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Current Opinion in Environmental Sustainability

Review

Status and perspectives of sustainability indicators applied in the water sector

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This review examines 74 original articles published between 2023 and partially 2026 in the Scopus database, focusing on how sustainability indicators are conceptualised and applied to support circular economy transitions in the water sector. Recent literature shows a rapidly expanding suite of assessment tools, ranging from life cycle and circularity metrics to indicators of water productivity, resource recovery potential, wastewater reuse efficiency and governance-oriented frameworks embedded in Water-Energy-Food-Environment nexus approaches. Emerging trends point toward increasingly multidimensional and integrated indicator systems, yet ongoing challenges, such as energy-circularity trade-offs, fragmented regulatory environments and difficulties in adapting indicators to diverse socio-economic and ecological contexts, limit wider implementation. The review highlights priority directions for advancing the field, including the development of harmonised yet flexible indicator sets, stronger alignment across governance levels, and the wider adoption of digital monitoring tools to enable real-time assessment and evidence-based decision-making in circular water systems.

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Current Opinion in Environmental Sustainability 2026, **81**:101647

This review comes from a themed issue on **Accelerating Transitionto Circular Economy in the Water Sector**

Edited by **Souryabrata Mohapatra, Bénédicte Rulleau, Dukhabandhu Sahoo** and **Konstantinos Tsagarakis**

Available online xxxx

Received: 25 November 2025; Revised: 19 March 2026; Accepted: 27 March 2026

https://doi.org/10.1016/j.cosust.2026.101647

Introduction

Managing water systems sustainably has become one of the defining challenges of our time. To support this discussion, it is important to clarify what sustainability entails. Sustainability is the principle of fulfilling present needs while preserving the environmental, social and economic foundations that allow future generations to thrive. It requires managing resources responsibly and confronting global challenges such as climate disruption, ecosystem decline, resource scarcity and social inequity [1]. As climate change, resource scarcity and urbanisation reshape hydrological realities, the water sector is shifting from narrow efficiency goals to integrated circular economy frameworks that promote resource reuse, social acceptance, economic resilience and policy coherence [2]. Sustainability indicators have therefore evolved from basic technical metrics to multidimensional tools that diagnose system performance, reveal trade-offs and guide actionable interventions. Over the past decade, it has become clear that no single indicator can fully capture the complexity of water sustainability. Foundational methods such as Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) remain indispensable [3,4], but their techno-centric focus is now complemented by social and governance dimensions, including public attitudes, community stewardship, institutional coherence and cross-sectoral interdependencies [5–8]. As circular economy thinking continues to expand, particularly through the growing landscape of R-strategies, it provides a critical foundation for developing more comprehensive and future-oriented sustainability indicators in the water sector, enabling organisations to measure better, manage and accelerate their transition towards circular and low-carbon water systems [9].

Recent assessment frameworks increasingly integrate scenario-based and stakeholder-informed components to strengthen alignment with the United Nations Sustainable Development Goals (UNSDGs) and enable more robust benchmarking across diverse contexts [10]. One such framework demonstrates how a multi-layered, stakeholder-driven assessment can capture technical, environmental, economic, social and governance dimensions while supporting SDG-aligned scenario evaluation [11]. Advances in water-treatment and resource-recovery technologies further highlight the need for indicator systems capable of assessing environmental, economic and socio-institutional performance in an

Abbreviations

LCA	life cycle assessment
LCC	life cycle costing
eLCC	Environmental Life Cycle Costing
UNSDGs	United Nations Sustainable Development Goals
CAPA index	Circular Agriculture Priority Assessment Index
GHG	greenhouse gas
MCDA	multi-criteria decision analysis
PIR	Policies, Institutions, and Regulations
DPSIR	Driving Forces-Pressure-State-Impact-Response
WRRF	wastewater resource recovery facilities
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
GWP	Global Warming Potential
WEF	Water-Energy-Food
DWGT	Diagnostic Water Governance Tool
WEC	Water, Energy and Carbon Emission
SMART	Scale-up of low-carbon footprint MAterial Recovery Techniques in existing wastewater treatment PLANTs

integrated manner [12,13]. Persistent tensions remain, especially where the high energy demands of advanced technologies highlight that circularity does not automatically ensure sustainability. These complexities underscore the need for balanced, transparent evaluation methodologies and ongoing innovation [14].

