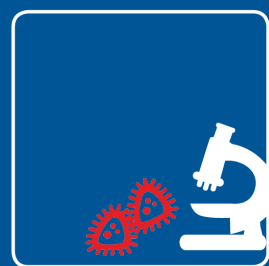


Serafim Bakalis:

SmartClean – Minimer miljøpåvirkningen fra CIP-rengøring (Cleaning in Place)

SmartClean – Minimise the environmental impact of cleaning in place



Final report

for collaborative projects funded via the Danish Dairy Research Foundation (DDRF)

1. Title of the project

Danish: SmartClean – Minimer miljøpåvirkningen fra CIP-rengøring (Cleaning in Place)

English: SmartClean – Minimise the environmental impact of cleaning in place

2. Project manager

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4. Sources of funding

Milk Levy Fund, funding from Arla Foods Ingredients, self-funding from University of Copenhagen

5. Project period

Project period with DDRF funding: Aug/2022 - Aug/2025

Total project period, if sub-project within a larger project: No sub-project

6. Project summary

Danish:

Clean-in-Place (CIP) er essentielt i mejeriindustrien, men kræver betydelige mængder tid, vand og energi. I takt med stigende krav til bæredygtighed bliver det stadig mere presserende at optimere CIP-processer for at reducere ressourcetilbruget. Dette studie fokuserer på at forstå og forbedre CIP i pladevarmevekslere (PHEs), der er tilsmudset med valleprotein.

Tilsmudsning og rengøring blev undersøgt i pladevarmevekslere på både laboratorie- og pilotskala. Der blev desuden udviklet et transparent kanal-testanlæg med en bund af rustfrit stål for at generere tilsmudsning via opvarmning og for at visualisere interaktionen mellem tilsmudsningsslaget og rengøringsopløsningen.

Resultaterne viste, at rengøring i pladevarmevekslere er meget uensartet. De sidste 2% af tilsmudsningen tegnede sig for 50% af den samlede rengøringstid, fordi der dannedes præferentielle strømningsveje under rengøringen, hvilket betød, at den resterende tilsmudsning primært skulle fjernes ved hjælp af alkalisk diffusion. Rengøringshastigheden i denne diffusionsstyrede fase kunne overføres kvantitativt på tværs af skalaer. En forøgelse af rengøringstemperaturen og -hastigheden eliminerede ikke denne langsomme slutfase; i stedet kunne den kun reduceres ved at kontrollere den indledende mængde tilsmudsning. Der blev derfor udviklet en mekanistisk model til at forudsige fordelingen af tilsmudsning i pladevarmevekslere.

Studiet viste også, at en konstant effluent koncentration målt ved UV-Vis ikke nødvendigvis er ensbetydende med en ren overflade. Der blev foreslået en datadrevet metode til mere nøjagtigt at estimere overfladens renhed. Samlet set fremmer dette arbejde den mekanistiske forståelse af CIP og understøtter en mere pålidelig og ressourceeffektiv rengøring uden behov for direkte observation af overfladen.

English:

Clean-in-Place (CIP) is essential in the dairy industry but requires significant time, water, and energy. As sustainability demands grow, optimizing CIP to reduce resource consumption is becoming increasingly urgent. This study focuses on understanding and improving CIP in whey protein-fouled plate heat exchangers (PHEs).

Fouling and cleaning were investigated in both laboratory- and pilot-scale PHEs. A transparent channel rig with a stainless-steel bottom was also developed to generate fouling through heating and visualize the interaction between the fouling layer and the cleaning solution. Machine Learning image analysis was used to determine kinetics of CIP.

The results showed that cleaning in PHEs is non-uniform. The final 2% of fouling accounted for 50% of the total cleaning time because preferential flow paths formed during cleaning. The removal of the last stages of fouling was controlled by slow alkaline diffusion. Increasing CIP temperature and velocity controlled the first stages of fouling and did not have a strong influence on the last stages of cleaning. The cleaning rate in this diffusion-controlled stage was the same at lab and pilot scale experiments. A mechanistic model was developed to describe fouling and cleaning. While in a practical setting it is possible to measure fouling concentration in the effluent, e.g. using UV-VIS, our work demonstrates that effluent measurements by themselves are not predictive of the end of clean. Through combining SmartClean models with on-line measurements it is possible to predict the end of clean. Overall, this work advances the mechanistic understanding of CIP and supports more reliable, resource-efficient cleaning without direct surface observation.

