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# Advancing Decentralized Water Management through Digital Twin Modeling: Control and Monitoring of Source-Separated Systems

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**Abstract:** This study advances the technical assessment of decentralized source-separation systems for urban water management through pilot systems, a model-based digital twin, and advanced monitoring and control systems. Three pilot systems representing distinct processes within source separation - anaerobic CSTRs for black/brown water, nature-based systems for grey water, and macroalgae reactors for yellow/grey water - are being operated and monitored to demonstrate the potential of integrated resource recovery. The control architecture includes modules for anaerobic digestion, grey water treatment, and nitrogen removal to simulate resource recovery processes. The digital twin processes operational data to predict system responses and optimize performance, and the modeling results based on the pilot operations provides further evidence that source-separated treatment could achieve 85% water reuse and 60% energy recovery. This integration of instrumentation with digital modeling demonstrates that decentralized systems can operate reliably under variable conditions. The study establishes monitoring requirements and control strategies for source separation implementation, contributing to the development of decentralized systems for sustainable urban water management.

**Keywords**: Real-time Control; Pilot Systems; Process Monitoring; Source-Separation.

## Introduction

Decentralized source-separation systems for water, energy, and nutrient recovery are emerging as promising solutions to address the mounting challenges in urban water management, particularly as traditional centralized infrastructure faces increasing pressure from population growth, climate change, and chronic underinvestment (Bhambhabi, 2025; Keller, 2024; Garrido-Baserba, 2024; Leigh, 2019; Capodaglio, 2020). Conventional water and wastewater treatment infrastructure, particularly the energy-intensive activated sludge process, face increasing scrutiny due to their environmental and economic costs and their vulnerability to extreme weather events driven by climate change (Daigger et al., 2019; IPCC, 2024; Olsson, 2015; Sedlak, 2024; van Loosdrecht & Brdjanovic, 2014).

This study presents the real-time digital twin of three pilots representing the distinct processes within a decentralized source separation approach (Brown/Yellow/Grey Water) to demonstrate that anaerobic co-digestion together filtration/nature-based technologies offer the highest recovery rates for water, energy, and nutrients. This comprehensive six-year investigation into the technical, economic, and environmental implications of implementing decentralized source separation systems for urban water management demonstrates the greatest potential to enhance the global water system's sustainability, reliability, and resilience.

