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Developing early-warning systems for improved microalgae PROduction and anaerobic DIGestIOn (PRODIGIO)

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INDEX

DEVELOPING EARLY-WARNING SYSTEMS FOR IMPROVED MICROALGAE PRODUCTION AND ANAEROBIC DIGESTION (PRODIGIO)

Abstract

Process monitoring is a crucial task for bioprocess optimization and will play a decisive role in the digitization of future biobased production systems. System failure prediction technologies must be an integral part of monitoring schemes; however, they are underdeveloped as far as the bioenergy industry is concerned. The objective of PRODIGIO is to establish a base of knowledge for the development of system failure prediction technologies that increase the performance of microalgae production and anaerobic digestion systems and advance towards more favorable techno-economic, environmental and social performance to achieve more sustainable microalgae biogas. By combining perturbation experiments in bioreactors systems and cutting-edge methods for big data analysis, PRODIGIO will decode the triggers, identify early-warnings, define threshold values, and calculate warning times for critical state transitions in bioreactors. Taking into account processes inefficiencies, we estimate that, along with the implementation of prevention countermeasures, PRODIGIO technology could contribute to increasing resource and energy efficiencies > 50% throughout the production chain, which would translate into OPEX savings and GHG emissions reduction. The technological solutions that will derive from the project, such as a catalog of early warning signals for the failure of microalgae production and conversion-to-biogas systems, will be pre-commercial in nature; however, a roadmap will be compiled and updated during the course of the project that will identify priority research lines for further development and future implementation of technology. The results of PRODIGIO will pave the way for moving the entire microalgae biogas production chain efficiently towards its theoretical maximum, enabling the development of a fully integrated and truly sustainable microalgae biogas production industry and contributing to strengthening the EU's leadership in renewable fuel technologies.

INTRODUCTION

The increasing energy demand in the World is drawing attention to the need for developing new supply pathways based on inexhaustible sources with reduced environmental impacts[1]. If managed sustainably, biofuels are renewable energy resources for heat, power and transportation that can contribute to less GHG emissions and atmospheric contaminants than fossil fuels. However, as of 2020, the adoption of biofuels falls short of the predicted expectations to align with the sustainable development scenario (SDS). For example, according to the International Energy Agency, transport biofuel consumption needs to almost triple by 2030 (to 298 Mt oil equivalent) to be on track with the SDS[2]. This equates to 9% of global transport fuel demand, compared with the current level of around 3%. To increase the adoption of biofuels and meet the SDS targets, it is mandatory to achieve performance breakthroughs and cost reductions for large-scale production of advanced biofuels[3].

Microalgae are some of nature's finest examples of solar energy conversion systems, transforming carbon dioxide into complex organic molecules through photosynthesis. They are capable of achieving solar energy to biomass conversion efficiencies up to one order of magnitude higher than oleaginous crops, and there is biotechnology potential to further increase conversion efficiency[4]. Due to their outstanding photosynthetic yields and ability to grow in non-arable lands, non-potable water sources (e.g. wastewater, seawater), and a wide range of environmental conditions, there is much interest in the use of microalgae biomass as a source of truly sustainable bioenergy feedstock[5]. Despite this potential, no commercial facilities for biofuel production from microalgae have been implemented in the EU. The dilute concentrations of microalgae in the growth media impact negatively on the biofuel life cycle energy balance as it takes much energy to harvest, concentrate and dry the biomass.

Anaerobic digestion (AD) is probably the most economically attractive process for the production of biofuel from microalgae since it does not require drying of biomass and it is a relatively simple procedure from an infrastructure and engineering perspective[6,7]. AD is a natural biomass degradation process carried out by microorganisms, which very efficiently transform the organic matter firstly into intermediate bioproducts and finally into biogas under anaerobic conditions. The potential of microalgae for biogas production stems from the fact that microalgae contain large amounts of biodegradable compounds, such as carbohydrates (5–50%), lipids (5–60%), and proteins (5–70% of total solids), which can produce methane (CH_4) with the theoretical yield of 0.42, 1.01, and 0.5 LSTP CH_4/g, respectively. Microalgal photobioreactors (PBRs) and anaerobic reactors (ARs) are key components involved in microalgae biomass production and conversion-to-biogas, respectively (Figure 1). However, none of these bio-based production systems is functionally optimized for large-scale applications, resulting in process instability and unfavorable economy[8,9,10,11,12].

