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Biological Water Systems as a Sustainable Urban Water Management Solution: Analysis and Findings for Water Treatment, Reuse and Urban Resilience

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ABSTRACT
Natural water systems can provide sustainable solutions for water management in urban environments. The paper discusses technical performance, environmental and economic sustainability, circular resource management and increased urban resilience, as well as a framework for integrated evaluation. Beyond conventional wastewater treatment, biological water systems can remove pollutants while recovering nutrients from wastewater. Treated water can be reused, and other resources, such as energy, can be recovered. Stormwater from urban surfaces can also be managed in biological water systems, and ecological values can be created. Climate change can be addressed by creating adaptive systems that can respond to extreme events.Biological and/or decentralised water systems can employ a range of processes, including microbial, plant-based, algal, filtration, and/or adsorption-based systems or combinations of the above (so-called hybrid systems). Laboratory- or pilot-scale performance does not automatically translate to suitable urban full-scale performance because factors such as incoming water quality, temperature, hydraulic loading, climate, scaling, and system monitoring and stability can affect performance.Many biological and decentralised water systems are environmentally friendly solutions that can reduce energy use, chemicals, pumping, and greenhouse gases, and decrease dependence on large, complex water conveyance systems. Furthermore, blue-green systems can increase biodiversity, allow groundwater recharge, provide urban cooling, and deliver a wide range of other ecosystem services. By transforming wastewater and stormwater flows into sources of water of suitable quality, nutrients, biomass, and energy, biological water systems offer a wide range of potential functions that complement urban drainage systems. Peak flow can be reduced, droughts and floods can be managed better, ecological values can be preserved and even increased, and the reliance on single central urban infrastructure systems can be decreased. This research's major contribution is a five-dimensional framework for assessing biological water systems and other green and grey infrastructure. The five dimensions, i.e., technical performance, environmental sustainability, economic viability, operational feasibility, and institutional readiness, are interlinked and therefore need to be assessed within the same system boundaries and by using the same set of indicators. In summary, biological water systems have many characteristics of a good multifunctional, adaptive and circular solution for water in urban areas. A number of full-scale studies are required to test the systems under normal urban conditions. Long-term monitoring and assessment using common assessment methods, life-cycle analysis and techno-economic evaluation are required. Good governance, enabling legislation, and coordination between stakeholders are also required. More research is also needed into the institutional aspects of the systems.

Keywords: Biological Water Systems; Sustainable Urban Water Management; Nature-Based Solutions; Water Reuse; Resource Recovery; Circular Economy; Urban Resilience; Blue-Green Infrastructure

4.0 Research Findings and Outcomes

In assessing the various functions that biological water systems can fulfill in the urban infrastructure of water-resilient cities, a number of environmental, technical, economic, operational and institutional factors have to be taken into account. By evaluating these factors in more detail, the potential of mono-functional stormwater management systems can be compared to that of multi-functional versions (Mclachlan et al., 2023). A particular example of a hybrid unit for sustainable urban agriculture was also presented (Grochulska-Salak et al., 2021).

Habitat services in water-sensitive cities are provided for densely populated landscapes through stormwater management practices. In order to preserve urban ecosystems and effectively

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manage water resources a multi-scale system of blue and green infrastructure is created in a Water Oriented City (Zaręba et al., 2022).

Sustainable water management with green infrastructure makes huge changes possible in urban environments (Rybicki et al., 2022). Blue-green infrastructure can treat urban stormwater in a sustainable way and can also be used as a source of potable water (Azadgoleh et al., 2025). Bio-physical aspects of green infrastructure can be combined with bio-physical aspects of the urban environment in order to create co-benefits for increased urban quality by means of an interdisciplinary approach (McNabb et al., 2024).

