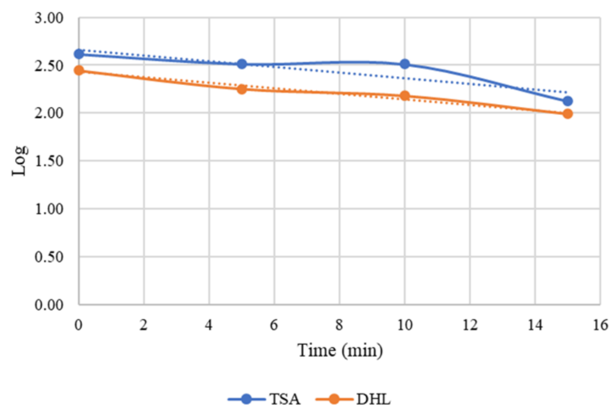

Figure 1. Reduction of *Cronobacter sakazakii* using Oxygen when exposed to cold temperature plasma for 0, 5, 10, and 15 min and spread plated on selective media (DHL) and general-purpose media (TSA).

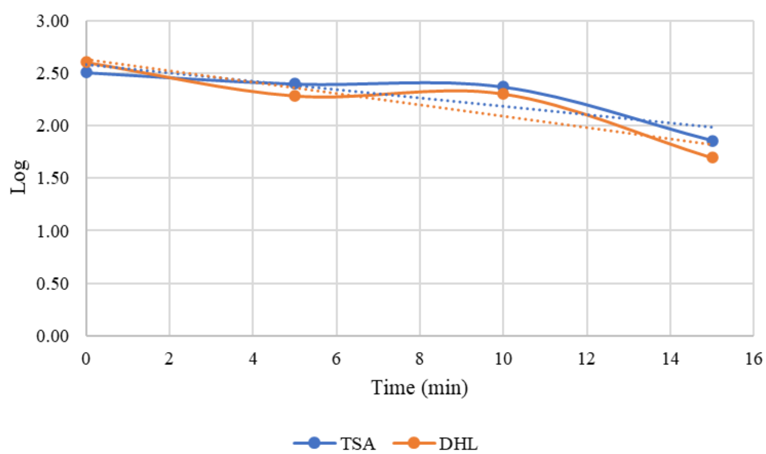

Figure 2. Reduction of *Cronobacter sakazakii* using Argon when exposed to cold temperature plasma for 0, 5, 10, and 15 min and spread plated on selective media (DHL) and general-purpose media (TSA).

.

6.2 Project 2: Reduction of *Salmonella* Enteritidis, Nalidixic Acid–Resistant *Salmonella* Heidelberg, and *Salmonella* Typhimurium on Chicken and *Listeria monocytogenes* on common processing surfaces using Cold Plasma

First, *L. monocytogenes* (6 log CFU/cm²) was inoculated on neoprene, conveyor belt, and stainless-steel coupons and exposed to helium-generated plasma for 0, 10, or 20 minutes at 5.75 kW. Significant reductions ($p < 0.05$) were observed on neoprene (1–2 log after 10–20 min) and on conveyor belt and stainless steel (2 log after 20 min). Second, chicken skin coupons inoculated with *Salmonella* Enteritidis, *Salmonella* Heidelberg, or *Salmonella* Typhimurium (~4 log CFU/cm²) were treated with cold plasma for 0, 10, or 20 minutes under helium, hydrogen peroxide (H_2O_2), or combined conditions. Cold-Plasma at 5.75 kV + H_2O_2 achieved the greatest reductions (up to >2 log), while helium or H_2O_2 alone had minimal effects. Notably, Cold Plasma without H_2O_2 at 5.75 kV still reduced *S.* Enteritidis by 2.46 log after 20 minutes. Together, these results demonstrate the strong antimicrobial potential of cold plasma against both Gram-positive and Gram-negative pathogens on food-contact surfaces and poultry products.