Process instability results from perturbations that alter the structure and dynamics of microbial communities and reduce the performance of ecosystems to provide services. The development of system failure prediction technologies is thus crucial for the timely implementation of preventive measures that ensure process stability over time. Concerning microalgal PBRs and ARs, these technologies are underdeveloped, which makes them work at sub-optimal performances. Only by improving the performance stability of microalgae biomass production and biogas conversion systems will this renewable energy technology become truly sustainable and profitable.

The MAIN objective of PRODIGIO is to establish a knowledge base for the development of a system failure prediction technology that increases the performance of microalgae biomass production and anaerobic digestion systems and advance towards more favourable techno-economic, environmental and social performance to achieve more sustainable microalgae biogas.

CONCEPT

Scaling-up biological processes from laboratory-scale experimental trials to industrial-scale applications leads to a systematic loss of efficiency, which impacts adversely the economic viability and the potential environmental benefits of the technology. Process instability is critical in nonlinear dynamical systems, such as microalgal photobioreactors (PBRs) and anaerobic reactors (ARs), where the functioning of complex microbial communities largely controls their performance stability[16,17]. These dynamical systems can undergo transitions where the system shifts from one stable state to another at a critical threshold, also called the tipping point[18]. Critical state transitions are the result of unexpected perturbations, which alter the structure and functioning of the microbial communities in confinement. Under these circumstances, the transient states of the bioreactors tend to diverge, which makes the steady-state to become unstable and much more vulnerable in the face of additional perturbations. Because critical state transitions alter the efficiency of microbial communities for the provision of services, anticipating the failure of the system is crucial for the timely implementation of prevention and/or mitigation countermeasures that ensure process stability and technology profitability in the long-term (Figure 1).

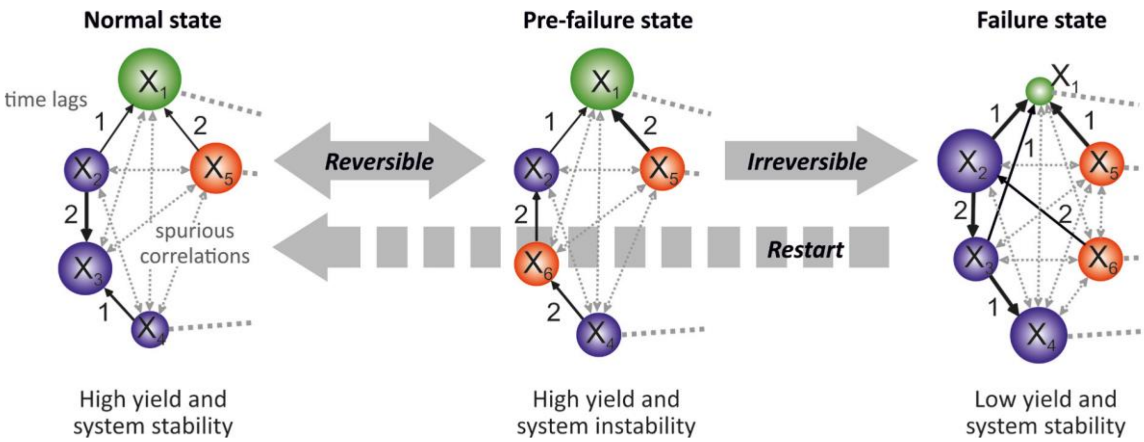

Figure 1. Conceptual diagram of PRODIGIO methodology.

METHODOLOGY

The methodology of PRODIGIO was devised by partners with a strong background in theoretical, experimental and computational ecology, analytical chemistry, bioprocess engineering, and data management. The project design aims to maximize the acquisition of new knowledge and provide innovative solutions for the development of advanced monitoring and control systems that contribute to the sustainability of biogas produced from microalgae and to its future commercial exploitation.

PRODIGIO is designed around three activity streams (AS#) including experimental simulations, big data analysis, and sustainability assessment of the proposed technology (Figure 2).