4.1 Alignment of Research Objectives, Questions and Outcomes

Research objective	Research question	Synthesised research outcome
RO1: Evaluate technical performance	RQ1: Effect on pollutant removal, nutrient recovery, water reuse and operational efficiency	Biological systems demonstrate multiple treatment and recovery functions through microbial, plant, filtration, algal and hybrid processes. Their strongest technical proposition is multifunctionality, but performance remains sensitive to influent quality, climate, scale, hydraulic conditions and process control.
RO2: Compare environmental and economic sustainability	RQ2: Environmental and economic sustainability relative to traditional infrastructure	The reviewed evidence supports lower-input and resource-recovery pathways with potential reductions in energy demand, emissions and conveyance requirements. Economic attractiveness is context-dependent and must include life-cycle cost, avoided infrastructure, maintenance, land, and the value of recovered water, nutrients, biomass and energy.
RO3: Examine circular resource management and resilience	RQ3: Contribution to circularity and resilience	Biological systems can close urban resource loops by converting wastewater and stormwater into reusable water, nutrients, biomass and energy. Distributed blue-green functions can also store runoff, reduce pressure on centralised networks, support biodiversity and strengthen adaptation to drought, flooding and heat.
RO4: Develop an integrated framework	RQ4: Factors required for evaluation and promotion	A five-dimensional framework is required: technical performance, environmental sustainability, economic viability, operational feasibility and institutional readiness. These dimensions interact and should be assessed under common system boundaries and standardised indicators.

4.2 Outcome for RO1 and RQ1: Technical Performance of Biological Water Systems

In wastewater treatment, natural processes are used for removing pollutants as well as for recovering resources from wastewater. Biological wastewater treatment systems include activated sludge systems, biofilm systems and also so-called static treatment systems like constructed wetlands.

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The efficiency of removal of different types of contaminants including pathogens and nutrients in biological systems has been the subject of recent studies and is found to be high (Burke et al., 2025; Shamshad & Ur Rehman, 2025).

Environmental factors, which can be outside of operators' control, significantly affect the performance of wastewater treatment systems. For example, increased temperature generally increases the rate of microbial activity within a treatment plant and therefore the rate of degradation of organic matter within wastewater (Lowe, Qin & Mao, 2022). The pH of wastewater can have less of an impact on the majority of organisms that are found in wastewater treatment plants. However, there are a number of key organisms that are involved in wastewater treatment whose metabolic processes could be severely affected by extremely low or high pH values (He et al., 2022).

Apart from pollution abatement, biological water systems can contribute to circularity of water and other resources by means of nutrient cycles and the production of biomass and energy from wastewater and sludge, by means of for example biochar. New concepts, technologies and research questions in urban water management, wastewater treatment and sludge management are needed in order to enhance the efficiency of biological wastewater treatment systems and to support the transition to sustainable urban water management systems (Rao et al., 2025; He et al., 2022; Burke et al., 2025; Shamshad & Ur Rehman, 2025).

Technical outcome area	Mechanism identified in the review	Expected urban-water outcome	Key condition/risk
Pollutant removal	Microbial degradation, filtration, adsorption, phytoremediation and hybrid treatment	Lower organic, nutrient and contaminant loads	Performance varies with influent quality, temperature, hydraulic loading and media condition.
Nutrient recovery	Plant/algal uptake, biomass harvesting and resource-recovery processes	Recovery of N and P for potential productive use	Requires safe recovery pathways and downstream markets
Water reuse	Localised treatment of stormwater, greywater and wastewater	Substitution of potable demand for suitable non-potable uses	Reuse quality standards and public/regulatory acceptance are necessary
Operational efficiency	Decentralized/modular treatment near source	Reduced conveyance and flexible capacity	Monitoring, automation and maintenance capability determine reliability
Energy/resource recovery	Bioelectrochemical, anaerobic and biomass-based pathways	Potential energy and value recovery from wastewater	Net benefit depends on full energy balance and life-cycle assessment

4.3 Outcome for RO2 and RQ2: Environmental and Economic Sustainability

A second research finding regards the increase of environmental sustainability with biological water systems compared to traditional, centralized water systems. However, the degree of sustainability increase cannot be quantified. Increase of sustainability is biggest if mechanical aeration is minimized, use of water treatment chemicals is reduced, need for pumping is decreased and transportation distance is reduced. This increased environmental sustainability can be even bigger if blue-green systems, such as constructed wetlands, bioretention, etc. are incorporated into the water system, by for example increasing the amount of groundwater that recharges, by providing aquatic and terrestrial habitats, by sequestering carbon and by reducing the urban heat island effect.

A comparison of the cost of conventional water infrastructure with that of decentralized biological water systems for water treatment is not straightforward. Although conventional water systems have the advantage of well established design standards and large-scale expertise and economies in operation and maintenance, there are many costs associated with connection to existing pipe networks that are not taken into account in simple capital cost comparisons for new treatment structures. Importantly, decentralized systems can provide a number of values that can be greater than the sum of their parts and so need to be assessed within a life cycle cost framework, with all the

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associated costs and benefits considered within a defined boundary.