This review synthesises recent advances and emerging insights from the latest literature to inform the development of next-generation sustainability indicators, robust and adaptable tools intended to guide policy and practice toward a more circular, resilient and socially inclusive water sector. The review structures its findings across five thematic domains: a) sustainability indicators and metric development, b) technological and infrastructural innovations, c) governance and policy coherence, d) nexus-oriented assessment methodologies and e) empirical case studies across diverse regions and institutional contexts.

Methodology

This review systematically examines how sustainability indicators, circular-economy principles and technological innovations intersect in the water sector. A comprehensive literature search was conducted in the Scopus database from October 2025 to March 2026, using the following search string: ("circular economy") AND ("water sector") AND ("indicator" OR "sustainability indicator") AND ("sustainability"). Quoted phrases preserved multiword concepts, OR grouped synonyms within parentheses and AND combined concept groups to enhance precision. In this review, the term *water sector* is used broadly to encompass urban water systems (including water supply, wastewater treatment and reuse), as well as agricultural and industrial water uses, reflecting the cross-sectoral nature of circular economy strategies. The search identified 411 relevant publications for initial screening. These were first assessed for relevance, and restricting the publication date to ≥ 2023 reduced the pool to 256 articles. The final selection comprised solely original research articles aligned with the review's thematic scope. From these, 74 studies were retained based on thematic relevance, indicator use and keyword alignment. The review followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 guidelines for reporting systematic reviews, including the use of a Preferred Reporting Items for Systematic Reviews and Meta-Analyses-compliant flow diagram to document identification, screening, eligibility and inclusion steps [15]. Figure 1 summarises the screening process and presents the total number of studies included in the review.

Results and discussion

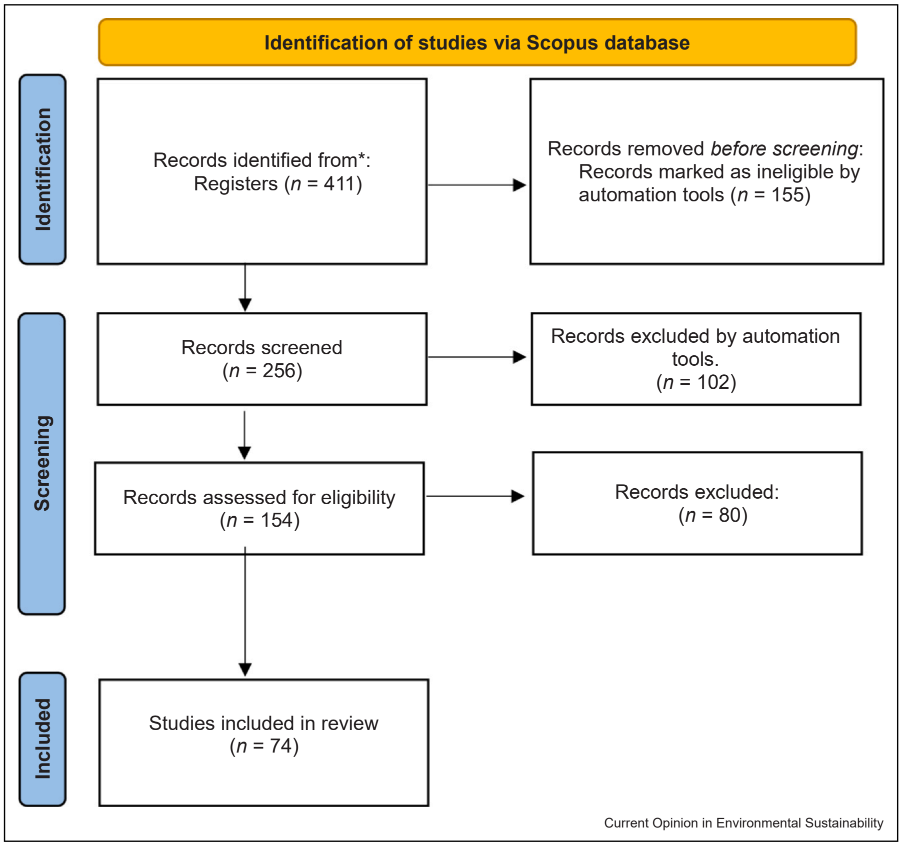
Case studies and global patterns: insights from sustainability indicators

To provide a structured overview of the selected literature, Table 1 presents the case studies approached within the research articles grouped by thematic category: (a) wastewater treatment and resource recovery, (b) Agricultural water reuse, (c) industrial water reuse, (d) Nexus and governance frameworks and (e) decentralised and alternative water systems. Within each category, the case studies are listed by geographic region and publication year. This organisation reflects the analytical structure of the subsequent discussion and enables a coherent comparison of sustainability indicators and findings across contexts.

