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FROM MICROBIAL DYNAMICS TO BIOPROCESS DIGITAL TWINS: MODELING, LEARNING AND CONTROL

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ABSTRACT

Microbial processes underpin applications ranging from food and precision fermentation to biomanufacturing, waste valorization, environmental remediation, and human and animal health. Mathematical and computational models offer powerful tools for understanding these systems and improving their operation, yet their predictive use remains challenging due to nonlinear interactions, partially observed dynamics, biological variability, parameter uncertainty, and limited availability of informative experimental data. This invited session will bring together advances at the interface of applied mathematics, computational science, control, machine learning, and microbial biotechnology. It will address methodological developments for the modeling, simulation, identification, and control of microbial and bioprocess systems, with a focus on how mechanistic and data-driven approaches can be combined to develop predictive and dynamically updated models of microbial processes. Topics will include mechanistic models of microbial populations and metabolic resources; qualitative and stability analysis; parameter identifiability and sensitivity; state and parameter estimation from sparse or heterogeneous observations; experimental design; optimal control; and uncertainty quantification. Particular attention will be given to hybrid approaches combining mechanistic knowledge with data-driven methods, including physics-informed learning, neural ordinary differential equations, hybrid models, and surrogate-based control. Such approaches offer new possibilities for reconstructing latent biological states, learning unresolved dynamics, optimizing operating conditions, and designing feedback strategies. Applications may span food and alcoholic fermentation, microbial production, anaerobic digestion, gut and rumen fermentation, and the management of microbial communities. By connecting fundamental mathematical questions to experimentally grounded, industrially relevant applications, the session aims to identify common methodological challenges and opportunities across microbial systems and operating regimes. Recent work has framed microbial-system digital twins as collections of models dynamically connected to their physical counterparts through data and control flows [1]. Building on this perspective, the session will explore how models can evolve from retrospective descriptions to predictive, dynamically updated tools for monitoring, optimization, and control.

REFERENCES

[1] S. Labarthe et al., *From Concept to Perspective: Digital Twins of Microbial Systems*. Preprint, HAL: hal-05613501 (2026).