SymbIO4WWTP: Multi-Symbiotic InterOperable Model for AI-Optimized Sustainable Wastewater Treatment Plants

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***Abstract*—Wastewater treatment plants (WWTPs) play a fundamental role in protecting public health and preserving water resources. However, their operation remains highly energy-intensive and resource-demanding, while also contributing to greenhouse gas emissions. Although numerous optimization strategies have been proposed, most focus on specific treatment processes and overlook the broader interactions between wastewater treatment, resource recovery, and neighboring sectors. The SymbIO4WWTP (Multi-Symbiotic InterOperable Model for AI-Optimized Sustainable Wastewater Treatment Plants) project addresses this challenge by introducing a holistic framework that combines industrial symbiosis, systems interoperability, and artificial intelligence. SymbIO4WWTP enables coordinated management of energy, water, and material exchanges across interconnected sectors, while AI-based monitoring and optimization support adaptive decision-making under dynamic operating conditions. This work-in-progress paper presents the conceptual framework of the project and discusses its potential to advance circular, resource-efficient, and climate-neutral wastewater treatment systems.**

***Index Terms*—Wastewater Treatment Plants, Industrial Symbiosis, Artificial Intelligence, Sustainability, Systems-of-Systems.**

I. Introduction

Wastewater treatment plants (WWTPs) are essential for protecting public health and preserving water resources by removing pollutants before treated effluents are discharged or reused [1]. Modern WWTPs are also expected to recover water, energy, and valuable materials, evolving into resource recovery systems that support circular economy strategies [2].

Despite these advances, WWTPs remain highly energy-intensive and are significant sources of greenhouse gas emissions. Biological treatment, particularly aeration, accounts for approximately 50–70% of the electricity consumption in conventional activated sludge plants [3]. Improving operational efficiency while reducing emissions and maximizing resource recovery is therefore a key challenge for sustainable wastewater management [2].

Artificial intelligence, machine learning, digital twins, and advanced process control have created new opportunities for predictive monitoring and real-time optimization of WWTPs [4]. However, most existing approaches focus on optimizing individual treatment processes, paying limited attention to resource recovery, industrial symbiosis, interoperability, and cross-sector resource exchanges within a unified framework [5]. Addressing these aspects jointly is essential for the next generation of sustainable WWTPs.

In this context, the SymbIO4WWTP (Multi-Symbiotic InterOperable Model for AI-Optimized Sustainable Wastewater Treatment Plants) project proposes a holistic framework integrating multi-symbiotic resource management, systems interoperability, digital technologies, and artificial intelligence. The framework supports coordinated exchanges of energy, water, and materials between WWTPs and urban, industrial, agricultural, and livestock sectors, enabling adaptive optimization and contributing to sustainable and climate-neutral wastewater treatment systems.

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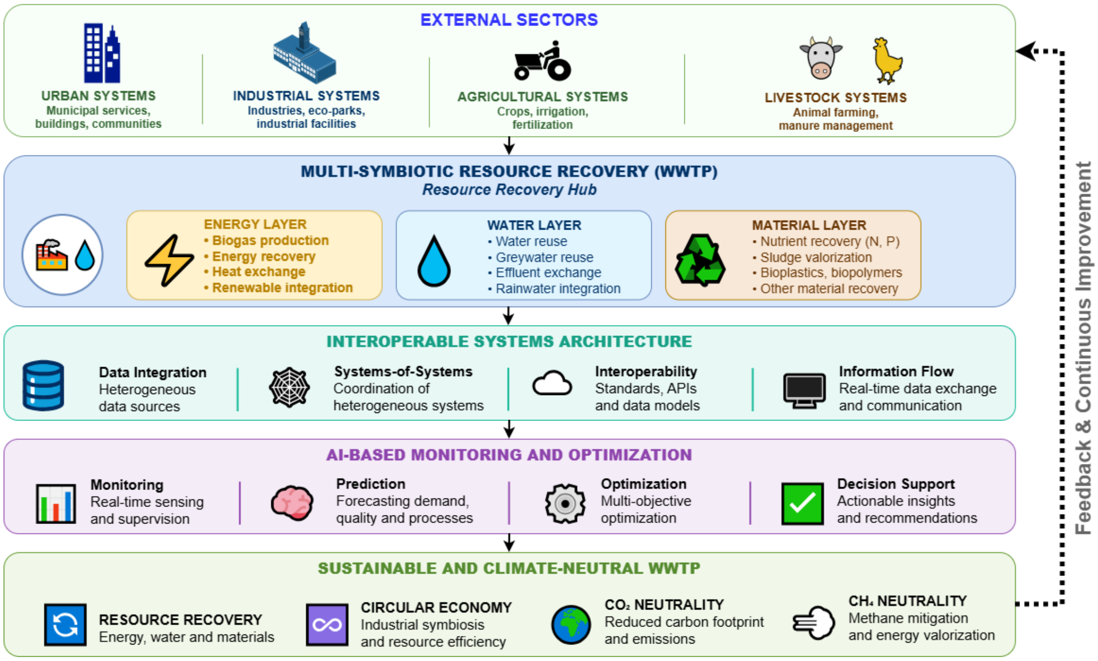

Fig. 1. Proposed Multi-Symbiotic InterOperable Framework illustrating the integration of multi-symbiotic resource recovery, interoperable systems architecture, and AI-based monitoring and optimization for sustainable and climate-neutral wastewater treatment plants.

II. Multi-Symbiotic InterOperable Framework

The proposed Multi-Symbiotic InterOperable Framework transforms conventional WWTPs into interoperable resource recovery hubs. As illustrated in Fig. 1, the framework combines three complementary components that jointly improve operational efficiency, resource recovery, and environmental sustainability.

At its core, the framework promotes **multi-symbiotic resource exchanges** between WWTPs and urban, industrial, agricultural, and livestock sectors through integrated energy, water, and material layers, enabling energy recovery, treated water reuse, and material valorization. These interconnected resource flows are coordinated through an **interoperable Systems-of-Systems architecture**, which integrates heterogeneous data sources using common data models, interoperable standards, and application programming interfaces, enabling seamless information exchange while preserving the autonomy of participating systems. Building on this digital infrastructure, the **AI-Based Monitoring and Optimization** layer transforms operational data into actionable knowledge through real-time monitoring, forecasting, optimization, and decision support, enabling adaptive operation and enhancing resource recovery, operational efficiency, and environmental sustainability.

III. Expected Contributions

The proposed framework is expected to provide a holistic foundation for next-generation wastewater treatment by integrating multi-symbiotic resource management, systems interoperability, and AI-driven optimization within a unified architecture. It is expected to improve resource recovery, operational efficiency, and environmental sustainability while supporting the transition towards interoperable, circular, and climate-neutral WWTPs. In addition, the framework establishes a flexible basis for future developments in digital twins, intelligent control, and advanced decision support.

IV. Conclusions

This paper introduced the conceptual foundations of the SymbIO4WWTP project and its proposed Multi-Symbiotic InterOperable Framework for sustainable wastewater treatment. By integrating multi-symbiotic resource management, systems interoperability, and AI-based optimization, the framework is expected to support the transition towards more intelligent, circular, and climate-neutral WWTPs. Ongoing research focuses on implementing and validating the proposed framework through representative case studies, with the aim of assessing its effectiveness in improving resource recovery, operational efficiency, and environmental sustainability.

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