Title

Modeling and analysis of an ecosystem of bacteria and phages to minimize sludge expansion and foam formation in activated sludge water treatment

Summary

Biological wastewater treatment has gained increasing prominence in global environmental concerns. Its operation presents more complex challenges than classical industrial processes, highlighting the need for efficient control strategies. Despite the ever-increasing advanced automation of wastewater treatment processes, open issues still require more analysis and the deployment of new control strategies.

Interest in phages' ability to control bacterial populations has extended from medical applications into agriculture, aquaculture, and the food industry. Specifically, several studies have proposed bacteriophages as a promising alternative to control foaming and bulking in wastewater treatment systems. This strategy has shown successful results at the laboratory scale. However, this technology is still in development, and several challenges must be overcome before bacteriophages can be widely used to control foaming and bulking in pilot or larger-scale treatment plants. Bacteriophage treatment for foaming control might be the basis for a more efficient, economical, and sustainable control than the current practice based on chemical treatments.

Assays at the pilot scale involve specifically targeted bacteria. The real-life scenario includes a complex community of microorganisms and certain environmental stress factors that might affect the performance of bacteriophages employed for phage therapy. To include these factors, a thorough study of the treatment plant parameters and microbial community involvement must be performed to implement a large-scale study of phage therapy. Computational modeling is necessary to start phage-based implementation of treatment against bulking and foaming caused by an overgrowth of filamentous bacteria. Several models of the infection mechanisms in individual bacteria-phage pairs have been reported, i.e., for controlled systems with only one bacterial species in the presence of one phage species. However, activated sludge treatment systems broadly differ from this situation.

This research begins with a literature review on the modeling, analysis, and application of phage-bacteria systems, emphasizing the importance of rigorous model formulation. Mathematical models play a key role in the development process, and the next chapter offers an overview of the proposed models, their structure, advantages, and disadvantages. Then, a candidate model of bacteria and phage populations is proposed that is simple enough to describe experimental results in the context of wastewater treatment and serve as a basis for process control.

The model is evaluated for essential system properties such as stability, identifiability, and observability—key prerequisites for process prediction, monitoring, and dynamic optimization. The development of software sensors based on the model would allow significant advances in monitoring important biological variables, such as the time evolution of filamentous bacteria concentration. It would alleviate the lack of online hardware sensors to achieve such tasks. The well-known Extended Kalman Filter (EKF) is implemented, achieving satisfactory reconstruction of nonmeasured variables.

Moving forward in exploiting the model, optimal control is developed to evaluate the critical parameters of phage therapy, such as phage doses and concentrations. This study demonstrates the feasibility of controlling bacteria that cause operational problems, such as bulking and foaming, in wastewater treatment with an activated sludge system.

The final component of this work integrates the proposed model into a broader framework based on the Activated Sludge Model No. 1 (ASM1), providing a more realistic context for evaluating bacteriophage-based biocontrol strategies within full-scale wastewater treatment operations.

In conclusion, this doctoral research substantially advances the scientific basis for phage therapy as a solution to bulking and foaming in activated sludge systems. The outcomes offer practical tools and insights for implementing phage-based treatments, positioning them as a viable, cost-effective, and environmentally sustainable alternative to traditional chemical controls. By incorporating ecological and physiological system dynamics, this study lays a solid foundation for the future deployment of bacteriophage-based control strategies.