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INNOVATIVE TECHNOLOGY FOR THE INACTIVATION OF ALLERGENIC COMPOUNDS ON COMPONENT SURFACES OF A PROTOTYPE PROCESSING LINE FOR THE MANUFACTURE OF PRODUCTS WITH CONTROLLED ALLERGENICITY

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ABSTRACT

The study aimed to develop and validate effective procedures for cleaning and allergen deactivation in a prototype processing line for crisp-coated meat products. Reliable cleaning methods are critical for ensuring food safety and preventing cross-contamination when conventional

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ABSTRACT

and allergen-controlled products are manufactured on the same line. Critical points along the processing line were identified through preliminary assessments. At these points, allergen residues were monitored using immunoassay-based tests targeting major food allergens, including gluten, soy, milk, nuts, sesame, and others. Several cleaning procedures were compared with regard to their ability to eliminate allergenic proteins from equipment surfaces. Lower-concentration protocols proved inadequate, particularly in high-risk areas such as cutting, mixing, and cooling zones. In contrast, the optimized procedure achieved complete removal of allergens at all critical points. This outcome was further confirmed during validation trials involving thirty pilot production batches, where no allergenic proteins were detected in environmental swabs or final products. The results demonstrate that carefully designed cleaning strategies can enable dual use of processing lines for both standard and allergen-controlled products. The validated procedure offers a cost-effective and practical solution for the food industry, supporting compliance with regulatory requirements and improved consumer safety.

Introduction

In the food processing industry, the application of effective cleaning and disinfection methods for components of processing lines is a key factor in ensuring food safety. The primary objective of cleaning procedures is the removal of microbiological, physical, and chemical hazards. One of the critical challenges associated with the innovative cleaning process (constituting an integral stage of the Project no. POIR.01.01.01-00-0130/18) is the effective inactivation of allergenic compounds on the surfaces of equipment components within the prototype processing line designed for the manufacture of meat products with a crispy coating. The process developed as part of this research enables the production of crispy-coated poultry-based products that meet defined criteria for controlled levels of allergenic compounds.

Cleaning refers to the removal of visible contaminants and soils of biological origin, with the aim of achieving visual cleanliness and mechanically removing bacteria and fungi or depriving them of their nutrient sources. Disinfection, in turn, refers to the destruction of pathogenic microorganisms and the reduction of their numbers to levels at which the cleaned object can no longer serve as a source of infection (Agüeria et al., 2021; Maes et al., 2019). Failure to maintain adequate hygiene may result in violations of regulations and standards, as well as increased operational costs associated with product recalls or corrective actions (Alzubeidi et al., 2018; Bakke, 2022; Obe et al., 2020).

When dealing with allergenic substances, maintaining cleanliness presents additional challenges. Operating a production line exclusively for the preparation of food products with controlled allergenicity significantly increases production costs and limits the range of such products. From an economic perspective, a more rational approach involves the shared use of processing lines for both conventional and controlled-allergenicity products, applying the principle of temporal separation. The type of surface material used in the construction of the processing line has a major impact on the efficiency of allergen compound inactivation. Therefore, there is a clear need to develop cleaning and disinfection technologies capable of

eliminating allergenic residues. Effective allergen inactivation requires the use of specialized agents-often costly-and multiple cleaning cycles, which extend processing time (Chen et al., 2022; Fabiola Ayres Cacciatore and da Silva Malheiros, 2021; Falcó et al., 2019; Katsigiannis et al., 2021; Tóth et al., 2024).

Cleaning time, the chemical agents used, mechanical action, and high temperature are the primary factors determining the success of allergen removal. Common cleaning agents include surfactants, acids, alkalis, and both water-soluble and water-insoluble solvents. The most frequently used cleaning techniques are: manual cleaning - removing soils from surfaces, equipment, and utensils using detergents and water; cleaning-in-place (CIP); cleaning-out-of-place (COP) - involving the disassembly of components that are difficult to access for cleaning, followed by washing in special washers or immersion in detergents and water; steam sterilization; and ultrasonic cleaning. The latter two methods are particularly effective for removing persistent contaminants (Delhalle et al., 2020; İpek and Demirel Zorba, 2018; Pant et al., 2023; Thilina, 2022; Tirpanci Sivri et al., 2023). In meat processing, CIP technology is applied for cleaning machinery, pipelines, and conveyor systems. Automation of cleaning processes ensures consistent hygiene while reducing time and labor costs compared to manual cleaning and equipment disassembly (Karuppuchamy et al., 2024).

Modern solutions that can improve the effectiveness and efficiency of cleaning include ozonation, closed water-loop systems, remote control, and low-energy technologies. Closed-loop water systems reduce water and detergent consumption, offering both economic and environmental benefits. Remote control allows precise monitoring and management of cleaning operations, improving efficiency and minimizing personnel involvement. Ozonation reduces the need for chemical agents, lowering environmental impact (Avila-Sierra et al., 2021; Canut and Pascual, 2008; Le Gentil et al., 2010).

Cleaning and disinfection processes are particularly important in the context of allergens. According to Regulation (EU) No. 1169/2011 of the European Parliament and of the Council, food business operators are required to declare the presence of allergenic substances in their products, including: cereals containing gluten, crustaceans, eggs, fish, peanuts, soybeans, milk, tree nuts, celery, mustard, sesame seeds, lupin, molluscs and their derivatives, as well as sulphur dioxide and sulphites. In cases where cross-contamination with allergens may occur during production—for example, due to shared equipment—manufacturers must indicate this risk on product labels (European Parliament, 2011). This information is essential for consumers with food allergies. Exposure to allergens can cause reactions ranging from mild symptoms to severe effects, including gastrointestinal, respiratory, and cardiovascular disturbances, potentially leading to anaphylactic shock (Kryuchenko et al., 2022; Seth et al., 2020).