The comparison between conventional water and wastewater treatment structures and biological water systems for water treatment has a number of challenges, not least that the comparison must be made on a life cycle cost basis and that the comparison must be made within a defined boundary. Furthermore, the comparison is not a simple one as the functions that are provided by the biological water systems have considerable value over time. These functions can have considerable value over time, in terms of the services that are provided and the costs which have been avoided. Therefore, the comparison is not one of simple treatment efficiency between different forms of infrastructure. Instead, it is a comparison of the service portfolios offered by each.

Comparison dimension	Biological/decentralized systems	Traditional centralized/grey systems	Evaluation implication
Energy and chemicals	Potentially lower where passive/ecological processes dominate	Often dependent on pumping, aeration and engineered treatment	Use life-cycle energy and emissions, not plant electricity alone
Conveyance infrastructure	Treatment can occur close to source	Extensive sewer and transfer networks often required	Include avoided or deferred network costs
Resource recovery	Designed to recover water, nutrients, biomass and sometimes energy	Historically optimised primarily for compliant discharge	Value recovered products using realistic market and quality assumptions
Land and maintenance	May require distributed land and many maintenance points	Concentrated sites with established operating routines	Account for land opportunity cost and distributed maintenance burden
Ecosystem services	Can support biodiversity, infiltration, cooling and amenity	Usually limited ecological co-benefits	Include co-benefits without double counting
Scalability	Modular and adaptable but evidence at municipal scale remains limited	Mature large-scale implementation	Treat scale-up risk as an explicit decision variable

4.4 Outcome for RO3 and RQ3: Circular Resource Management and Urban Resilience

A third important finding relates to the principal strategic value of biological water systems, which is to connect water management to circular resource management. In contrast to the traditional view of water as a linear resource (input = output) such as extract, use and discharge, wastewater and stormwater can be viewed as a carrier of water, nutrients, organics and energy that can be reused in urban environments. In this sense, water treatment structures can move from simply pollution abatement to potential urban resource structures.

A supply pathway for increased water resources is provided through locally generated and distributed reclaimed water of suitable quality for a number of end uses in addition to normal supply provided through the central water supply system. A hydraulic pathway is provided through the use of distributed systems of detention, infiltration and storage as blue-green structures to reduce peak flows and alleviate pressure on the urban drainage system. An ecological pathway is provided through inclusion of vegetated treatment structures to provide habitats and a range of ecological services as well as cooling. An infrastructure pathway is provided through the use of modular systems to increase urban water system capacity and distribute risk of failure from reliance on a single large centralized asset.

However, for a closed-loop system to function, circularity must be interlinked with resilience. This means that for example nutrient recovery from wastewater must be supplied to safe agricultural or industrial use to close the loop. Reclaimed water of suitable quality that has no demand, no storage and no distribution does not bring any benefits to the city. This therefore means end-use integration of the resource recovery functions provided by biological water systems through appropriate quality controls and through appropriate institutional and/or governance arrangements to allow for stable urban functions and services provided over time.

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Resilience/circularity pathway	Immediate output	Long-term urban contribution
Water reuse	Reclaimed water available near demand	Reduced pressure on potable supply and improved drought resilience
Nutrient recovery	Recovered N, P and biomass	Reduced resource loss and potential substitution of virgin inputs
Runoff attenuation	Storage, infiltration and delayed discharge	Lower peak flows and reduced flood pressure on drainage networks
Ecological services	Vegetation, habitat, evapotranspiration and cooling	Biodiversity support, urban cooling and improved environmental quality
Distributed capacity	Multiple local treatment/recovery nodes	Greater flexibility and reduced dependence on single centralised assets
Hybrid integration	Biological/blue-green functions linked with grey infrastructure	Adaptive system capable of using strengths of both centralised and decentralised assets

4.5 Outcome for RO4 and RQ4: Integrated Multi-Dimensional Evaluation Framework

The integrated framework for large-scale adoption of wastewater treatment and reuse presented in this review paper goes beyond assessing the ability of wastewater treatment to remove pollutants in order to ensure large-scale adoption of wastewater treatment and reuse. Five dimensions for assessment of wastewater treatment and reuse need to be considered, with immediate outcomes for each of the dimensions, but long-term value of biological water systems through the interactions of the five dimensions: technical performance, environmental sustainability, economic viability, operational feasibility, and institutional readiness.