7. Project aim

Danish: Målet med SmartClean er at udvikle validerede modeller, der muliggør optimering af CIP-processer (Cleaning in Place) i mejeriindustrien. SmartClean vil tage udgangspunkt i følgende spørgsmål: Hvad er en ren overflade, og hvad er kinetikken bag opnåelse af en ren overflade ved rengøring?

English: The aim of SmartClean is to develop validated models that enable the optimisation of Cleaning-in-Place (CIP) processes in the dairy industry. The project addresses two fundamental questions: What is a clean surface, and what are the kinetics behind achieving a clean surface during cleaning?

8. Background for the project

CIP-processes have a significant environmental impact in terms of energy consumption, water consumption and use of chemicals. There is considerable risk to product quality and safety associated with reducing the intensity of CIP processes, making optimization challenging. Monitoring tools and advanced data analysis at industrial scale can enable reductions in energy and water use, supported by models that simulate the relevant physicochemical phenomena.

9. Sub-activities in the entire project period

SmartClean: Minimise the environmental impact of Cleaning in Place			YEAR 1				YEAR 2				YEAR 3			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
WP1	Small Scale Capability	Developing experimental capability	Design	Implement	D 1.1									
		Data generation: What is clean?				Cleaning kinetics for 10 repeated cycles	D 1.2	Effect of remaining fouling material	D 1.3					
WP2	Model Development	Building a cleaning database			Cleaning database	D 2.1								
		Hybrid Models				Hybrid cleaning + fouling models validated @ lab	M1	Models validated @ pilot	D 2.2					D 2.3
WP3	Cleaning @ pilot scale	Cleaning Coupons						Fouling + Cleaning Coupons	D 3.1					
		Cleaning "real" surfaces								Fouling and Cleaning real surfaces	M2			
WP4	Cleaning @ factory scale	Effect of complex geometries /Manufacturing on cleaning											Applicability at industrial scale	D 4.1
		Manuscripts							D 1.4 & D 2.5				D 3.3	D 4.2

10. Deviations

No deviations have occurred with respect to the scientific objectives, financial plan, or project timetable. The project is progressing as originally planned and all activities remain consistent with the approved proposal.

11. Project results

Project objectives

The project aimed to improve the efficiency and reliability of Clean-in-Place (CIP) processes in the dairy industry, with a particular focus on plate heat exchangers (PHEs) fouled by whey protein deposits. CIP is a major consumer of water, chemicals, and energy in dairy manufacturing, and current cleaning procedures are often operated using fixed cleaning times without direct information on surface cleanliness. The project therefore pursued two overall objectives:

1. To improve the mechanistic understanding of fouling removal during CIP.
2. To develop monitoring and modelling approaches that enable more reliable prediction and control of the final stages of cleaning.

To achieve these objectives, three research questions were formulated:

- What governs fouling removal under controlled conditions?
- What is the cleaning pattern inside plate heat exchangers?
- How is fouling distributed inside plate heat exchangers?

Research area 1: Mechanistic understanding of fouling removal

Initial aim: The first objective was to understand the mechanisms governing whey protein fouling removal under well-controlled conditions and to identify the dominant cleaning phenomena during alkaline cleaning.

Results achieved: A transparent channel rig was developed to enable controlled fouling generation and direct visualization of cleaning dynamics (Figure 1). Optical measurements were used to quantify local fouling thickness during cleaning. The experiments demonstrated that fouling removal is primarily diffusion-controlled during most of the cleaning process. The fouling layer decreased relatively uniformly across the surface. However, once the remaining fouling thickness fell below approximately 0.5 mm, cleaning became increasingly non-uniform and proceeded sequentially along the flow direction.

Furthermore, the fouling layer was not uniform. Although a fouling layer with uniform thickness was initially generated, cleaning consistently left several visible fouling islands (approximately 1 cm in diameter) on the membrane surface. These residual deposits could sometimes double the required cleaning time. To address this issue, SmartClean developed a neural-network-based imaging tool to quantify the removal of these final fouling residues and proposed a mechanistic model to predict their removal.

