PhD position

Understanding and modeling browning reactions during drying and storage of dairy powders, from droplet to semi-industrial scale

Context and objective

Many food products are processed into powders because this dry form extends their shelf life while facilitating storage and transport through reduced water content and volume. The dairy sector is particularly concerned, with 12 million tons of dairy powders produced annually worldwide, allowing their storage for 1 to 3 years. These powders are obtained through a succession of thermal unit operations (heat treatment, concentration, drying) which, given the complex composition of dairy matrices (water, fat, proteins, minerals), give rise to heat-induced chemical reactions (Maillard reaction, caramelization and protein denaturation/aggregation). These reactions alter the original quality of the products and continue in the dry state during ageing, storage and transport. Among them, non-enzymatic browning, resulting primarily from Maillard reactions, is a particularly undesirable phenomenon, since it significantly compromises nutritional, sensory and functional properties of the powders [1]. It is therefore essential to understand the mechanisms behind these changes to predict the shelf life of powders, especially in a context of climate change and global trade where these products are often exposed to temperatures of 60°C or higher for several weeks [2].

This is not an easy task due to the lack of knowledge in browning reactions for dried dairy products. Some studies have been carried out on liquid model systems and kinetic models have been proposed [3] but the results are not directly transposable to powders as the mobility of precursors in a liquid medium is much greater than that observed in a medium undergoing a phase transition and subsequently solid. On a mechanistic level, few studies exist. For instance, kinetic studies by Miao and Roos [4, 5] on spray-dried model systems that showed that the rates of non-enzymatic browning reactions during storage increase with both water content and temperature, highlighting that the glass transition temperature is not the absolute threshold for reaction kinetics. Norwood et al. (2017) [6] emphasized the impact of lactose content on browning and protein denaturation during storage at low water activity, whereas Paul et al. (2022) [7] reported that browning during storage was unrelated to lactose content, being instead driven by initial levels of lactosylated proteins at high water activity.

The storage does not begin from an arbitrary initial condition, but rather from a result of the reaction dynamics that occurred during spray-drying which remain largely unknown

[8]. The few studies available have monitored color and global markers during the pilot-scale spray-drying of skim milk and of lactose:whey protein isolate model systems [9], and modeled the corresponding kinetics under simulated conditions [10], without elucidating reaction pathways. Access to measurements is indeed particularly difficult: i) short drying time (≈ 4-5 s), ii) non-uniform distribution of particles and iii) closed nature of the drying chamber make it difficult to quantify temperature and water content at a given time and position. Thus, reactions occurring during spray-drying have often been approximated to a simple first-order reaction, whereas the Maillard reaction involves multiple elementary reactions and competes with caramelization and protein denaturation/aggregation.

An additional difficulty specific to dry matrices is that the molecular mobility of the precursors continuously changes during drying, when the droplets undergo a sol-gel transition from a homogenous solution to a non-uniform solid matrix, and then from a glassy to a rubbery state during storage. These phase transitions have a significant influence on reactivity [11].

In this context, the objective of this PhD position is to understand the reaction mechanisms responsible for non-enzymatic browning of dairy powders during spray-drying and storage, with a gradual increase in complexity, from a single droplet to the semi-industrial scale. The work will identify the influence of temperature and water content on reaction kinetics and then build and validate multi-response kinetic models enabling the prediction of browning intensity during storage.

Missions

The recruited person will be responsible for:

i) Study of reaction dynamics during simulated drying

- development and use of miniaturized set-ups for observation of reaction dynamics under controlled temperature and humidity;
- on-line and off-line monitoring of reaction markers, followed by kinetic modeling;

ii) Study of reaction dynamics during pilot-scale drying and storage

- spray-drying of model powders with varying process parameters to determine their influence;
- determination of reaction markers before and after drying and of physico-chemical properties;
- development of a browning prediction model and of a water content-dependent multi-response model for storage;

iii) Validation of the models at semi-industrial scale

- production of powders with a more representative composition and storage under controlled conditions;

- validation of the kinetic models and of the browning prediction model.

Required profile

Education: MSc or engineering degree in chemical engineering, process engineering, physics or food science.

Skills:

- Strong interest in experimental laboratory work (processes, physico-chemistry, analytical techniques)
- Basic knowledge of modeling and scientific programming (Python, Matlab, R)
- Knowledge of process engineering (heat and mass transfer) and/or food chemistry.