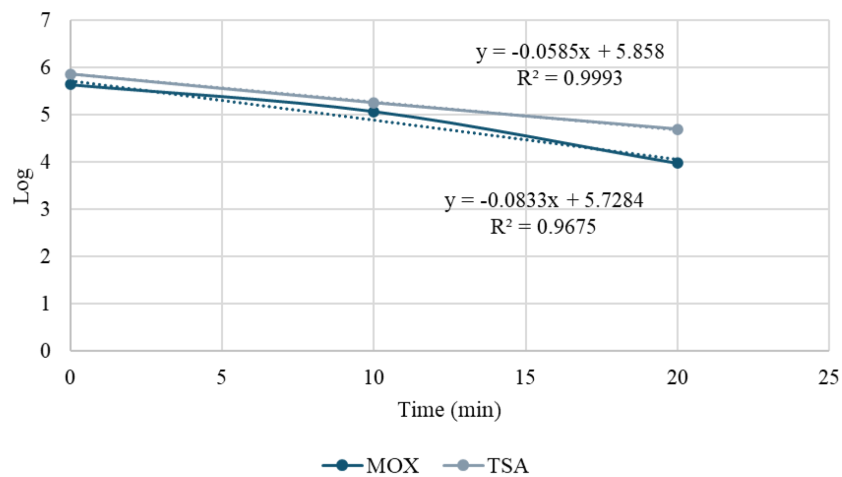

Figure 3**.** Reduction of *Listeria monocytogenes* on stainless steel surface using RT-Plasma, with two different media types: Modified Oxford Agar (MOX) and Trypticase Soy Agar (TSA). Significant differences in reduction were observed ($P < 0.05$) after 10 and 20 minutes of exposure.

7. Economic and Industrial Feasibility/Sustainability

7.1 Savings for the company after air plasma installation:

The economic feasibility of implementing an air plasma dry-cleaning system in dry milk powder processing facilities is supported by projected reductions in labor, production downtime, and contamination-related financial risk. In a typical dry milk powder processing facility, manual dry cleaning and partial equipment disassembly of critical piping sections, including elbows, valves, and crevices, may require approximately 65-115 minutes of labor per cleaning event, often performed multiple times per week. Assuming an average labor rate of $18.50-20.00 per hour and there are two sanitation personnel per cleaning event, the labor cost per cleaning cycle ranges from approximately $40 to $77 per event. If cleaning occurs three times per week, the annual labor cost associated with manual residue removal may range from approximately $6,000 to $11,550 per processing line. The proposed air plasma system has the potential to reduce manual intervention time by 40-60%, resulting in an estimated annual labor savings of $2,400 to $6,930 per line, while also improving sanitation efficiency and reducing worker fatigue.

Perhaps the most critical economic benefit is the reduction in microbial contamination risk, which can lead to costly product recalls, regulatory enforcement actions, and brand damage. Dairy product recalls related to pathogen contamination can cost manufacturers between $1 million and $10 million per event when considering product disposal, lost sales, regulatory penalties, and corrective actions. By reducing microbial harborage and achieving a target microbial reduction of the air plasma system may significantly lower the probability of contamination events. Even a small reduction in recall risk represents substantial financial protection and improves overall process reliability.

Category	Estimated Annual Savings
Labor reduction	$2,400 – $6,930
Recall risk reduction	$1M–$10M risk mitigation (event-based)

7.2 Cost for air plasma installation:

Air Plasma System Parameters

• Voltage: 120 V

• Current: 0.2 A

• Total power: 50 W (~0.05 kW)

If milk powder companies decide to implement air plasma systems for sanitization within their processing lines, the total cost will depend on the number of machines installed. Our proposed approach includes the implementation of four plasma units distributed throughout the production line to ensure effective sanitation coverage at critical points.

The estimated cost per air plasma machine ranges from $20,000 to $30,000. Therefore, the total initial investment for four units would be approximately $80,000–$120,000.