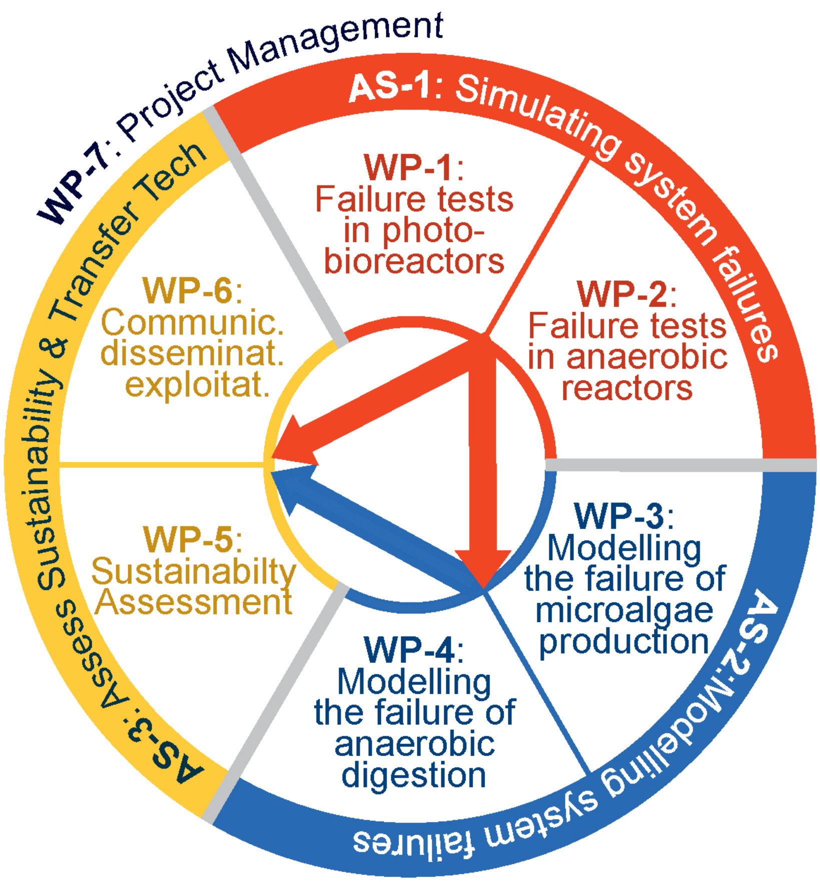

Figure 2. The workflow of PRODIGIO

- The first activity stream (AS1) is devoted to simulate the failure of lab-scale PBRs (WP1) and ARs (WP2). We will conduct time-course experiments in which the bioreactors will be forced to fail (i.e. to move from the normal state to the failure state). These experiments will generate high-resolution time series of routine, metaOMICs and chemical fingerprinting data with the potential to i) uncover the mechanisms underlying critical state transitions and ii) identify early-warning signals.

- The second activity stream (AS2) will be built upon the routine, metaOMICS and chemical fingerprinting data generated in AS1 (WP1, WP2), and aims to examine from an analytical/modelling perspective the failure of bioreactors, PBRs (WP3) and ARs (WP4), using bioinformatic tools, mathematical models, and state-of-the-art causal detection methods. The aims are to obtain a deep understanding of the eco-genomics in bioreactor systems and its linkage to the stability of bioreactor processes, and to develop a new method to identify efficient warning signals. AS1 and AS2 will be carried out sequentially so AS2 is readily fed from the experimental data derived from AS1.

- The third activity stream (AS3) is focused on evaluating the extent to which the implementation of PRODIGIO technology will improve the sustainability and profitability of algal PBRs and ARs for biofuels production (WP5). AS3 will also contribute to technology transfer through communication, diffusion and intellectual property exploitation activities (WP6). AS3 will be carried out in parallel with AS1 and AS2 in order to optimize project's time and resources. AS3 will receive continuous feedback from AS1 and AS2 (Figure 2).

EXPECTED IMPACT

One of the main aims of PRODIGIO is to transfer scientific results in general and shared knowledge for the development of innovative system failure prediction technologies that help optimize the functionality of microalgal biomass production and conversion systems. New solutions identified within the project will show the main benefits for the sectors of algae biomass production (nutraceuticals, aqua-feed, C-sequestration, etc), WWT, bio-waste management and biogas production in Europe. The technological outputs (pre-commercial) will be a catalogue of pest predictors (for microalgal production) and early warnings (for AD) anticipating process failures. These results will provide a solid knowledge base to produce more efficient and premature warnings and more affordable monitoring systems aimed at improving bioreactor performance stability. Further development of the proposed technology for its future implementation in industrial-scale bioreactors, will improve resource-, energy-, and cost-efficiency.

The project will contribute to the regulation and standardization in the field of secure, clean and efficient energy. More specifically, PRODIGIO will provide policy briefs about the future generation of alternative fuels derived from microalgae biomass, thus streamlining the interest of mainly the bioenergy, aquaculture and wastewater treatment sectors.

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