Table 1 summarises only the key case studies and their associated sustainability indicators.

Across all thematic categories, several cross-cutting patterns emerge. Energy intensity and greenhouse gas (GHG) emissions remain persistent concerns, particularly in wastewater treatment and decentralised systems, where resource recovery often entails elevated energy demands. Governance and institutional readiness consistently function as either enablers or constraints, especially in contexts involving decentralised infrastructure or cross-sectoral coordination. Additionally, social acceptance, regulatory coherence and economic feasibility are critical determinants of success across both technological and policy-driven interventions. These findings highlight the importance of multidimensional indicator frameworks that integrate environmental,

Figure 1



Studies included in the review (PRISMA flow diagram).

socio-economic and institutional dimensions to support effective transitions to the circular economy.

Figure 2a shows the geographic distribution of the 29 case studies analysed in detail in Tabel 1, with the largest contributions from Italy, India and Spain. Only case studies for which the country of implementation was explicitly specified in the original articles were included in this figure. Figure 2b presents the geographical distribution of all 74 research articles included in the review, based on the corresponding authors' affiliation.

Sustainability indicators and metrics in the water sector

Recent literature reveals substantial diversification in sustainability indicators for water systems. Frameworks are shifting beyond conventional engineering performance metrics to integrate dimensions of circularity, LCA and socio-institutional context. Common indicator categories include:

Environmental indicators

Environmental metrics remain central to water-sector assessments, with LCA serving as the methodological standard. Frequently employed indicators encompass GHG emissions and climate change contributions [42], energy demand and intensity associated with treatment and distribution operations, eutrophication potential, ecotoxicity and resource depletion [19], as well as water footprint and freshwater appropriation indices [4]. Notably, recent studies show that circular water reuse does not always reduce environmental burdens; in some contexts, increased energy or chemical inputs may offset anticipated benefits [3]. Holistic water cycle studies like those from Shenzhen's illustrate how energy-GHG accounting and scenario modelling help identify emission hotspots and support low-carbon planning [46]. Comparative LCA studies of drinking-water treatment show that chemicals drive toxicity impacts while electricity dominates Global Warming Potential, highlighting the need for multi-criteria assessment to avoid impact shifting [23]. LCA studies of potable-reuse systems show that nutrient and energy recovery reduce Global Warming Potential, reinforcing the need for multi-criteria indicators [47].

Circularity indicators

The integration of circular economy frameworks has propelled the development of novel circularity metrics,

Table 1

Summary of key case studies by thematic category and associated sustainability indicators.