Technical performance: Does the system effectively treat wastewater and recover resources? Environmental sustainability: Do the system's outputs not shift impacts to other areas of energy use, emissions, land use and ecosystem use? Economic viability: Is the system's long-term affordability a given? Operational feasibility: Can the system be maintained, monitored and managed under real climate and hydraulic conditions? Institutional readiness: Are all governance, regulation, planning, stakeholder and policy issues in place to support large-scale implementation?

Each of the five dimensions for evaluating performance has immediate outcomes but long-term value is only created by interactions between them. Therefore, a high removal efficiency of pollutants does not automatically translate into successful scale-up if the long-term costs of maintenance are perceived to be too high. Similarly, low energy consumption is not automatically translated into successful scale-up where there are non-compliances with rules and regulations, or where high levels of policy support exist but variable treatment performance.

Framework dimension	Core indicators for future validation	Decision question
Technical performance	Pollutant removal; nutrient recovery; reuse quality; hydraulic performance; process stability	Does the system reliably deliver the required treatment and recovery functions?
Environmental sustainability	Energy demand; GHG emissions; biodiversity; ecosystem services; life-cycle impacts	Does the system reduce total environmental burden rather than shift it elsewhere?
Economic viability	CAPEX; OPEX; life-cycle cost; avoided infrastructure; value of recovered outputs	Is the service portfolio affordable and financially sustainable over its life?
Operational feasibility	Maintenance; monitoring; automation; land; climate sensitivity; robustness	Can operators keep the system functioning under real urban conditions?

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Institutional readiness	Regulation; governance; stakeholder coordination; planning integration; policy support	Can institutions authorise, coordinate, finance and sustain implementation?

4.6 Descriptive Evidence Profile of the Manuscript

To give a better overview of the huge qualitative literature that has been read for this manuscript than converting it into non-existence performance data, a simple descriptive keyword tagging has been applied to the literature review, the research gap as well as the conceptual framework sections of the manuscript. Thus, the counts only reflect the different emphasis placed by the author of the manuscript on the respective topics. Hence, the counts do not allow for a comparison of studies with respect to the size of effects, quality of evidence etc. However, they very clearly indicate the huge research gap that needs to be tackled in future validation studies by means of more empirical studies on the governance and implementation conditions of wastewater treatment and reuse in different contexts. Five dimensions need to be assessed, and each will have immediate outcomes, but the long-term value of the system will come from the interactions between the five dimensions of technical performance, environmental sustainability, economic viability, operational feasibility, and institutional readiness.

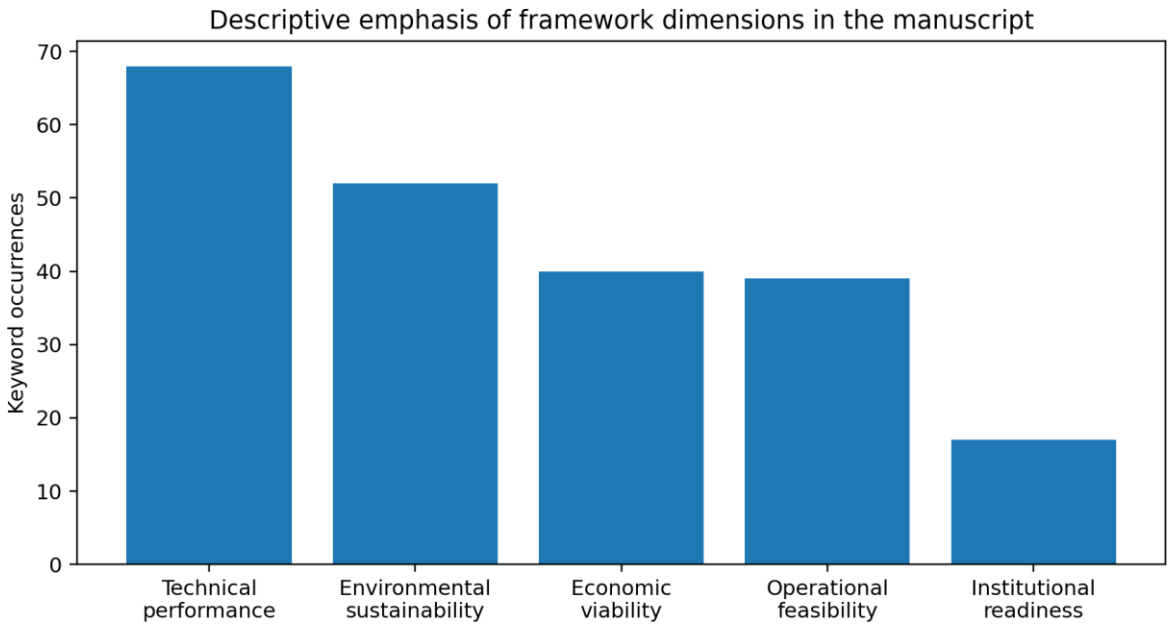

Figure 1. Descriptive keyword-coded emphasis of the five framework dimensions in the manuscript (technical = 68; environmental = 52; economic = 40; operational = 39; institutional = 17). Counts are descriptive text occurrences, not performance scores.