To integrate the air plasma machines into existing piping systems, Tri-Clamp T fittings can be installed. Each fitting cost approximately $40. For four installations, the total additional cost would be $160.

Electricity Consumption and Operating Cost

Each unit operates at 120 V and 0.2 A, with a total power consumption of approximately 0.05 kW.

According to the U.S. Energy Information Administration (EIA), the cost of electricity ranges from $0.813–0.853 per hour. If the air plasma system operates for 0.5 hours per day, the estimated energy usage and cost are as follows:

• Daily consumption: 0.020 kWh

• Weekly consumption: ~0.10 kWh

• Monthly consumption: ~0.40 kWh

• Annual consumption: ~4.9 kWh

Based on these values, the operational electricity cost remains minimal compared to the initial capital investment, making the technology economically feasible for long-term implementation in dry powder processing facilities. And these numbers will vary based on how many machines will be installed on the processing lines. (Based on different scenarios in section 4.1).

8. Conclusion

The proposed air plasma–assisted dry sanitation system introduces a scientifically grounded approach that integrates fluid dynamics and plasma chemistry to enhance cleanability in dry processing equipment. By combining turbulent airflow with reactive oxygen and nitrogen species (RONS), the system is designed to (1) reduce particle–surface adhesion forces, (2) facilitate powder detachment in non-line-of-sight regions, and (3) reduce microbial load on residual dry milk powder deposits. The engineering modeling demonstrates that, within a 4-inch sanitary pipe, turbulent flow conditions and measurable wall shear stress can be achieved at practical airflow rates, supporting mechanical powder removal while maintaining compatibility with dry-processing constraints.

Although this proposal represents a conceptual hygienic design enhancement rather than a commercially deployed system, it provides a technically feasible and economically justifiable framework for improving dry sanitation performance. The integration of plasma technology into scheduled dry-cleaning cycles has the potential to strengthen preventive controls under FSMA-compliant food safety management systems while maintaining the integrity of low-moisture processing environments.

9. Limitations and Future Work

The proposed system has not yet been validated in a continuous milk powder pneumatic conveying system. Pilot studies in a milk processing facility need to be done.

Studies and calculations based on each processing plants needs to be done before implementation.

9. References

- Centers for Disease Control and Prevention. (2024). Salmonella. U.S. Department of Health and Human Services. https://www.cdc.gov/salmonella/about/index.html
- Domonkos, M., Tichá, P., Trejbal, J., & Demo, P. (2021). Applications of cold atmospheric pressure plasma technology in medicine, agriculture and food industry. Applied Sciences, 11(11), 4809.
- Hayman MM, Edelson-Mammel SG, Carter PJ, Chen YI, Metz M, Sheehan JF, Tall BD, Thompson CJ, Smoot LA. Prevalence of Cronobacter spp. and Salmonella in Milk Powder Manufacturing Facilities in the United States. J Food Prot. 2020 Oct 1;83(10):1685-1692. doi: 10.4315/JFP-20-047
- Khosravi, S., Jafari, S., Zamani, H., & Nilkar, M. (2021). Inactivation of Staphylococcus aureus and Escherichia coli Biofilms by Air-Based Atmospheric-Pressure DBD Plasma. Appl Biochem Biotechnol, 193(11), 3641-3650. https://doi.org/10.1007/s12010-021-03636-3
- Munson, B. R., Okiishi, T. H., Huebsch, W. W., & Rothmayer, A. P. (2017). Fundamentals of fluid mechanics (8th ed.). Wiley. https://www.wiley.com/en-us/Munson%2C+Young+and+Okiishi's+Fundamentals+of+Fluid+Mechanics%2C+8th+Edition-p-9781119722236
- U.S. Energy Information Administration. (2024). Electric power monthly: Average retail price of electricity. https://www.eia.gov/electricity/monthly/
- Von, A., & Schulz-Von, V. (2017). Foundations of low-temperature plasma physics—an introduction. Plasma Sources Science and Technology, 26(11), 113001.