Data-Driven Engineering of Sustainable Food Processes: From Machine Learning Models to Techno-Economic Optimization

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The food industry faces increasing pressure to develop sustainable, resource-efficient processes while maintaining product quality and safety. Meeting these challenges requires moving beyond empirical approaches toward quantitative, model-assisted process engineering. This talk presents an integrated framework in which machine learning, hybrid modelling, and techno-economic analysis support the rational design and scale-up of innovative food processes.

A first pillar concerns predictive modelling of complex processing operations. Through meta-analysis of literature data and systematic incorporation of dimensionless numbers encoding fluid-mechanical, microorganism-specific, and equipment-related variables, hybrid grey-box models, combining empirical Weibull kinetics with random forest components, were developed for microbial inactivation by high-pressure homogenization. This hybrid approach outperformed purely black-box models, achieving lower prediction errors while preserving physical interpretability.

A second pillar addresses the integration of economic and sustainability metrics into process decision-making. Using pulsed electric field (PEF)-assisted polyphenol extraction from red grape pomace as a case study, techno-economic analysis through process simulation, scale-up, and Monte Carlo uncertainty analysis showed that PEF pretreatment can reduce unit production costs and improve return on investment compared to conventional extraction, with outcomes depending critically on product price, solvent composition, and raw material costs.

Together, these results illustrate how the coupling of artificial intelligence, mechanistic insight, and economic assessment defines a new paradigm for engineering future foods, one in which sustainable processing technologies can be systematically optimized and scaled with confidence.