Cross-contamination is often the result of producing different product variants on the same processing lines. Technologically, contamination can occur at various stages, such as carcass cutting, marination, breading, frying, baking, or internal transport (Michelsen-Huisman et al., 2018; Spychaj et al., 2018). Therefore, maintaining cleanliness requires careful planning of cleaning and disinfection operations for the entire processing line. The choice of detergents and cleaning agents is crucial for effective allergen removal. Their efficiency depends on parameters such as temperature and pH. Detergents work by removing and degrading allergens, often through enzymatic components—particularly important for difficult-to-remove allergens such as gluten and casein. They may also exhibit emulsifying properties, enabling the removal of allergens bound to fats and lipids (Falcomer et al., 2020; Herrera-Márquez et al., 2020).

Regular monitoring and verification of cleaning processes are essential to ensure that they are properly configured and adapted to changing production conditions. Monitoring enables continuous assessment of process performance through parameters such as time, pressure, temperature, and detergent quantity. It also allows early identification of potential problems-such as equipment failures or improper use of detergents and supports optimization of efficiency, resource savings, and process duration. Allergen tests are a key part of monitoring cleaning effectiveness, confirming that allergen removal is achieved. These include lateral flow devices (LFDs), enzyme-linked immunosorbent assays (ELISA), and polymerase chain reaction (PCR) tests. LFDs offer simplicity and rapid results by indicating the presence of allergens via color change. ELISA is a more advanced and sensitive method, capable of detecting even trace amounts of allergens through an enzymatic reaction (Do et al., 2019; Pachołek et al., 2018; Shelver et al., 2021).

The main ingredient in cleaning agents is water (approx. 90%). In contrast, the other ingredients can be divided into physically active ingredients and chemically active ingredients (Figure 1). Physically active ingredients are designed to change the physical properties of contaminants, increasing their solubility (change in colloidal stability, emulsification, dispersion, moisturising, etc.). Chemically active ingredients react with the components of contaminants to form water-soluble compounds that can be removed. Physically active ingredients are called surfactants. Their molecules consist of a hydrophobic and a hydrophilic part, the ratio of which affects the molecule's properties. The polar part affects hydrogen bonds in water, therefore reducing its surface tension. This allows the surface of the contaminants to be moistened and, therefore, facilitates their removal. Surfactants are characterised by their ability to form micelles, making the removal of oil-like contaminants possible. Depending on the ionic charge in the solution, these substances are classified as anionic, cationic and non-ionic.

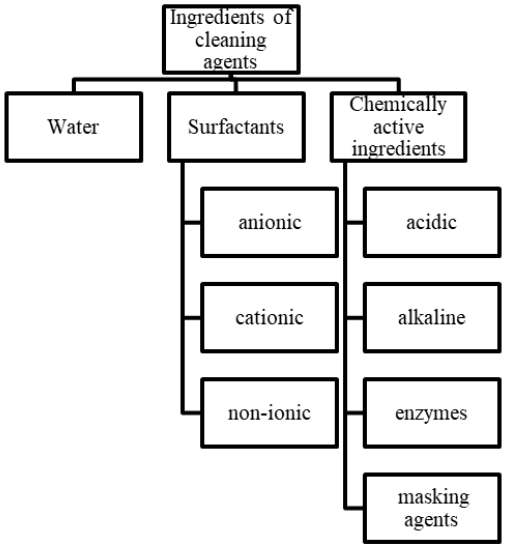


Figure 1. Classification of ingredients used in cleaning agents (author's elaboration)

Table 1 shows the applicability of different types of detergents to specific categories of contaminants. The majority of allergens belong to the protein category. This type of contaminant is challenging to remove, especially when proteins undergo thermal denaturation, so it is recommended to start the cleaning process by rinsing the surface with cold water. To remove proteins, including allergenic proteins, it is necessary to use strongly alkaline cleaning agents or agents with added oxidants.

Table 1.
The use of detergents depends on the type of contamination (author's elaboration).

Type of contamination	Example	Recommended detergent
carbohydrates	sugar, starch	weak alkaline cleaner
proteins	milk proteins	strong alkaline cleaner, weak chlorinated alkaline cleaner, alkaline cleaner with oxidizing agent
fats	plant oil	alkaline cleaner
inorganic	calcium salts	acid cleaner

Fat contaminants should be removed by rinsing with water at a temperature above their melting point. More difficult contaminants may require the use of alkaline cleaning agents containing emulsifiers. Due to their high solubility in water, simple sugars are relatively easy to remove. However, more complex carbohydrates (e.g. starch) require acidic or weakly alkaline cleaning agents. In the case of starch bound to other ingredients, it is necessary to use a strong alkali or acid. Accumulated mineral deposits are relatively difficult to remove. For this purpose, acids and/or detergents containing chelating agents are used. After the cleaning and deactivation of allergenic compounds, it is necessary to validate the cleaning process to approve the pilot line for producing products with controlled allergenicity.