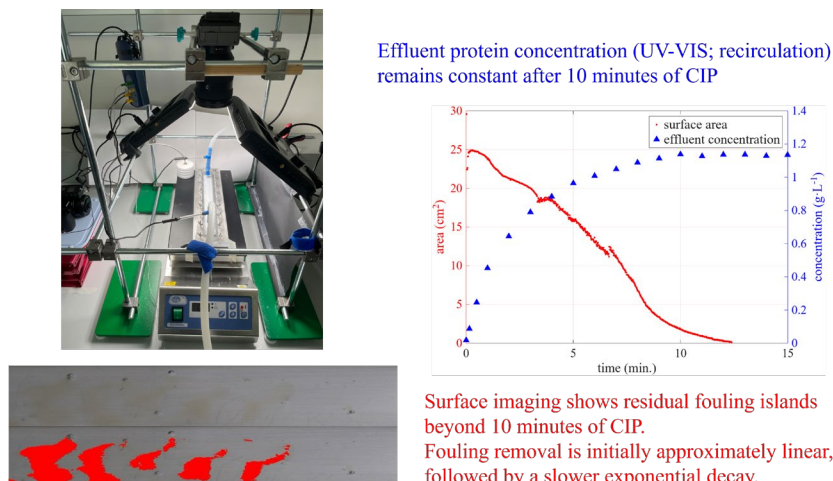


Figure 1. Lab-scale PHE rig combining UV-Vis measurements of the effluent with direct camera visualization of the stainless-steel surface.

Comparison with initial aim: The original objective of identifying the governing cleaning mechanisms was fully achieved. The work provided detailed insight into the transition from relatively uniform fouling removal to diffusion-dominated cleaning and established a mechanistic basis for describing cleaning progression during the final cleaning stage.

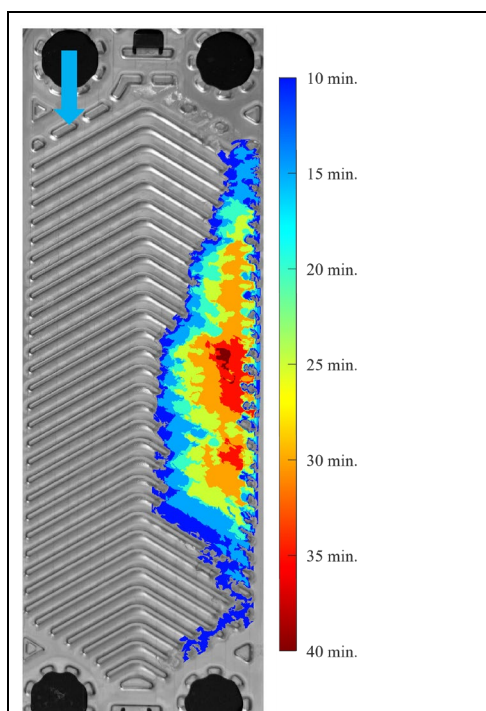


Figure 2: Removal fouling material on the surface of a plate, blue arrow indicates the direction of flow of CIP fluid and the entrance point of the liquid

Research area 2: Cleaning patterns inside plate heat exchangers

Initial aim: The second objective was to determine whether cleaning mechanisms observed on flat laboratory surfaces are representative of cleaning behavior inside industrially relevant plate heat exchangers.

Results achieved: Cleaning experiments were performed in both laboratory-scale and pilot-scale PHEs (both KU FOOD and AFI pilot plants). During cleaning, preferential flow paths of CIP fluids affect remaining fouling deposits (Figure 2). As a result, the later cleaning stages became increasingly governed by diffusion of the cleaning agent into the residual fouling layer. Approximately 50% of the total cleaning time was required to remove the final 2wt% of fouling material.

Comparison with initial aim: The project successfully validated that flat-surface cleaning studies provide a reliable representation of cleaning inside PHE channels. At the same time, it identified preferential flow leading to fouling remaining at certain parts of the plates (Figure 2). The removal of this inhomogeneous fouling residue, occurs only at the edge of the layer, resulting in extended CIP times.

Research area 3: Fouling formation and prediction of fouling distribution

Initial aim: The third objective was to understand fouling distribution inside PHEs and to establish predictive approaches capable of estimating fouling accumulation and cleaning requirements.