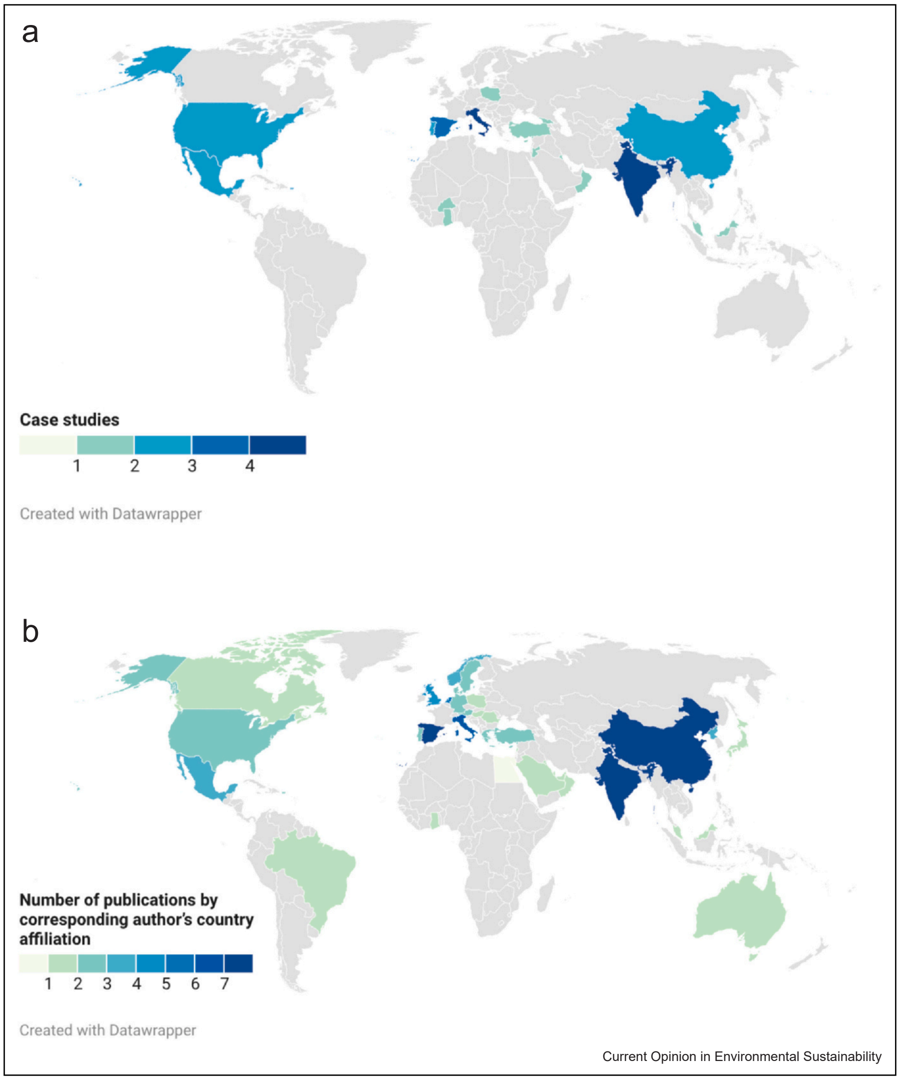
Location	Focus	**Key indicators**	Main finding	Reference
a) Water and wastewater treatment and resource recovery				
Cyprus	Upgraded WWTP	Circularity, LCA, LCC	Reuse increases but energy demand also rises; benefits improve with renewable energy integration.	[13]
Portugal	Multiple WWTPs	Circularity scores	Sludge and energy valorisation increase; harmonised framework, policy support needed.	[16]
Georgia	WWTP biogas recovery	GHG emissions, energy, economics	Biogas recovery is viable but requires stable feedstock and grid integration	[17]
India	Natural treatment systems	GHG emissions, cost, land	Hybrid natural systems reduce cost and GHG emissions compared to conventional treatment	[18]
EU Poultry Industry	Industrial WWTP	LCA, metals, chemicals	Batch reactors reduce chemical and metal use; economic viability depends on scale	[19]
Global	Net-negative WE systems	CO_2, energy, resource flows	Balanced supply-demand strategies reduce emissions and improve system sustainability	[20]
Global	Sludge valorisation pathways	Energy, GHG emissions, circularity, nutrient recovery	Reduces GHGs and improves recovery	[21]
USA	Food waste valorisation at WRRF	GHG, LCA, MFA, economics, energy, P recovery	WRRF valorisation yields net-negative emissions and remains economically viable; AnMBR maximises P recovery.	[22]
China (Shanghai)	DWTP, chemical -energy, LCA	GWP, toxicity, acidification, eutrophication	Chemical choice shifts toxicity vs GWP; no scenario is environmentally optimal	[23]
Oman	Produced water for green hydrogen	Water use, GWP, H_2 yield, LCA	Produced water enables green H_2; solar-powered electrolysis maximises yield and cuts emissions	[24]
Turkey (groundwater treatment)	Biochar-based CO_2 capture industrial symbiosis	CO_2 reduction, adsorption efficiency, DEA optimisation	Biochar reduces CO_2 ~29%; circular and regenerable.	[25]
- (lab-scale study)	Hydrothermal carbonisation (HTC) pretreatment for volatile fatty acid (VFA) production	VFA yield, biodegradability, carbon partitioning	HTC increases VFA yields; recalcitrant organics and hydrochar management shape overall sustainability	[26]
b) Agricultural water reuse				
Italy (Mediterranean)	Tomato farming reuse	Water footprint, LCC	Reuse reduces water and fertiliser demand, requires regulatory and social acceptance	[4]
Italy	Bioreactors and soil amendments	Nutrients, soil quality	Biochar reuse improves soil structure and reduces salinity impacts	[27]
c) Industrial water reuse				
Spain	Industrial reuse	LCA, energy/chemical	Reuse reduces freshwater demand but may increase energy and chemical impacts	[3]
Poland	Coal mine/brine reuse	Circular water, value, chemistry	Pilot-scale feasibility demonstrated; scaling requires governance and economic validation	[28]
d) Nexus and governance frameworks				
Singapore	WEF nexus governance	Coordination metrics	Multi-level coordination is necessary for integrated resource management	[7]
Malaysia	Micro-nexus groundwater sustainability	Hydrochemistry, LCA, material toxicity, circularity	Good irrigation quality; infrastructure impacts dominate, but circularity reduces them	[29]
Miami (USA)	Urban FEW/Agri nexus	Governance, equity	Governance structures and climate vulnerability strongly influence outcomes	[30]
Volta Basin (Africa)	Transboundary DPSIR	Drivers, pressures, impacts	Land use change and water scarcity are key pressures; governance remains fragmented	[31]