4.7 Consolidated Answers to the Research Questions

RQ	Consolidated answer
RQ1	Biological water systems can improve pollutant removal, nutrient recovery and local water reuse through combined biological, physical and ecological processes. Operational efficiency is promising but depends on climate, loading, scale, monitoring and process stability; long-term full-scale evidence remains necessary.
RQ2	Their sustainability advantage is strongest when life-cycle and techno-economic assessments capture lower energy/chemical demand, avoided conveyance, resource recovery, and ecological co-benefits. No universal economic or environmental superiority can be concluded across all contexts.

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RQ3	They support circularity by converting wastewater and stormwater into reusable water, nutrients, biomass and energy, and support resilience through distributed capacity, runoff attenuation, ecosystem services and climate adaptation. Benefits depend on actual end-use integration.
RQ4	Evaluation and promotion require simultaneous consideration of technical, environmental, economic, operational and institutional factors under consistent system boundaries and standardised indicators, preferably within hybrid green-grey infrastructure planning.

5.0 Discussion, Conclusion and Implications

5.1 Discussion of the Main Findings

Biological water systems can provide more than just functions of an alternative (wastewater) treatment unit. The multifunctionality of a same infrastructure can treat water, extract values from water, decrease peak flows of surface waters, create ecological values and support climate change adaptation. These viewpoints are in line with the current trends in urban resources management, i.e. from a linear approach to urban sanitation to a more circular approach to urban resources management.

Many promising wastewater treatment technologies are running into problems on scaling up. Although a treatment process is performing very well in laboratory scale, it can behave completely differently in a large urban environment. In addition to good treatment performance, many other goals have to be reached by the wastewater treatment systems in urban areas. Also, within the distributed systems, different conditions than in the controlled environment of a laboratory have to be met. Resources have to be recovered and have to be used by others. The solutions have to be economically sound for a long period of time. Also, the necessary enabling legislation for the treatment and reuse of wastewater has to be in place.

These systems therefore have more added value than just treating wastewater. Their functionalities can be multiplexed in order to treat wastewater as well as extract values from wastewater and decrease peak flows of surface waters in order to create ecological values and support climate change adaptation. These new views and perspectives on the ways that biological water systems can function are in line with trends in urban resources management such as a shift from a linear approach to sanitation in urban areas to a more circular urban resources management.

5.2 Discussion of the main findings in relation to RO1/RQ1: From treatment efficiency to reliable multi-function performance

RO1 addresses the research goal for technical performance of biological water systems in urban environments in addition to removal of pollutants. High pollutant removal rates proven in lab experiments are not sufficient to ensure good performance in urban environments. In addition to stable removal of pollutants, the systems must be able to deal with fluctuating hydraulic loads and changing temperatures, solar irradiance and influent water quality throughout the seasons. This is especially true for systems that are based on algae, microorganisms or plants. The activities of these organisms can change strongly under changing external conditions.

In order to enable a meaningful comparison of different technologies, a comprehensive set of indicators should be presented for a biological water system. In addition to the classical indicators of technical performance such as the influent and effluent water quality, removal of different pollutants, the system should also be able to provide information on the production of nutrients for reuse, the quantity and quality of the produced reclaimed water, the hydraulic performance as well as the energy production and the process stability. For systems that harvest, process and utilize energy from biomass, the net yield of biomass after all stages should be reported.

5.3 Discussion of RO2/RQ2: Sustainability Requires Life-Cycle Comparison

Sustainability of wastewater treatment systems for RO2 is highly dependent on the system boundaries chosen for comparison of different technologies. A conventional wastewater treatment plant might seem very efficient when only the treatment step is considered and not the energy for transport of wastewater to the treatment plant, the operation and maintenance of sewerage systems, treatment of sludge etc. and future costs for extensions of collection systems. In contrast, biological treatment systems have many “drawbacks” which are often not taken into account, e.g. the surface required for the system, the

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maintenance trips, replacements of parts, processing of biomass etc. and possibly even additional energy required for further treatment steps.