In summary, the objective of this research was to design and validate an innovative cleaning strategy that ensures effective allergen deactivation on the surfaces of a prototype processing line, thereby enabling the safe manufacture of poultry products with controlled allergenicity. The research aimed to develop an innovative technology for deactivating allergenic compounds from the surfaces of a prototype processing line designed for producing poultry products with a crispy coating and controlled allergenicity. In this context, the term innovative refers to the creation of a cleaning and deactivation procedure that goes beyond conventional CIP and COP methods, which are often insufficient to completely eliminate allergenic residues. The developed approach integrates optimized parameters of cleaning agents and operating conditions into a reproducible and validated protocol that ensures the effective inactivation of allergenic proteins across all critical points of the line. This technological advancement enables the safe use of a single processing line for both conventional and allergen-controlled products, reducing the risk of cross-contamination while maintaining production efficiency.

Materials and Methods

Production line

A block diagram of the production line for the manufacture of poultry products with controlled allergenicity is shown in Figure 2.

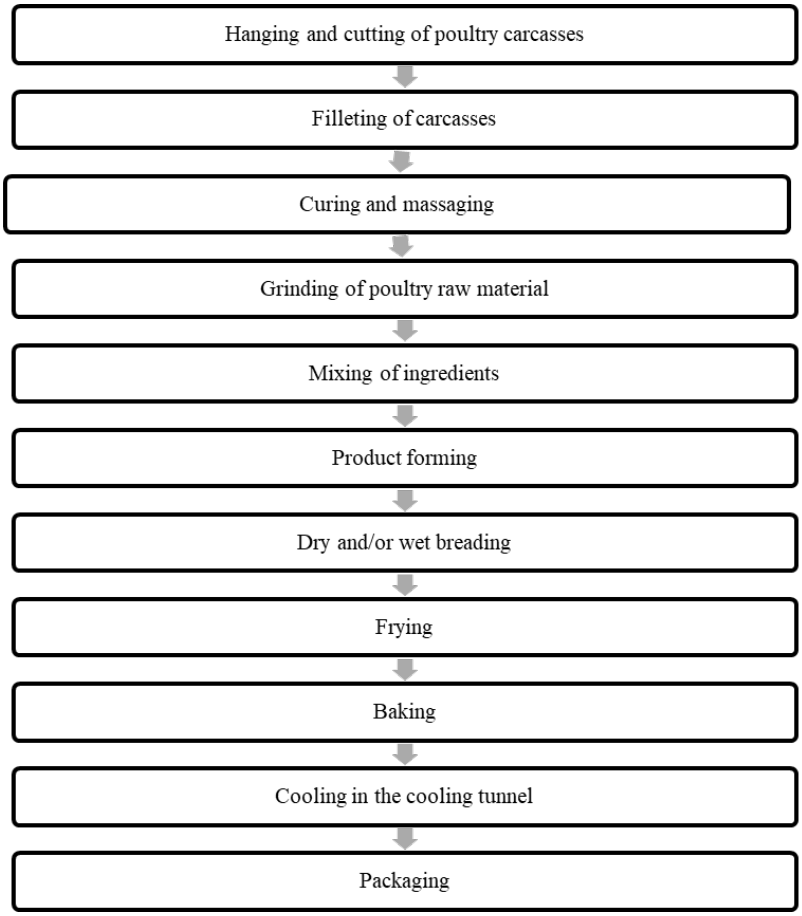


Figure 2. Block diagram of a production line for poultry products with a crispy coating and controlled allergenicity

The production line was divided into different zones to create appropriate documentation of the allergenic protein removal process, based on the division of spaces and the location of water intake points (Table 2).

Table 2.
Division of the prototype production line into zones with identification of critical points

Zone code	Name of zone	Number of critical points per zone	Critical point symbols *
S1	cutting and filleting zone	7	from S1_a to S1_g
S2	meat raw material curing zone	11	from S2_a to S2_k
S3	meat raw material grinding and mixing zone	3	from S3_a to S3_c
S4	poultry product forming zone	2	from S4_a to S4_b
S5	poultry product breading zone	10	from S5_a to S5_j
S6	poultry product thermal processing zone	2	from S6_a to S6_b
S7	poultry product cooling zone	2	from S7_a to S1_b
S8	poultry product packaging zone	2	from S8_a to S1_b

*a, b … – designation of critical points in the zone

All elements of the production line located in zones S1 to S5 and S8 are subject to manual cleaning, which is carried out according to the instructions for each station. Zones S6 (furnace) and S7 (cooling tunnel) have internal cleaning systems.

Detergents for deactivating allergenic proteins

Based on literature data and a review of commercially available cleaning and cleaning-disinfecting agents, 33 products containing active substances effective for deactivating allergenic proteins and approved for use in the food industry were selected. Preliminary trials were conducted to evaluate cleaning efficacy, industrial applicability, and cost in accordance with current regulations (URPLWMiPB, 2025; Regulation (EC) No 1272/2008). Based on these results, two formulations were selected for detailed evaluation (Table 3).

Table 3.
Selected mixtures of chemical compounds are used to deactivate allergenic proteins from the production line.

Brand name	Trade name	Composition	pH (1%-solution)
Sane-Chem	SANALTEN	sodium hydroxide (NaOH): 5–10%; sodium hypochlorite (NaOCl, active chlorine): <10% (5.2 g/L); amines, C12-14-alkyldimethyl, N-oxides: 1–5%	12.2
Sane-Chem	ACID FOAM	phosphoric acid (H_3PO_4): 20–40%; hydrochloric acid (HCl): 1–5%; amines, C12-14-alkyldimethyl, N-oxides: 1–5%; ethanol (ethyl alcohol): <0.5%	≤ 2.5

The tested concentrations of these detergents are presented in Table 4.

