

AQUA-LOOP: Low-Energy Phosphorus-Recovering Membranes for Circular Municipal Wastewater Treatment

October 2026

Scientific Ambition: Closing the Urban Phosphorus Loop Through Energy-Neutral Membrane Separation

AQUA-LOOP addresses the critical dual challenge of phosphorus scarcity and wastewater energy intensity by developing next-generation electro-responsive nanocomposite membranes. Current state-of-the-art reverse osmosis and nanofiltration systems require high pressure and frequent chemical cleaning, resulting in significant carbon footprints. Our ambition is to redefine this baseline by achieving simultaneous >92% phosphorus recovery as struvite-precursor and >99.5% pathogen removal at an operational energy demand of <0.3 kWh/m³. This represents a 60% reduction compared to existing tertiary treatment technologies.

Performance Target. Operational energy demand <0.3 kWh/m³ while maintaining >92% phosphorus recovery efficiency.

By integrating biofouling-resistant surface chemistry with dynamic pore-size modulation, AQUA-LOOP enables energy-neutral resource recovery, directly supporting the EU Green Deal's circular economy objectives. The project moves beyond incremental efficiency gains to establish a new paradigm where municipal wastewater treatment plants function as nutrient refineries rather than disposal sites, ensuring long-term agricultural security and water quality compliance.

Integrated Methodology: From Lab-Scale Membrane Synthesis to Pilot-Scale Wastewater Validation

The AQUA-LOOP methodology employs an iterative, co-designed workflow across five technical work packages to bridge the gap between material innovation and industrial application. The process begins with combinatorial membrane fabrication, where electro-responsive nanocomposites are synthesized and optimized for selective phosphorus binding. This is followed by dynamic fouling simulation to assess long-term stability under realistic hydraulic conditions. Real-time phosphorus speciation monitoring ensures precise control over struvite-precursor recovery rates. The final phase involves cross-consortium validation using representative influent and effluent matrices sourced from municipal wastewater treatment plants in Lisbon, Helsinki, and Rotterdam. This multi-site approach guarantees that the technology performs ly across diverse European water chemistries and operational contexts, ensuring scalability and regulatory compliance.

Open Science Commitment: FAIR Data, Reproducible Protocols, and Pre-Competitive IP Sharing

AQUA-LOOP strictly adheres to the FAIR (Findable, Accessible, Interoperable, Reusable) data principles mandated by Horizon Europe. All experimental datasets generated during membrane synthesis, electro-responsive nanocomposite characterization, and pilot-scale validation will be deposited in Zenodo upon publication or project completion, whichever occurs first. These datasets will be assigned Digital Object Identifiers (DOIs) and licensed under CC-BY 4.0 to ensure maximum reusability by the scientific community.

This includes raw spectroscopy data, flux performance logs, and phosphorus speciation metrics from the Lisbon, Helsinki, and Rotterdam test sites.

To enhance reproducibility, the consortium will publish detailed synthesis protocols for the low-energy membranes in the Journal of Open Source Software (JOSS) or equivalent open-access platforms. These publications will include code repositories for the dynamic fouling simulation models and real-time monitoring algorithms developed in Work Package 3. By making these computational tools openly available, AQUA-LOOP enables other researchers to validate our energy demand calculations ($<0.3 \text{ kWh/m}^3$) and adapt the models for different wastewater matrices.

Pre-Competitive IP Management. A Consortium Agreement establishes an IP Management Board to govern the exchange of background and foreground knowledge. Pre-competitive know-how related to fundamental membrane chemistry is shared openly among partners to accelerate development, while specific commercial applications for SME partners are protected through defined licensing pathways post-project.

Impact Pathways: Accelerating Uptake Across the EU Water Innovation Ecosystem

The regulatory impact pathway focuses on supporting the revision of Annex I of the Urban Wastewater Treatment Directive. By demonstrating consistent phosphorus recovery rates exceeding 92% and pathogen removal above 99.5% at energy demands below 0.3 kWh/m^3 , AQUA-LOOP provides the empirical evidence base required for EU policymakers to tighten nutrient discharge limits. This data will be synthesized into policy briefs for the European Environment Agency and DG ENV, facilitating the integration of resource recovery metrics into future compliance frameworks.

Industrial uptake is driven by the two SME partners, who will lead manufacturing scale-up by Month 36. The pathway transitions from lab-scale synthesis to pilot production, ensuring that the low-energy membranes are commercially viable and ready for market entry. This route includes dedicated webinars on membrane licensing and technology transfer protocols, aimed at establishing a supply chain for circular water technologies across Europe.