As for the previous point regarding economic assessment and life-cycle assessment (LCA), in economic assessment of decentralized systems consideration needs to be given to direct revenues and avoided costs and also to non-market ecosystem benefits. In LCA consideration needs to be given to all environmental impacts including greenhouse-gas emissions, energy use, materials required, land use and water-quality impacts, whereas in techno-economic assessment of such systems consideration needs to be given to all stages of the system from capture to end use, and also to all actors involved. Furthermore, the economic value of nutrients or biomass recovered needs to be assigned based on product quality, required processing, and realistic markets, rather than on a theoretical value.

5.4 Discussion in Relation to RO3/RQ3: Circularity and Resilience as System-Level Outcomes

Objective 3 aims to identify the value of biological water systems and the scope for their implementation in urban environments. These systems must be integrated into a complete chain of functions, that is to say, capture, treatment, recovery, quality, distribution and use of water. Furthermore, when aiming to increase the resilience of urban water management systems by means of distributed systems, these must be designed and managed within the framework of a complete urban system with clear operational responsibilities for the green and gray parts of the system and interfaces with existing central systems.

In terms of the water-energy-food-ecosystem services, a nutrient recovery for agricultural use can contribute to reducing wastewater in terms of quantity and improving food production. This would however require additional processes and quality control measures. Algal systems can produce biomass and nutrients; however, managing light for growth and harvesting algal biomass can require a significant amount of energy. In terms of flood and biodiversity management, wetlands and bioretention systems can provide a range of benefits; however, they require a significant amount of land to be effective and therefore may not be suitable in areas where land is a constraint.

5.5 Discussion relating to Research Objective 4 (RO4) / Research Question 4 (RQ4): The Five-Dimensional Framework for Sustainability Decision Support

The five dimensions as a decision support tool: The Five Dimensional Framework can be used by decision makers to identify key characteristics of sustainable urban water management solutions. Minimum requirements, trade-offs and dependencies between different dimensions can be determined and serve as a decision support tool in the preliminary planning stage of cities to compare different alternatives before detailed engineering design.

First, a technical screening of the possible technologies within each configuration option is undertaken to check if the required water quality and/or nutrient removal can be achieved. Then an environmental and economic assessment is made of the short- and long-term environmental and economic effects to check if there is any added value. An operational assessment of the system's maintainability and robustness follows. Then an institutional assessment is made of the possible configurations in terms of the required institutional changes and the possible ways to implement the new system within the existing governance structure. Finally, the technically feasible options are compared as decentralized systems or as part of a hybrid green-grey centralized system.

Assessment stage	Primary evidence required	Illustrative decision output
1. Technical screening	Treatment targets, hydraulic loading, recovery yields, process stability	Technically feasible / redesign required
2. Environmental assessment	Energy, emissions, materials, land, ecosystem effects, life-cycle impacts	Net environmental benefit and major trade-offs
3. Economic assessment	CAPEX, OPEX, avoided costs, product value, life-cycle cost	Affordability and long-term financial case
4. Operational assessment	Maintenance tasks, skills, monitoring, automation, climate sensitivity	Operating model and reliability requirements
5. Institutional assessment	Regulations, permits, governance,	Implementation readiness and

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	ownership, stakeholder coordination	governance actions
6. Hybrid integration	Interfaces with sewer, drainage, water supply and urban planning systems	Preferred role within the wider urban water portfolio

5.6 Theoretical Contribution

The study contributes to the theory in several ways. Firstly, it integrates the ecological function of water treatment with the main aspects of the circular economy, urban resilience, and the implementation of water infrastructure. In contrast to previous studies that focus on one of these aspects, the framework conditions all of these domains as interdependent conditions of a single socio-technical-ecological system. This may help to explain why technically sound systems fail to achieve the expected level of implementation, and why non-treatment benefits of green and grey infrastructure are frequently undervalued in conventional cost-benefit analyses for water and land management.

Another important contribution of the study is based on the distinction between system outputs and system outcomes. Immediately relevant system outputs are the treatment of pollutants, the production of recovered water, the recovery of nutrients and the production of energy. Runoff attenuation and related environmental benefits can also be considered as immediate system outputs. In contrast, important long-term system outcomes are financial sustainability, increased ecological resilience, higher replicability and increased institutional mainstreaming of the respective water system. These long-term outcomes are stable and have value only if the corresponding immediate system outputs have similar properties over time.