Table 4.
Concentrations of the working solution of detergents.

Brand name	Trade name of the preparation	Tested concentrations [%]		
SaneChem	SANALTEN	2.0	3.5	5.0
SaneChem	ACID FOAM	2.0	3.5	5.0

Cleaning procedures

Three cleaning procedures were applied to assess allergen inactivation efficacy:

- Procedure 1 (low-concentration protocol): A 2% alkaline solution (Sanalten, SaneChem) was applied at 30°C for 10 min, followed by rinsing with water. Subsequently, a 2% acidic solution (Acid Foma, SaneChem) was applied at 30°C for 15 min, followed by rinsing.
- Procedure 3 (medium-concentration protocol): A 3.5% alkaline solution was applied at 30°C for 10 min, rinsed, followed by a 3.5% acidic solution for 15 min at 30°C, and rinsed.
- Procedure 5 (high-concentration protocol): A 5% alkaline solution was applied at 30°C for 10 min, rinsed, followed by a 5% acidic solution for 15 min at 30°C, and rinsed.

These procedures were selected to represent increasing cleaning intensities within the range recommended by the manufacturer (1–5%).

Sampling strategy and allergen detection

Representative critical control points were designated according to: (i) representativeness of the technological stage, (ii) risk of allergen occurrence (based on hazard analysis), and (iii) feasibility of swab sampling.

Surface swabs were collected after each cleaning procedure. Detection of allergenic proteins was carried out using AgraStrip® (RomerLabs) lateral flow device (LFD) kits for gluten, macadamia nut, cashew/pistachio, Brazil nut, sesame, soy, almond, crustaceans, milk, lupin, mustard, and egg. The principle involved extraction with buffer followed by immunochemical detection. Results were expressed qualitatively as presence/absence at the manufacturer's detection limit.

Validation of cleaning procedures

For validation, Procedure 5 was applied in 30 full production batches (≥3 t of product). Cleaning efficacy was assessed at seven critical control points. If any allergen was detected, the procedure was repeated for the entire line.

Results and Discussion

Results are presented for four representative zones: S1 (cutting and filleting), S3 (grinding and mixing), S6 (thermal processing), and S7 (cooling).These zones were selected as they represent critical points within the processing line where allergenic residues are most likely to accumulate and persist. Data for the remaining zones (S2, S4, S5, S8) are available upon request.

Zone S1 – cutting and filleting

Seven swabbing points (S1_a–S1_g; Figure 3) were analyzed.

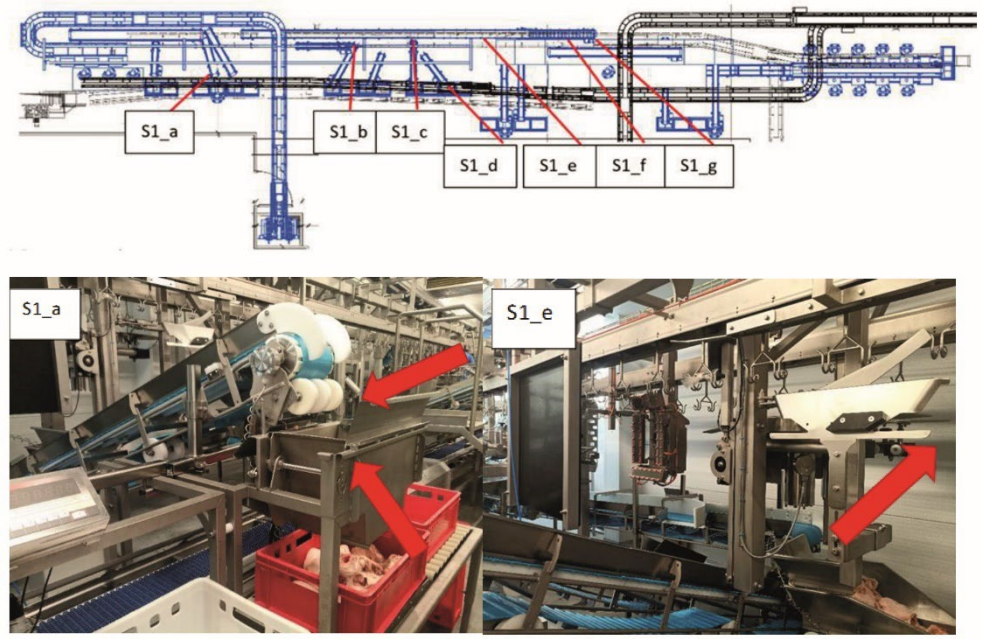


Figure 3. Designated control points in Zone S1 – poultry carcass cutting and filleting

As shown in Table 5, Procedure 1 (2% solutions) was ineffective, with multiple allergens consistently detected at nearly all sampling sites. Extending the contact time to 20 minutes did not substantially improve removal efficiency, suggesting that under these conditions the concentration of the active components, rather than exposure time, was the limiting factor.

In contrast, Procedure 5 (5% solutions) resulted in the complete elimination of all tested allergens. This observation underscores the concentration-dependence of allergen removal, which is particularly relevant for surfaces with high levels of organic matter. Chen et al. (2022) reported similar findings, showing that detergent concentrations below 3% failed to achieve full removal of allergenic residues from stainless steel surfaces under CIP conditions. The present results therefore confirm that high-risk zones such as cutting and filleting require intensified cleaning strategies to ensure compliance with allergen management standards.