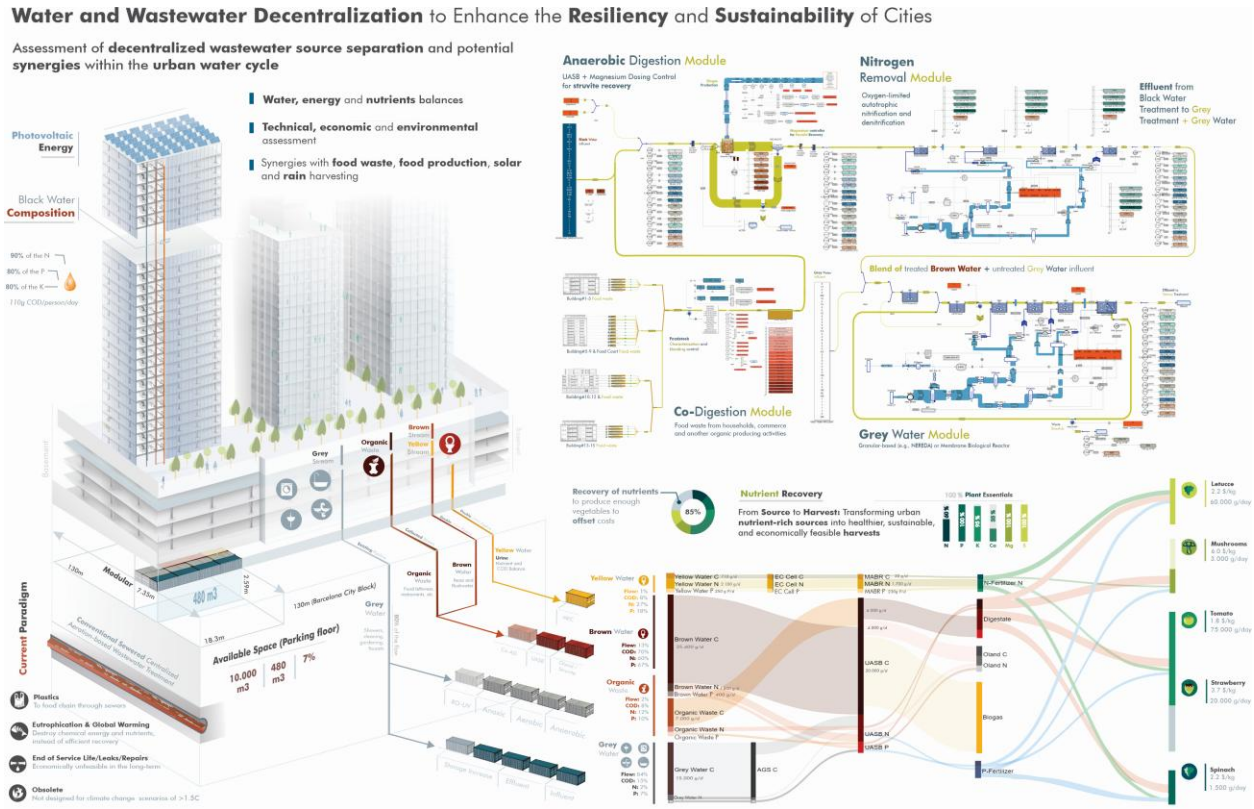


**Figure 1.** Representation of the source separation-based approach in an urban cluster [city block] together with a SIMBA# Model implementation and LCA model to link the water-food-energy nexus. The model is fed from three different pilots corresponding to the distinct processes within a typical source separation approach (Brown/Yellow/Grey Water).

## Methodology

The research infrastructure integrates three parallel pilot systems (Anaerobic CSTRs for black/brown water, nature-based systems for grey water, and macroalgae-based reactors for grey/yellow water) with real-time process modeling capabilities. The digital architecture comprises specialized modules: an Anaerobic Digestion Module incorporating co-digestion functionalities, a Grey Water Module for treatment process simulation, and a dedicated Nitrogen Removal Module. This modeling framework enables comprehensive techno-economic analysis across three critical dimensions: Resource Recovery (achieving 85% water reuse potential and 60% energy recovery through anaerobic digestion), Economic Analysis (incorporating capital and operational expenditures with revenue streams), and Environmental Impact Assessment (quantifying Global Warming Potential and Eutrophication Potential through standardized LCA methodology). The integrated approach enables simultaneous optimization of treatment efficiency, resource recovery, and environmental performance while maintaining economic viability under various operational scenarios.