5.7 Practical and Policy Implications

For the urban water management practitioner, the key message is that biological water systems should be assessed within the context of a portfolio of measures and that the greatest value will be achieved where there is greatest drainage pressure, non-potable water demand, space for 'green' infrastructure and a market for recovered resources. The framework thus provides a basis for improved evaluation of the different technologies for biological water treatment.

Policymakers and regulators can make use of the structure of the framework to set adequate standards for safe reuse and recovery of resources, as well as for the environmental impact of water treatment. In addition, clear responsibilities within urban governance should be assigned to the monitoring of decentralized treatment structures, the proper functioning of the systems and the distribution and quality control of recovered resources. The framework can be used by planners to recognize treatment elements in urban green spaces as valuable urban infrastructure rather than only as aesthetics.

When designing and operating distributed biological systems, the designer should consider monitoring and automation from the start as manual inspection of many small assets would be too time consuming. Use of sensors, remote monitoring, predictive maintenance and adaptive control can alleviate these problems but needs to be evaluated against reliability, cybersecurity, cost and the capacity of the operator to use them.

5.8 Proposed Indicators for Future Empirical Validation

Dimension	Core quantitative indicators	Complementary qualitative evidence
Technical	Removal efficiency (%); effluent concentration; nutrient recovery (% or mass); reuse yield; hydraulic retention; downtime	Process stability, ease of process control, sensitivity to influent variability
Environmental	kWh/m³; kg CO2e/m³; material use; land footprint; biodiversity/ecosystem indicators	Ecological co-benefits, local environmental compatibility
Economic	CAPEX; OPEX; life-cycle cost; cost/m³; avoided network cost; revenue/value from recovered products	Affordability, financing model, market reliability for recovered products
Operational	Maintenance hours; failure	Skills availability, maintenance

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	frequency; monitoring coverage; recovery time; seasonal variability	complexity, operator acceptance
Institutional	Permit duration; compliance rate; number/clarity of responsible agencies; policy support measures	Governance quality, stakeholder coordination, public acceptance, planning integration

5.9 Limitations

The limitations of this study arise from the fact that the study presented outcomes derived from a conceptual literature review study that has not yet been validated with a common data set for comparative purposes. The cited studies reviewed were based on different technologies, climates, scales, system boundaries, time frames and performance measures. For this reason, Chapter 5 does not provide synthetic performance percentages to enable comparative rankings of the various technologies reviewed in this study.

However, a number of significant limitations remain to be addressed in future work. First, the majority of long-term performance data relate to laboratory and pilot-scale tests of the leading treatment technologies, rather than full-scale systems within a range of different municipalities. Thus, there is currently a lack of data relating to the long-term key issues of maintenance, system instability, extreme weather events, system degradation and the longer-term institutional and market issues affecting the range of recovered resources.

5.10 Future Research

Future research should aim to validate the outcomes identified within this conceptual framework using a variety of full-scale case studies from across the globe, set within a range of different climatic, regulatory and socio-economic contexts. The use of a common 'protocol' to define a number of key elements including functional units, system boundaries, time frame for study and a minimum set of core indicators, would enable assessment of a range of technologies including purely biological, conventional and hybrid systems.

Integrating process modelling, life-cycle assessment and techno-economic studies would also be highly relevant. A dynamic model would enable simulation of systems subject to variable influent loads and of the effects of temperature, rainfall and solar irradiance, whilst Life-Cycle Assessment and economic studies could provide means to assess the implications of different operational strategies for a biological water system. Indicators could then be combined within a multi-criteria decision analysis to support site-specific decision taking; however, the weights for indicators should be elicited transparently from stakeholders rather than assigned universally.

A third priority for future research is institutional and implementation studies of biological water systems. Matters to be investigated include the issues related to the necessary permits, ownership of systems, public acceptance, funding for construction, financing for operation and maintenance, and inter-institutional coordination. Given that, in the descriptive evidence profile presented in this manuscript, the dimension of institutional readiness for biological water systems received less explicit attention than the technical and environmental dimensions, strengthening the related body of evidence is necessary for these systems to move from pilot projects to 'business as usual' urban water infrastructure.