Table 1 (*continued*)

Location	Focus	**Key indicators**	Main finding	Reference
EU27	Water security index	Environmental, socio-economic	Water security is closely linked to environmental and economic performance; policy integration needed	[32]
Portugal	Governance for reuse	PIR	Governance gaps and reforms needed	[33]
Jordan	KAP study on water	Knowledge, practices	Stewardship boosts sustainable behaviours.	[5]
Kuwait	Water supply reliance	Water stress, LCA, cost, governance	High water stress, high consumption, significant economic burden	[34]
China (Nansihu Lake Basin)	Ecosystem services-based watershed management	Agricultural supply, water services, soil conservation, ES trade-offs, zoning	Crop-water purification trade-offs; agricultural drivers dominate TN; zoning guides watershed governance	[35]
Mexico	WEF nexus security, stakeholder conflict mediation	WEF accessibility/availability/ sustainability indices, multi-criteria evaluation, soft-clustering	Consensus modelling boosts WEF security and reconciles stakeholder interests.	[36]
Mexico	WEF-ecosystem nexus optimisation	SDGs, Eco-indicator 99, CE metrics, nexus security	Multi-objective modelling identifies trade-offs; food sector dominates impacts; integrated CE strategies improve resource security	[37]
e) Decentralised and alternative water systems				
Worldwide (26 sites)	Decentralised circular systems	MCDA	High feasibility globally; legal and institutional barriers limit adoption	[38]
India	Decentralised sewerage sizing	Resilience, sustainability	Scaled decentralisation improves resilience and sustainability	[39]
India	Urban water reuse scenarios	LCA	Diversified reuse pathways reduce environmental impacts.	[40]
Spain	Salinity gradient energy pilot	Energy generation, water reuse	Strong potential; scaling requires cost reduction and improved membranes	[41]
India (Himalayan region)	Himalayan reuse scenarios	Energy, GHG, water	Pumping dominates impacts; geography and system design is very important	[42]
Spain	Solar desalination for irrigation	Energy, social, environmental	Positive acceptance; high energy intensity.	[43]
Italy	Renewable seawater reverse osmosis	levelized cost of water, energy configurations, grid price sensitivity	Hybrid renewables reduce seawater reverse osmosis costs and price risk	[44]
Italy (Lampedusa island)	Minimal liquid discharge desalination circularity	Resource flows, circular actions, LCIA, economics	High circularity; energy/chemical hotspots remain; waste-heat reduces impacts	[45]

GWP, Global Warming Potential; WEF, Water-Energy-Food.

Figure 2



Geographical distribution of selected original articles: **(a)** by case studies, **(b)** by the corresponding author's country.

including the water circularity ratio[2], resource flow tracking for water, nutrients, carbon and materials [48] and indicators of circular action [13]. Specific valuation frameworks, such as circular water value, are utilised in the assessment of brine reuse, further broadening the evaluative scope [28]. Recent critiques of widely used circularity indicators, like the Material Circularity Indicator, highlight significant limitations, such as single-cycle assumptions and insensitivity to energy and material quality, underscoring the need for next-generation indicators capable of capturing multi-cycle resource retention, system-wide impacts [49]. Emerging value-impact frameworks complement these efforts by distinguishing between environmental burdens and circular value creation, offering a tool for assessing tradeoffs often overlooked by conventional metrics [50].