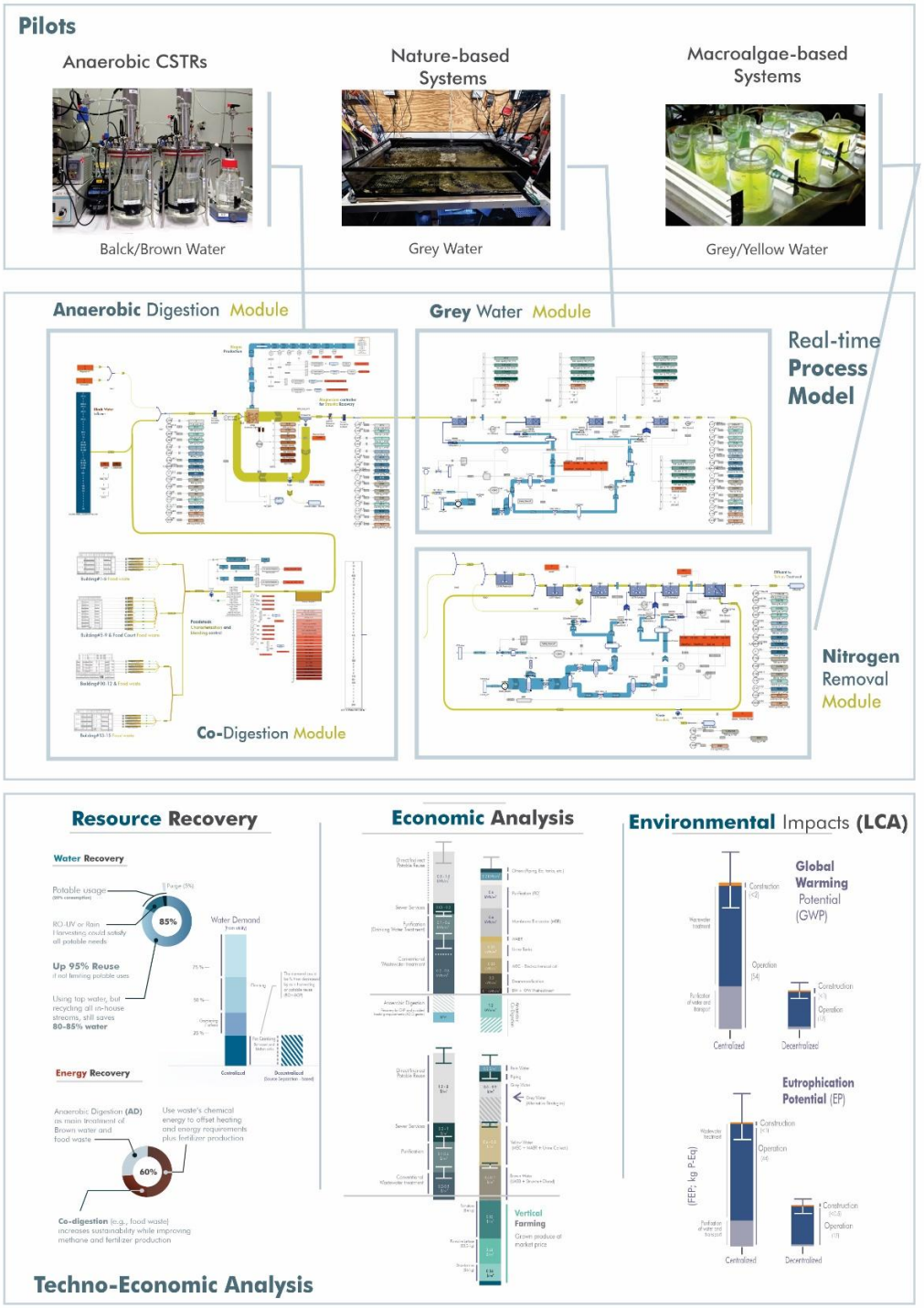


**Figure 2.** Multi-scale framework architecture integrating pilot systems, real-time process models, and techno-economic assessment: from pilot-scale validation to integrated assessment of source-separated water systems. The framework combines three pilot systems (Anaerobic CSTRs, Nature-based Systems, and Macroalgae-based Systems) with specialized process modules (Anaerobic Digestion, Grey Water treatment, and Nitrogen Removal) to evaluate resource recovery potential, economic feasibility, and environmental impacts through Life Cycle Assessment (LCA).

## Results

Instrumentation and control considerations for decentralized source-separated systems were evaluated through the integration of digital twin modeling with pilot operations. The research

confirms that source separation inherently enables higher recovery efficiencies while establishing a monitoring framework for concentrated resource streams.

The digital twin framework elucidates system dynamics and process behaviors, providing insights into instrumentation requirements for full-scale implementation. This advances the development of resilient water infrastructure that optimizes resource recovery through targeted process control, laying the groundwork for efficient urban-scale deployment.

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