5.11 Conclusion

Biological water systems have the potential to create more circular, adaptive and multifunctional urban water management. However, the value of such systems cannot be measured based on their ability to remove pollutants from water. The described biological and nature-based water systems have the ability to remove pollutants from water, to recover nutrients, to reuse water, and to recover local resources. They can also be used to manage stormwater runoff, to provide ecological services and to support climate change adaptation. Therefore, these systems have the potential to become part of the urban infrastructure for water-resilient cities as an alternative to conventional wastewater treatment systems.

The research objectives RO1 through RO4 as well as the research questions RQ1 through RQ4 have been addressed in the present study. The RO1/RQ1 focus on the technical multifunctionality of biological water systems has shown the potential of these systems for water treatment while also addressing constraints related to scale, climate and operational stability. The RO2/RQ2 focus on the evaluation of environmental and economic performance of biological water systems over their life cycle has shown that an assessment based on equivalent system boundaries is necessary to allow for a fair comparison. The RO3/RQ3 focus on circularity and resilience has highlighted the importance to link the output of a treatment system

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to real end uses of the treated water, as well as the integration of distributed treatment systems into the overall urban water system. The RO4/RQ4 focus has resulted in a five-dimensional framework to evaluate biological water systems for urban water management.

The integration of a set of conditions, used for the evaluation of biological water systems to fulfill various functions within the urban infrastructure of water-resilient cities, forms the basis for future research to validate the framework using a set of indicators to be evaluated on a large number of full-scale case studies. Based on this empirical evidence, cities can select the most appropriate configuration that is not only technically reliable but also environmentally beneficial, economically viable, operationally manageable and also institutionally supported.

For assessing biological water systems for fulfilling various tasks within the urban water management infrastructure of water-resilient cities, five aspects have to be considered: technical, environmental, economic, operational and institutional. While treating stormwater in a sustainable way, biological water systems also have the potential for increasing urban multifunctionality. Stormwater management systems can be transitioned from mono-functional to MFS (McLachlan et al., 2023). A hybrid unit such as sustainable urban agriculture can even increase urban resilience (Grochulska-Salak et al., 2021).

A Water Sensitive City maintains habitat services for very dense landscapes through effective Rainwater Management. A Water Oriented City is a multi-scale system consisting of Blue & Green Infrastructure for urban ecosystems and effective water management (Zaręba et al., 2022).

Sustainable water management with green infrastructure is able to bring about significant changes to the urban environment (Chandratreya, 2024; Rybicki et al., 2022). Blue-green infrastructure can be sustainably used for the treatment of urban stormwater runoff (Azadgoleh et al., 2025). The bio-physical aspects of green infrastructure can be combined with the bio-physical aspects of the urban environment in order to generate co-benefits for increased urban quality by means of an interdisciplinary approach (McNabb et al., 2024).

5.12 Summary of Research Contributions

Contribution	Summary
Conceptual	Reframes biological water systems as multifunctional socio-technical-ecological infrastructure.
Analytical	Integrates five interdependent dimensions into one assessment architecture.
Methodological	Identifies the need for common system boundaries, standardised indicators, LCA and techno-economic assessment.
Practical	Provides a staged decision pathway for screening, assessing and integrating biological systems with existing urban infrastructure.
Policy	Highlights governance, regulation, stakeholder coordination and planning integration as conditions for scale-up.
Research	Defines empirical priorities for long-term validation, monitoring, dynamic modelling and institutional research.

In evaluating biological water systems to fulfill various functions within the urban infrastructure of water-resilient cities, it is essential to consider technical, environmental, economic, operational and institutional factors. These factors can be used to assess the opportunities offered by a transition from mono-functional to multi-functional stormwater management systems (Mclachlan et al., 2023). Sustainable urban agriculture, as a hybrid unit, can also contribute to increase urban resilience (Grochulska-Salak et al., 2021).

The water-sensitive city provides for habitat services for densely populated landscapes through rainwater management. The concept of a Water Oriented City is based on a multi-scale system consisting of blue and green infrastructure to preserve urban ecosystems and to manage water resources effectively (Zaręba et al., 2022).

Sustainable water management with green infrastructure can bring about great changes in urban environments (Chandratreya, 2024; Rybicki et al., 2022). Blue-green infrastructure can treat urban stormwater in a sustainable way and even provide a

source for drinking water (Azadgoleh et al., 2025). Bio-physical aspects of green infrastructure can be combined with bio-physical aspects of urban environments to provide co-benefits, in order to create higher urban quality by means of an interdisciplinary approach (McNabb et al., 2024).

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