Municipal integration involves pilot deployment with four utility partners by Month 30. These pilots, located in Lisbon, Helsinki, Rotterdam, and a fourth site to be confirmed, will validate the technology under real-world operating conditions. The pathway ensures that local water operators can adopt the technology with minimal infrastructure retrofitting, directly contributing to the Zero Pollution Action Plan targets for nutrient reduction in urban water cycles.

Impact Route	Key Performance Indicator	Target Value	Timeline
Regulatory	Evidence packages for UWWTD revision	3 comprehensive dossiers	Month 42

Impact Route	Key Performance Indicator	Target Value	Timeline
Industrial	SME manufacturing readiness level	TRL 7 achieved	Month 36
Municipal	Pilot sites operational	4 utilities integrated	Month 30

Dissemination, Exploitation, and Communication Strategy: Targeted Engagement Across Policy, Industry, and Practice

The AQUA-LOOP consortium implements a tiered Dissemination, Exploitation, and Communication (DEC) strategy designed to maximize uptake across regulatory, industrial, and municipal domains. Coordinated by a dedicated Communication Officer, this strategy ensures that scientific outputs translate into tangible market and policy impacts. Activities are tracked via a shared impact dashboard, updated quarterly, to monitor reach and engagement against predefined Key Performance Indicators aligned with the EU Green Deal.

Target Audience	Activity Type	Key Output	Frequency/Timing
Scientific Community	Open Access Publication	Minimum 12 peer-reviewed articles	Months 12-48
Policy Makers (EEA, DG ENV)	Policy Briefs	Evidence-based recommendations for Urban Wastewater Treatment Directive	Months 18, 36, 48
Industrial Partners/SMEs	Webinars & Workshops	Membrane licensing and scale-up protocols	Quarterly from Month 12
Water Utilities/Public	Multilingual Toolkits	Operational guides for phosphorus recovery integration	Month 30 onwards

Exploitation and IP Management. SME partners lead the exploitation route, supported by dedicated webinars on membrane licensing. Pre-competitive know-how is exchanged under a Horizon Europe-compliant agreement, governed by a consortium-wide IP management board to ensure fair access and rapid commercialization post-project.

Work Plan: 48-Month Gantt Chart with Interdependent Work Packages and Critical Dependencies

The AQUA-LOOP implementation strategy is structured into seven interlinked Work Packages (WPs) spanning 48 months, designed to transition low-energy membrane technology from laboratory synthesis to pilot-scale validation. WP1 (Project Management & Coordination), led by TU Delft, runs continuously from Month 1 to 48, ensuring administrative compliance, financial monitoring, and risk mitigation through quarterly Steering Committee meetings.

WP2 (Membrane Material Synthesis & Optimization), led by Fraunhofer IGB, operates from Month 1 to 24, focusing on the development of electro-responsive nanocomposites. This WP is a critical predecessor to WP3, as membrane performance data must be finalized before pilot integration. WP3 (Module Design & Prototyping), led by the SME partners, runs from Month 12 to 36, translating lab-scale materials into scalable module formats. WP4 (Pilot-Scale Validation & Performance Testing), led by Universidade do Porto, commences in Month 18 and concludes in Month 42, utilizing real municipal wastewater streams in Lisbon and Helsinki to validate phosphorus recovery rates (>92%) and energy efficiency (<0.3 kWh/m³).

WP5 (Environmental & Economic Life Cycle Assessment), led by Aalto University, runs parallel to WP4 from Month 24 to 48, providing real-time sustainability metrics to inform design iterations. WP6 (Dissemination, Exploitation & Communication), led by TU Delft, spans the entire project duration, ensuring stakeholder engagement and IP management. WP7 (Ethics & Data Management), integrated across all WPs, ensures GDPR compliance and FAIR data principles.

Critical Path Dependency. The initiation of WP4 pilot testing is contingent upon the successful completion of Milestone M2.3 (Finalized Membrane Formulation) in WP2. Quality assurance checkpoints are embedded at the end of each major phase, requiring formal sign-off by the Technical Advisory Board before subsequent funding tranches are released.

The AQUA-LOOP work plan comprises 28 distinct deliverables designed to track progress from membrane synthesis to pilot-scale validation. These outputs include technical reports, prototype specifications, open-access datasets, and exploitation strategies. Each deliverable has defined acceptance criteria and a responsible beneficiary, ensuring accountability across the consortium of TU Delft, Fraunhofer IGB, Universidade do Porto, Aalto University, and two SME partners.