Table 5.
Detection of selected allergenic compounds at critical points of prototype technological line components in zone S1 – poultry carcass cutting and filleting, after the application of Procedure 1 and Procedure 5 (results expressed as presence/absence with detection limits of the test kits).

	Procedure 1						
	S1_a	S1_b	S1_c	S1_d	S1_e	S1_f	S1_g
Soy	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+	< 2
Crustaceans	LFD+	< 2	LFD+	LFD+	LFD+	LFD+	< 2
Nut	LFD+	LFD+	LFD+	LFD+	< 2	LFD+	LFD+
Lupin	LFD+	< 10	LFD+	LFD+	LFD+	LFD+	< 10
Milk	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+
Gluten	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+	< 4
Sesame	< 5	LFD+	< 5	LFD+	< 5	< 5	LFD+
Almonds	LFD+	LFD+	< 2	< 2	< 2	LFD+	LFD+
Fish	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+
Mustard	< 2	LFD+	LFD+	LFD+	LFD+	LFD+	< 2
Egg	LFD+	< 1.25	LFD+	LFD+	LFD+	< 1.25	LFD+
	Procedure 5						
	S1_a	S1_b	S1_c	S1_d	S1_e	S1_f	S1_g
Soy	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Crustaceans	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Nut	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Lupin	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Milk	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Gluten	< 4	< 4	< 4	< 4	< 4	< 4	< 4
Sesame	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Almonds	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Fish	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Mustard	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Egg	< 1.25	< 1.25	< 1.25	< 1.25	< 1.25	< 1.25	< 1.25

*LFD+ - allergen detected using lateral flow device

Zone S3 – grinding and mixing

Three swabbing points (S3_a–S3_c; Figure 4) were tested in the grinding and mixing zone, which is characterized by increased homogenization of raw materials and a high potential for cross-contact between ingredients.

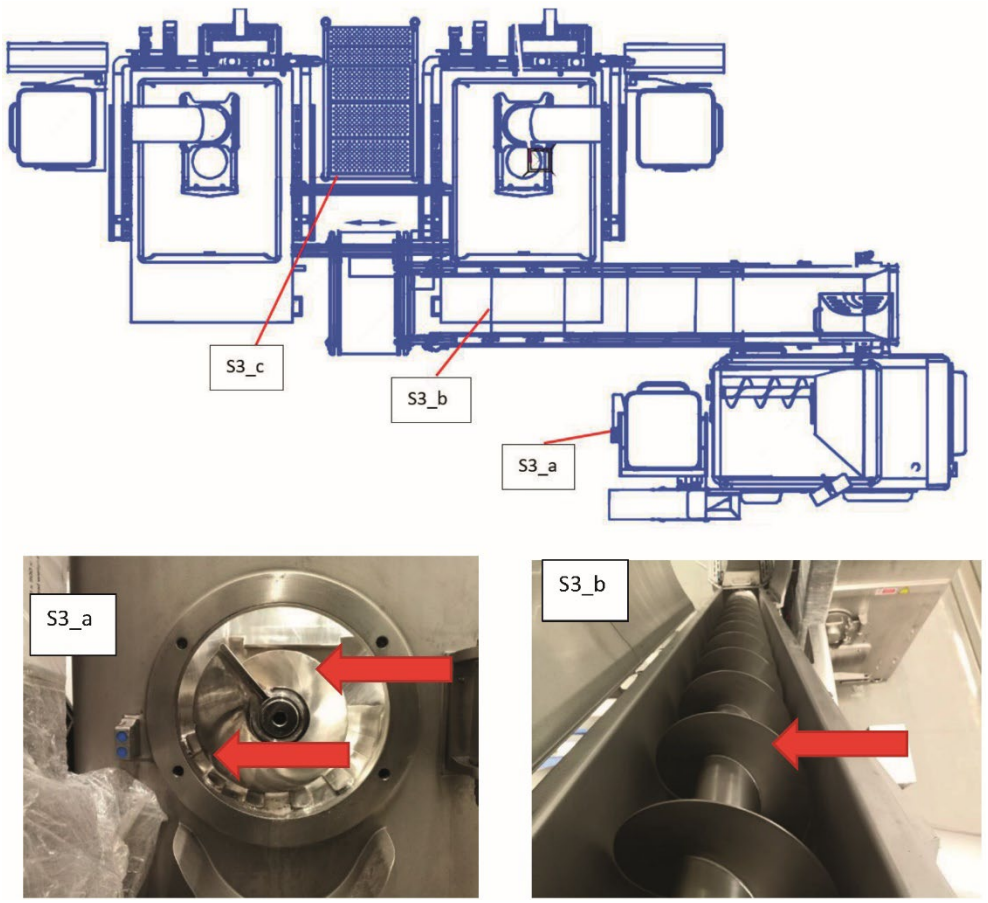


Figure 4. Identified control points within zone S3, corresponding to the processes of ingredient comminution and blending

Results (Table 6) indicated that Procedure 1 was ineffective, with nearly all allergens detected except sesame and almond. Procedure 3 (3.5% solutions) improved outcomes, but mustard and egg proteins remained detectable, highlighting their known resistance to standard cleaning protocols due to their physicochemical properties (e.g., strong protein–surface interactions and heat stability).