Results achieved: The study investigated fouling formation under both laboratory and pilot-scale conditions. Fouling distribution was found to be highly non-uniform along the flow path. Less fouling was often observed at positions with higher bulk temperatures. The results demonstrated that once the bulk liquid temperature exceeds the protein aggregation temperature, protein aggregation increasingly occurs in the liquid phase rather than on the heat-transfer surface. As such fouling can be potentially reduced through appropriate control of bulk-wall temperature management.

Based on experimentally determined protein aggregation kinetics and measured temperature profiles, a mechanistic modelling framework was developed to estimate fouling distribution inside PHEs. Pressure-drop measurements were further shown to provide useful information on total fouling accumulation during operation.

Comparison with initial aim: The objective of predicting fouling distribution was successfully achieved. The developed approach provides a practical framework for estimating the location and amount of fouling inside industrial heat exchangers and offers a foundation for predicting cleaning requirements before CIP is initiated.

Research area 4: Monitoring and data-driven cleaning assessment

Initial aim: SmartClean aimed was to improve online monitoring of CIP and explore the potential of determining the CIP endpoint.

Results achieved: During the last CIP stages the amount of released fouling material approaches the measurement uncertainty. Even highly sensitive techniques monitoring techniques such as UV–Vis spectroscopy become unreliable (Figure 1).

To address this, a deep learning-based image analysis model was developed and applied to quantify fouling removal during the end-stage of CIP. Top-view images of the heat exchanger surface were segmented using a U-Net convolutional neural network trained with the RootPainter tool, enabling automated tracking of individual protein fouling spots over time. This provided quantitative measurements of fouling area reduction that are inaccessible to effluent-based monitoring methods.

The project therefore combined mechanistic understanding with data-driven estimation methods to infer surface cleanliness from online measurements (Figure 3). A mechanistic crossover model, derived from sessile-droplet dissolution theory, was fitted to the segmented area over time to describe the transition from linear to exponential removal kinetics, yielding physically interpretable parameters including the linear removal rate and the exponential decay constant. This enabled extrapolation of cleaning progress beyond the observed time window to a predefined cleanliness threshold. This approach enables more reliable determination of cleaning progress, particularly during the diffusion-controlled final cleaning stage where direct measurement becomes impractical.

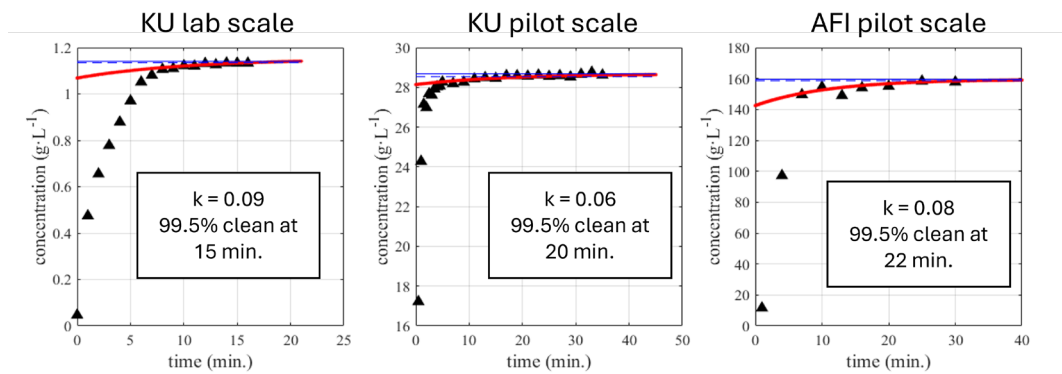


Figure 3. Combine data from on-line monitoring of the effluent with a mechanistic model to estimate the end of cleaning time. For comparison, the conventional cleaning time used is 30 min.

Comparison with initial aim: The project successfully demonstrated the limitations of existing monitoring approaches and developed a new framework combining online measurements with model-based estimation. The integration of deep learning segmentation with mechanistic curve fitting provides a principled route from raw image data to an estimated cleaning endpoint, offering a basis for condition-based CIP termination criteria rather than fixed cleaning durations. This represents an important step toward condition-based CIP operation.

The project generated several scientific contributions:

- Development of a lab scale experimental platform for visualization of CIP kinetics.
- Identification of diffusion-controlled cleaning as the dominant mechanism during the final cleaning stage.
- Demonstration that preferential flow formation is responsible for prolonged cleaning times in PHEs.
- Quantification of the disproportionate impact of residual fouling, where the final 2wt% of fouling requires approximately 50% of total cleaning time.
- Establishment of transferable cleaning kinetics across laboratory and pilot scales.
- Development of a mechanistic model for predicting fouling distribution in plate heat exchangers.
- Development of a data-driven framework for estimating surface cleanliness from online monitoring data.