Desired qualities:

- Scientific curiosity and ability to take the initiatives
- Autonomy, rigor, and strong organizational and teamwork skills
- Proficiency in English (writing articles, conference presentations).

Work environment

The recruited person will carry out their activities within the Process-Structure-Functionality (PSF) team of the Joint Research Unit Science and Technology of Milk and Eggs (UMR STLO) (https://eng-stlo.rennes.hub.inrae.fr/). This work is part of the "Predicting the browning of dairy powders by kinetic modeling of Maillard reaction and caramelization during drying and storage (MARACAS)" project, funded by the French National Research Agency (ANR) under the Generic Call for Projects (AAPG) 2025.

STLO aims to generate knowledge about milk and egg and their transformation into ingredients or finished products for human consumption. By leveraging expertise in biochemistry, physico-chemistry, process engineering, physics, technology, and microbiology, its goal is to contribute to safe, healthy, and nutritious food that respects the environment and meets the needs of specific populations.

STLO is equipped with state-of-the-art facilities to support its multidisciplinary research activities. The dairy platform offers pilot scale equipment with advanced instrumentation capabilities. The unit also has high-performance tools for chemical, physical, and microbiological analyses, specifically adapted for dairy products. The recruited person will fully benefit from these resources to successfully carry out the required tasks, under the supervision of three permanent members: Romain Jeantet, Luca Lanotte and Jeehyun Lee. The PhD student will also work in close interaction with the post-doctoral fellow recruited on the project.

Employment conditions

Contract: 36-month fixed-term doctoral contract

Salary: according to the current French doctoral contract salary scale

Location: 65 rue de Saint-Brieuc, 35000 Rennes, France

Start Date: From January 1st or February 1st 2027

Application process

Submit applications to jeehyun.lee@institut-agro.fr by October 4th 2026

- Detailed CV
- Cover letter
- Academic transcripts from the last two years of study
- Recommendation letters.

[1] Phosanam, A., Chandrapala, J., Zisu, B., & Adhikari, B. (2021). Storage stability of powdered dairy ingredients: a review. Drying Technology, 39(11), 1529–1553. https://doi.org/10.1080/07373937.2020.1774891

[2] Leinberger, D. (2006). Ocean container temperature and humidity study. Dimensions, 6.

[3] van Boekel, M. A. J. S. (2022). Kinetics of heat-induced changes in dairy products: Developments in data analysis and modelling techniques. International Dairy Journal, 126, 105187. https://doi.org/10.1016/j.idairyj.2021.105187

[4] Miao, S., & Roos, Y. H. (2004). Comparison of nonenzymatic browning kinetics in spray-dried and freeze-dried carbohydrate-based food model systems. Journal of Food Science, 69(7), 322-331

[5] Miao, S., & Roos, Y. H. (2006). Isothermal study of nonenzymatic browning kinetics in spray-dried and freeze-dried systems at different relative vapor pressure environments. Innovative Food Science & Emerging Technologies, 7(3), 182-194

[6] Norwood, E. A., Pezennec, S., Burgain, J., Briard-Bion, V., Schuck, P., Croguennec, T., Jeantet, R., & Le Floch-Fouéré, C. (2017). Crucial role of remaining lactose in whey protein isolate powders during storage. Journal of Food Engineering, 195, 206-216

[7] Paul, A., Gaiani, C., Cvetkovska, L., Paris, C., Alexander, M., Ray, C., Francius, G., El-Kirat-Chatel, S., & Burgain, J. (2022). Deciphering the impact of whey protein powder storage on protein state and powder stability. Journal of Food Engineering, 326, 111050

[8] Zhou, Z., & Langrish, T. (2021). A review of Maillard reactions in spray dryers. Journal of Food Engineering, 305, 110615. https://doi.org/10.1016/j.jfoodeng.2021.110615

[9] Zhou, Z., & Langrish, T. (2022). Color formation and Maillard reactions during the spray drying process of skim milk and model systems. Journal of Food Process Engineering, 45(1), e13936. https://doi.org/10.1111/jfpe.13936

[10] Zhou, Z., & Langrish, T. (2024). Modeling Maillard reaction kinetics in spray dryers using both lumped- and distributed-parameter modeling approaches. Journal of Food Process Engineering, 47(4), e14599. https://doi.org/10.1111/jfpe.14599

[11] Roos, Y., & Karel, M. (1991). Applying state diagrams to food processing and development. Food Technology, 45(12), 66, 68–71, 107.