Only Procedure 5 achieved complete deactivation across all control points. These results are consistent with Pant et al. (2023), who reported that conventional CIP approaches often fail in complex matrices such as dairy and meat systems, where protein-lipid interactions hinder cleaning efficacy. The findings reinforce the importance of adapting cleaning protocols to the biochemical characteristics of specific allergens.

Table 6.
Concentrations of selected allergenic compounds [ppm] at swab sampling points on components of the prototype processing line in zone S3 — stations for ingredient comminution and blending.

	Procedure 1			Procedure 3			Procedure 5		
	S3_a	S3_b	S3_c	S3_a	S3_b	S3_c	S3_a	S3_b	S3_c
Soy	LFD+	LFD+	LFD+	< 2	LFD+	LFD+	< 2	< 2	< 2
Crusta-	LFD+	LFD+	LFD+	< 2	< 2	LFD+	< 2	< 2	< 2
Nut	LFD+	LFD+	< 2	< 2	LFD+	< 2	< 2	< 2	< 2
Lupin	LFD+	LFD+	LFD+	< 10	< 10	< 10	< 10	< 10	< 10
Milk	LFD+	LFD+	LFD+	< 1	< 1	< 1	< 1	< 1	< 1
Gluten	LFD+	LFD+	LFD+	< 4	LFD+	LFD+	LFD+	< 4	< 4
Sesame	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Almonds	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Fish	LFD+	LFD+	LFD+	LFD+	LFD+	< 5	< 5	< 5	< 5
Mustard	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+	< 2	< 2	< 2
Egg	LFD+	LFD+	LFD+	LFD+	LFD+	LFD+	<	<	<

Zone S6 – Thermal processing

Two control points (S6_a, S6_b; Figure 5) were analyzed in the thermal processing zone, where residues are exposed to elevated temperatures, potentially leading to protein denaturation and aggregation.

As presented in Table 7, Procedure 1 yielded positive detection for all allergens, highlighting the inadequacy of low-concentration cleaning agents against heat-modified residues. Procedure 3 improved results, with no allergens detected at S6_b, but five allergens (soy, crustaceans, lupin, fish, egg) persisted at S6_a.

Procedure 5 achieved complete removal at both sites, demonstrating that high-concentration cleaning can overcome the challenges posed by thermal residues. Delhalle et al. (2020) similarly noted that conventional chemical cleaning agents were insufficient to remove denatured protein matrices, and that optimized formulations or enzymatic aids were necessary. The present study confirms that without such optimization, allergenic proteins can remain in thermal zones, posing a significant risk of cross-contamination.

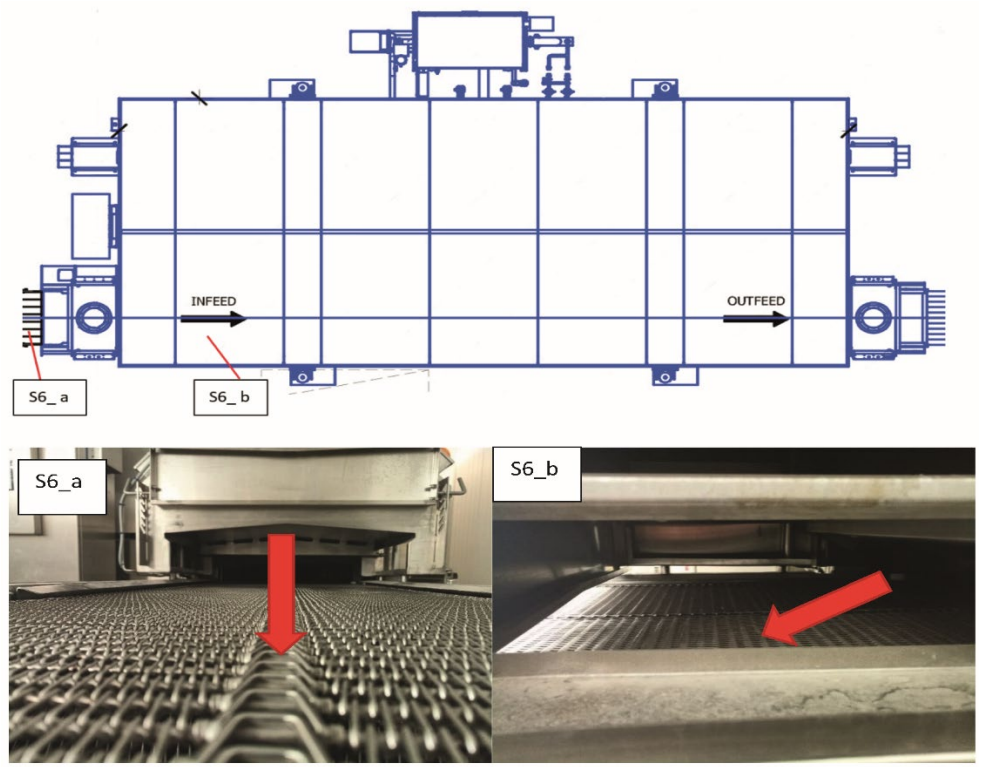


Figure 5. Designated control points in the thermal processing zone (S6) of the poultry product with controlled allergenicity

Table 7.
Concentrations of selected allergenic compounds [ppm] at surface swab sampling points on components of the prototype processing line in Zone S6 – thermal processing of the poultry product