Conclusion

The project achieved all major objectives and delivered new insights into both fouling formation and fouling removal in plate heat exchangers. The results demonstrate that cleaning is highly heterogeneous and that the final stages of CIP are primarily governed by diffusion rather than bulk flow. Understanding this behaviour is essential for reducing cleaning times and improving resource efficiency.

By combining mechanistic experiments, pilot-scale validation, modelling, and online monitoring approaches, the project established a foundation for more reliable and condition-based CIP operation. These outcomes contribute directly to the development of more sustainable dairy processing systems and provide a framework for future optimization of industrial cleaning processes.

12. The relevance of the results, including relevance for the dairy industry

The results contribute to a better scientific understanding of the mechanisms governing CIP processes, particularly the final stages of cleaning and the relationship between surface cleanliness and effluent measurements. This knowledge supports the development of more reliable predictive models and monitoring approaches.

For the dairy industry, the results provide a foundation for optimizing CIP processes while maintaining hygiene and product safety. Improved understanding of cleaning kinetics and cleaning endpoints may contribute to reducing water, energy, and chemical consumption, thereby lowering both operational costs and environmental impact.

From a societal perspective, more efficient cleaning processes can support sustainable food production through reduced resource use and waste generation.

The results have also opened new research areas related to sensor-based monitoring of cleaning processes, prediction of cleaning endpoints, scale transferability of cleaning mechanisms, and the integration of mechanistic and data-driven models for industrial CIP optimization. In addition, the knowledge generated has contributed to the development of the new GREENClean project, which further explores sustainable industrial cleaning through enzymes and digital technologies.

13. Communication and knowledge sharing about the project

Papers in international journals:

Zhang, Yimin, et al. "Cleaning in place of whey protein fouling-mechanisms of removal." *Journal of Food Engineering* 400 (2025): 112636.

Zhang, Yimin, et al. "Cleaning in place of plate heat exchangers–Removal behavior of whey protein fouling." *Chemical Engineering Science* (2025): 122395.

Zhang, Yimin, et al. "Spatial distribution of whey protein fouling in a plate heat exchanger." (under preparation).

Changdar, Satyasan, et al. "Quantifying Last-Stage Fouling Removal During Clean-in-Place of Dairy Processes Using Deep Learning." (under review).

Changdar, Satyasan, et al. "Estimating Cleaning Kinetics for Clean-in-Place (CIP) of Dairy Processes Using Physics-Informed Machine Learning." (under preparation).

Easily read papers:

Zhang, Yimin, et al. "Smart CIP: From fundamental understanding to optimized processes through digital tools." *Mejerimedier* (2024 September).

Student theses:

Yimin Zhang, Ph.D. Thesis

Cleaning of Plate Heat Exchangers - Fundamentals, understanding and mathematical modelling of alkaline CIP of whey protein fouling.

Oral presentations at scientific conferences, symposiums etc.:

2024 ESBES Copenhagen, Cleaning in Place of whey protein fouling: experiment and mechanistic model of mass removal rate in dairy systems.

2024 AIChE Annual Meeting San Diego, Physics-Informed Machine Learning for CIP Optimization in Dairy Manufacturing.

2025 Mejeriteknisk Selskab Billund, SmartClean: Cleaning-in-Place of plate heat exchangers with whey protein fouling.

2025 ECCE Lisbon, Cleaning in Place of Plate Heat Exchangers: Removal behaviour of whey protein fouling.

2025 FORCE Technology Vejen, Improving Non-Intrusive CIP Monitoring: From current limitations to data-driven solutions.

2026 Mejeribrugets Dag, Herning, SmartClean – minimering af miljøpåvirkning ved rengøring.

14. Contribution to master and PhD education

Yimin Zhang, University of Copenhagen, PhD education.

15. New contacts/projects

SmartClean has contributed to the development of a new related project, GREENClean: Sustainable industrial cleaning through enzymes and digital technologies. The project builds on related themes, including CIP optimisation, sensor-based monitoring, modelling, and reduced resource use in industrial cleaning.