Socio-economic indicators

There is increasing acknowledgement that sustainability assessments must encapsulate socio-economic variables, such as LCC, eLCC, capital and operational expenditures, public acceptance and awareness [5,43], institutional readiness and governance capacity [33], as well as water security indices [32]. The literature emphasises that technical feasibility alone is insufficient; socio-economic context, financial structuring and policy coherence are frequently determinants in driving successful circular economy transitions. Evidence from India shows that the treated wastewater reuse for groundwater recharge yields substantial environmental and socio-economic benefits, highlighting the need for multi-dimensional indicators [51]. Urban water-metabolism analyses, such as the Paju study, show how circular strategies like wastewater recycling, demand management and loss reduction can enhance water efficiency, self-sufficiency and supply diversification, underscoring the value of context-specific water-security indicators in circular-water planning [52]. Emerging social LCA applications in desalination demonstrate how social indicators can complement environmental and economic metrics in evaluating circular water systems [53].

Governance and institutional indicators

Governance-related indicators have become central to interpreting enabling conditions for circularity. Instrumentation for measuring governance quality includes policy coherence assessment tools [6], Policies-Institutions-Regulations analyses [33], stakeholder integration metrics and traceability mechanisms within the water cycle [48]. Such frameworks elucidate the decisive role of multi-level institutional alignment and cross-sectoral coordination in sustainable resource management. Nexus-based optimisation studies, such as the Lebanon Water-Energy-Food-nexus framework, further demonstrate how SDG-aligned, multi-objective modelling can reveal trade-offs among water availability, energy transitions, food self-sufficiency, carbon emissions and economic costs, supporting integrated governance in resource-constrained contexts [54].

Technological and infrastructural innovations measured through sustainability indicators

Wastewater treatment plants are increasingly reconceptualised as resource-recovery hubs, with indicator-based assessment revealing trade-offs between enhanced nutrient and water recovery and higher energy inputs [13]. Photobioreactors, biogas systems and hydrothermal liquefaction show strong potential for reducing carbon footprints and generating economic value [17,55,56]. Decentralised circular solutions remain viable but face governance and legal constraints, while sustainability indices help optimise system sizing and emissions reductions [18,38,39]. Recent analyses show that wastewater treatment plants can supply substantial reclaimed water, energy and nutrient-rich by-products, with economies of scale significantly improving recovery potential [57]. Algal-bacterial aerobic granular sludge systems further demonstrate the shift toward integrated resource recovery, enabling water reuse, nutrient recycling, energy generation and biomaterial production [58]. Membrane-based processes also contribute to water reuse and reduced environmental impacts, though their wider adoption is limited by energy demand, fouling and operational cost [59]. Emerging innovations such as advanced process controls [12], salinity gradient energy conversion [41] and net-negative water-energy nexus systems [20] expand the technological landscape for circular economy implementation.

Governance, policy coherence and institutional indicators

Effective implementation of the circular economy in the water sector requires aligned governance, coherent policy frameworks and active societal engagement. Key factors include policy coherence and institutional alignment for integrated decision-making, robust regulatory frameworks to standardise practices and social acceptance to support sustained adoption. Collectively, these elements create the enabling conditions necessary for both the feasibility and long-term impact of circular interventions.