	Procedure 1		Procedure 3		Procedure 5	
	S6_a	S6_b	S6_a	S6_b	S6_a	S6_b
Soy	LFD+	LFD+	LFD+	< 2	< 2	< 2
Crustaceans	LFD+	LFD+	LFD+	< 2	< 2	< 2
Nut	LFD+	LFD+	< 2	< 2	< 2	< 2
Lupin	LFD+	LFD+	LFD+	< 10	< 10	< 10
Milk	LFD+	LFD+	< 1	< 1	< 1	< 1
Gluten	LFD+	LFD+	LFD+	< 4	< 4	< 4
Sesame	LFD+	LFD+	< 5	< 5	< 5	< 5
Almonds	LFD+	LFD+	< 2	< 2	< 2	< 2
Fish	LFD+	LFD+	LFD+	< 5	< 5	< 5
Mustard	LFD+	LFD+	< 2	< 2	< 2	< 2
Egg	LFD+	LFD+	< 1.25	< 1.25	< 1.25	< 1.2

Zone S7 – cooling

Two points (S7_a, S7_b; Figure 6) were examined in the cooling tunnel, which represents a particularly challenging environment for cleaning due to low temperatures, condensation, and favorable conditions for biofilm development.

As shown in Table 8, Procedures 1 and 3 failed to achieve complete deactivation, with several allergens persisting despite cleaning. The limited effectiveness of these protocols may be explained by the reduced activity of cleaning agents at low temperatures and the enhanced stability of protein aggregates and biofilm-associated allergens.

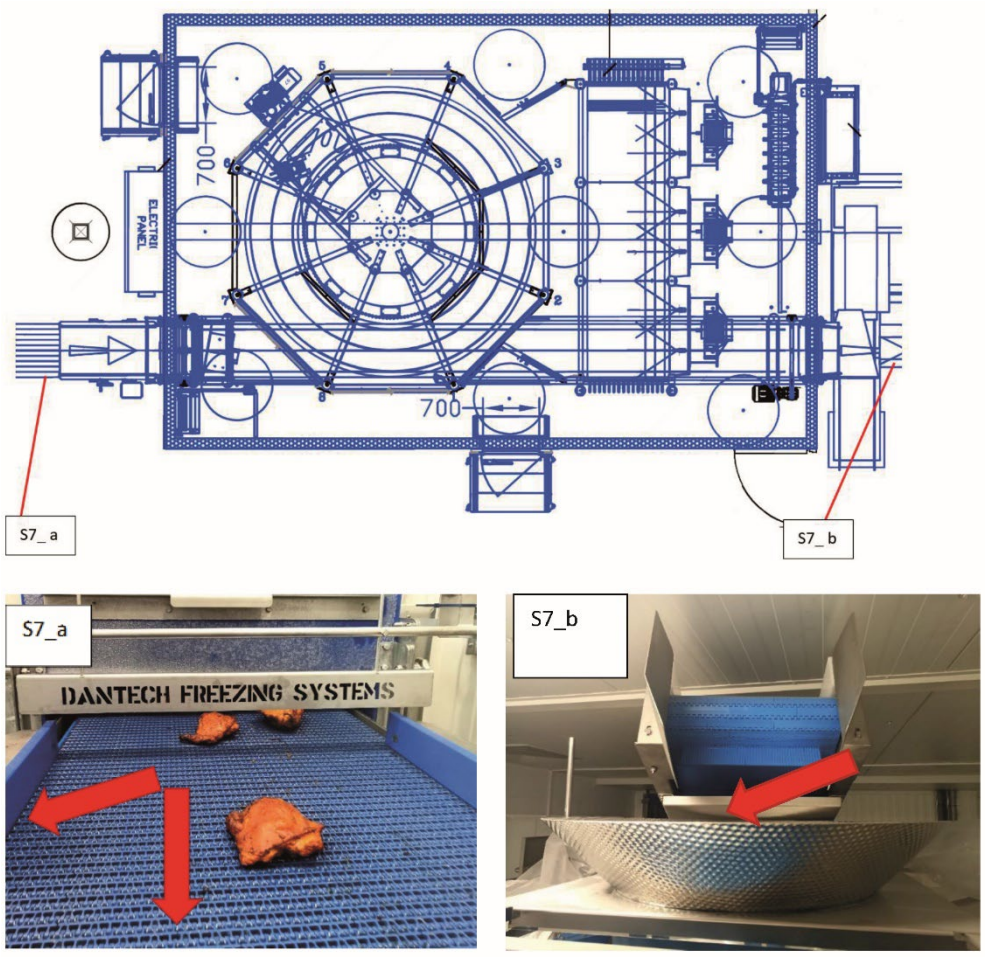


Figure 6. Designated control points in the cooling zone (S7) of the poultry product with controlled allergenicity

The Procedure 5, in contrast, eliminated all allergens at both sampling sites, confirming its robustness even under adverse conditions. These findings are consistent with Tirpanci Sivri et al. (2023), who demonstrated that biofilms formed under cold-chain conditions are highly resistant to cleaning and require intensified or alternative treatments.

Table 8.
Concentrations of selected allergenic compounds [ppm] at surface swab sampling points on components of the prototype processing line in Zone S7 — cooling of the poultry product with controlled allergenicity.