ID	Title	Type	Due Date (Month)	Lead Beneficiary
D3.2	TRL 4 Validation Report: Membrane Performance in Real Wastewater	Report	18	Fraunhofer IGB
D4.1	Integrated Pilot Unit Design and Safety Protocol	Design Doc	24	TU Delft
D5.3	Life Cycle Assessment and Techno-Economic Analysis	Report	36	Aalto University

ID	Title	Type	Due Date (Month)	Lead Beneficiary
D7.1	Final Exploitation Plan and IP Management Strategy	Strategy	48	Universidade do Porto

Critical Decision Gate. M4.1: Milestone M4.1 (First Integrated Prototype Demonstration) at Month 30 is a binding decision point. Successful demonstration of >92% phosphorus recovery and <0.3 kWh/m³ energy use is required to trigger full-scale pilot deployment in WP5. Failure to meet these KPIs will initiate a predefined contingency plan involving membrane surface modification iterations.

In addition to deliverables, five major milestones structure the project timeline. M1.1 (Project Kick-off and Data Management Plan Approval) occurs at Month 1. M2.3 (Completion of Lab-Scale Membrane Optimization) is scheduled for Month 12. M4.1 (First Integrated Prototype Demonstration) serves as the mid-term technical gate at Month 30. M6.2 (Regulatory Compliance Review for Urban Wastewater Treatment Directive) is set for Month 42. The final milestone, M7.1 (Project Closure and Final Reporting), concludes the action at Month 48. These milestones ensure that technical risks are managed iteratively and that exploitation activities align with regulatory developments.

Consortium Strength: Complementary Expertise, Proven Collaboration, and Governance Rigour

The AQUA-LOOP consortium unites six partners with complementary expertise in membrane science, process engineering, and commercialization. TU Delft (Coordinator) leads membrane modelling and system integration. Fraunhofer IGB provides pilot-scale validation infrastructure. Universidade do Porto contributes advanced material synthesis. Aalto University specializes in biofouling mechanisms. Two SMEs drive rapid prototyping and market uptake. The partners have a proven track record of collaboration, having jointly executed the H2020 WATER-RECYCLE project, ensuring established communication channels and shared technical standards.

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Governance is structured around a Steering Committee for strategic oversight and a Technical Advisory Board for scientific guidance. All partners have signed conflict-of-interest declarations. Task allocation is equitable, reflecting core competencies: TU Delft handles WP1 and WP7; Fraunhofer IGB leads WP4; Universidade do Porto leads WP2; Aalto University leads WP3; and the SMEs lead WP5 and WP6.

Resources and Budget: EUR 5,920,000 Allocation Aligned with Technical Effort and Risk Profile

The total requested EU contribution for the AQUA-LOOP project is EUR 5,920,000 over a duration of 48 months. This budget is structured to reflect the intensive experimental phases in membrane synthesis and pilot-scale validation, ensuring sufficient resources for high-fidelity testing across diverse municipal wastewater matrices. Personnel costs constitute the largest share at 62%, reflecting the highly skilled research effort required from TU Delft, Fraunhofer IGB, Universidade do Porto, Aalto University, and the SME partners. Equipment costs account for 18%, primarily allocated to the acquisition and modification of cross-flow filtration units and real-time phosphorus speciation sensors at the pilot sites. Consumables represent 12% of the budget, covering chemical reagents for struvite precipitation trials and membrane materials. Subcontracting is limited to 8%, focused on specialized life-cycle assessment services. A 10% contingency reserve is embedded within the work package allocations to mitigate technical risks associated with scaling up nanocomposite membrane fabrication. All financial figures provided are indicative estimates derived from standard national cost models for research institutions in the Netherlands, Germany, Portugal, and Finland. Confirm current supplier prices for specialized membrane equipment and chemical reagents before final submission to ensure accuracy.

Cost Category	Amount (EUR)	Percentage of Total	Primary Allocation
Personnel	3,670,400	62%	Research staff across all beneficiaries
Equipment	1,065,600	18%	Pilot infrastructure and sensors
Consumables	710,400	12%	Membrane materials and reagents
Subcontracting	473,600	8%	Life-cycle assessment and external validation
Total	5,920,000	100%	-

Percentage of Total



Figure 1. Percentage of Total

Budget Validation Note. All financial figures provided are indicative estimates derived from standard national cost models for research institutions in the Netherlands, Germany, Portugal, and Finland. Confirm current supplier prices for specialized membrane equipment and chemical reagents before final submission to ensure accuracy.