	Procedure1		Procedure 3		Procedure 5	
	S7_a	S7_b	S7_a	S7_b	S7_a	S7_b
Soy	LFD+	LFD+	< 2	< 2	< 2	< 2
Crustaceans	LFD+	< 2	LFD+	< 2	< 2	< 2
Nut	LFD+	LFD+	< 2	< 2	< 2	< 2
Lupin	LFD+	< 10	< 10	< 10	< 10	< 10
Milk	LFD+	LFD+	< 1	< 1	< 1	< 1
Gluten	LFD+	LFD+	< 4	< 4	< 4	< 4
Sesame	< 5	LFD+	< 5	< 5	< 5	< 5
Almonds	LFD+	LFD+	< 2	< 2	< 2	< 2
Fish	LFD+	LFD+	LFD+	< 5	< 5	< 5
Mustard	< 2	LFD+	< 2	< 2	< 2	< 2
Egg	LFD+	< 1.25	< 1.25	< 1.25	< 1.25	< 1.2

Cross-sectional assessment of cleaning efficacy in critical processing zones

Across all tested zones, Procedures 1 and 3 (≤3.5% solutions) were insufficient for reliable allergen deactivation, while Procedure 5 (5% solutions) consistently ensured complete removal. This outcome highlights detergent concentration as a critical determinant of allergen control and validates the robustness of Procedure 5 across diverse processing environments, including high-risk, heat-modified, and low-temperature zones.

The results align with prior studies showing the limitations of conventional cleaning (Chen et al., 2022; Delhalle et al., 2020; Pant et al., 2023; Tirpanci Sivri et al., 2023) and emphasize the necessity of validated, high-intensity protocols in allergen management. At the same time, they raise important questions regarding the balance between cleaning efficacy, economic cost, and environmental sustainability.

Future research should therefore investigate resource-efficient alternatives such as ozone-based cleaning (Avila-Sierra et al., 2021), enzymatic cleaning (Delhalle et al., 2020; Pant et al., 2023), or cold plasma treatment (Katsigiannis et al., 2021). These approaches may demonstrate comparable efficacy, thus enabling reduced chemical utilization, decreased water requirements, and a mitigated ecological footprint.

Conclusions

This study demonstrated that an optimized cleaning protocol (Procedure 5) effectively ensured complete deactivation of allergenic proteins across multiple critical points in a prototype processing line for crisp-coated poultry products. Validation through thirty pilot production batches confirmed that the procedure consistently eliminated allergens, thereby enabling the safe use of a single line for both conventional and allergen-controlled products.

The novelty of this work lies in the systematic identification of critical control points and the development of a validated procedure that combines effectiveness with practical applicability in an industrial setting. The approach provides a framework for integrating allergen management into cleaning-in-place and cleaning-out-of-place strategies. Nevertheless, several limitations should be acknowledged. The procedure relies on relatively high concentrations of cleaning agents, which may increase chemical costs, extend processing time, and raise concerns regarding environmental impact. Further studies are needed to optimize resource use and assess scalability to full-scale industrial lines.

Overall, the proposed technology contributes to improved allergen control in food processing and offers a practical solution for balancing food safety with production efficiency.

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INNOWACYJNA TECHNOLOGIA INAKTYWACJI ZWIĄZKÓW ALERGENNYCH Z POWIERZCHNI ELEMENTÓW PROTOTYPOWEJ LINII DO PRODUKCJI WYROBÓW O KONTROLOWANEJ ALERGENNOŚCI

Streszczenie. Celem badania było opracowanie i walidacja skutecznych procedur mycia i dezaktywacji alergenów w prototypowej linii do produkcji wyrobów mięsnych w chrupkiej otoczce. Niezawodne metody czyszczenia mają istotne znaczenie dla zapewnienia bezpieczeństwa żywności i zapobiegania zanieczyszczeniom krzyżowym, szczególnie wówczas gdy na tej samej linii wytwarzane są produkty konwencjonalne i produkty z kontrolowaną zawartością alergenów. Punkty krytyczne na linii produkcyjnej zidentyfikowano poprzez wstępną ocenę procesu dezaktywacji zwiazków alergennych. W tych punktach monitorowano pozostałości alergenów za pomocą testów immunoenzymatycznych ukierunkowanych na główne alergeny pokarmowe, w tym gluten, soję, mleko, orzechy, sezam i inne. Porównano wybrane procedur mycia pod kątem ich zdolności do eliminowania białek alergennych z powierzchni urządzeń. Procedury o niższych stężeniach środków dezaktywujących okazały się niewystarczające, szczególnie w obszarach wysokiego ryzyka, takich jak strefy rozbioru, łaczenia składników oraz chłodzenia. Zoptymalizowana procedura pozwoliła na całkowite usunięcie alergenów we wszystkich punktach krytycznych. Wynik ten został potwierdzony podczas badań walidacyjnych obejmujących trzydzieści pilotażowych partii produkcyjnych, w których nie wykryto białek alergennych w wymazach z powierzchni lini jak również w gotowych produktach. Badania wskazują, że odpowiednio opracowane strategie dezaktywacji zwiazków alergennych pozwalają na wykorzystanie linii produkcyjnych, zarówno do wytwarzania produktów standardowych, jak i tych z kontrolowaną alergennoscią. Zwalidowana procedura oferuje ekonomiczne i praktyczne rozwiązanie dla przemysłu spożywczego, zapewniając zgodność z regulacyjnymi prawnymi i zwiekszając bezpieczeństwo konsumentów.

Słowa kluczowe: kontrola alergenności, higiena przetwórstwa żywności, system mycia CIP, dezaktywacja związków alergennych, produkcja wyrobów drobiowych