Circular economy outcomes in the water sector are intricately shaped by policy interplay spanning water, energy, agriculture and waste management. Analytical instruments such as the policy coherence assessment framework enable identification of sectoral synergies and conflict zones (*nexus hotspots*), necessitating integrated governance [6]. Persistent regulatory fragmentation remains a significant impediment to the advancement of wastewater reuse and resource recovery [33]. Standardised risk and product quality indicators are increasingly recognised as a mechanism to bridge regulatory gaps [60]. Collective behavioural responses and public perception are critical for the successful implementation of circular innovations; the literature documents the importance of societal knowledge, stewardship and acceptance, particularly in relation to high-profile interventions such as desalination [5,43]. Building on these foundations, recent research shows that governance functions not only as an enabling condition but as the central driver of circular economy transitions in the water sector. Digital governance tools such as Diagnostic Water Governance Too illustrate how algorithm-based diagnostics can alleviate capacity constraints and strengthen multi-level coordination [61], while the water-smart society framework reinforces the need for inclusive governance, long-term planning and cross-sectoral alignment [62]. Developments in the Spanish water sector further demonstrate how digitalisation is reshaping governance structures, operational practices and the design of performance indicators, highlighting the transformative role of data-driven management approaches [63]. Emerging evidence highlights that institutions must adopt indicators tailored to biogeochemical resource flows, as modified circularity metrics reveal systematic underestimation of nitrogen and water recovery when conventional material-based metrics are applied [64]. Integrated modelling approaches, from urban metabolism analyses (e.g. Suzhou) to Water, Energy and Carbon Emission-Nexus optimisation in Beijing, demonstrate that cross-sectoral trade-offs across water, energy, emissions and costs become visible only under coherent governance structures [65,66]. National-level assessments, such as those from Saudi Arabia, further show that policy coherence and cross-sectoral alignment are essential for circular economy transitions in resource-intensive contexts [67]. At the organisational scale, utilities continue to face capacity constraints, including limited technical skills, staffing shortages and rigid procurement processes, which hinder the implementation of efficiency and sustainability measures [68]. Economic analyses of circular economy-oriented upgrades, such as Scale-up of low-carbon footprint MAterial Recovery Techniques in existing wastewater treatment PLANTs, indicate that tariff design, regulatory incentives and markets for recovered products are decisive for financial viability [69]. Complementary studies propose SDG-aligned brine-management indicators for evaluating desalination sustainability [70], while the Ceara hydrogen case illustrates how governance and water-supply choices shape environmental outcomes, with recycled water outperforming desalination [71]. Although reclaimed-water reuse offers clear benefits such as nutrient recycling and drought resilience, uptake remains constrained by weak demand and regulatory-financial barriers [72]. Taken together, these findings underscore that technological readiness alone is insufficient; circularity ultimately depends on institutional capacity, regulatory coherence and governance arrangements capable of scaling and sustaining circular strategies.

Nexus approaches and multidimensional indicator frameworks

Water's interdependencies with energy, food and ecosystems are increasingly measured through nexus indicators. Advanced indicator frameworks, exemplified by the Circular Agriculture Priority Assessment index, facilitate integrated planning for resource recovery at macro scales [14], while nexus-oriented circular economy strategies reveal synergistic possibilities such as coupling wastewater-to-energy and floating solar photovoltaic [73]. Insights from Singapore's integrated governance showcase the significance of cross-sectoral coordination [7].

The Driving Forces-Pressure-State-Impact-Response (DPSIR) conceptual model effectively links socio-economic drivers to environmental impacts and institutional responses in transboundary settings [31]. Composite indicators integrating energy, water and emissions are increasingly used to evaluate net-negative interventions, particularly in challenging environments such as the Himalayan urban context [20,40,42]. Multi-level nexus frameworks, such as decision-pyramid approaches that integrate molecule, process and governance-level interactions, further demonstrate how cross-scale synergies and trade-offs can be captured to support coordinated decision-making across water, energy and food systems [74].

Conclusions

Recent advances reveal a clear shift towards integrating environmental, circularity, socio-economic and governance indicators within unified assessment frameworks. These multidimensional tools enable comprehensive evaluation of trade-offs and synergies in water-sector sustainability. Despite progress, the lack of a standardised, widely adopted set of indicators continues to hinder comparability across regions and technologies.

Circularity strategies have shown promise in enhancing resource recovery and efficiency; yet they do not inherently guarantee improved environmental outcomes. Energy-intensive processes and decentralised systems may increase GHG emissions or operational complexity. This underscores the need for indicators that rigorously account for energy use, environmental impacts and socio-economic dimensions.

Governance consistently emerges as a decisive factor, often more influential than technical readiness, in determining the success of circular economy initiatives. Integrated and adaptive governance structures are essential for scaling innovation and enabling long-term transformation. In parallel, digitalisation is advancing the development of dynamic, real-time sustainability metrics that support system resilience and operational efficiency. Context specificity and equity also remain critical, as geographic, institutional and socio-economic conditions shape the feasibility and effectiveness of circular interventions. While robust regulatory frameworks in high-income regions often facilitate implementation, low- and middle-income contexts may face institutional, financial, or social barriers.

Looking ahead, the development of scientifically robust yet practical and regionally adaptable indicator systems will be essential. Strengthening governance through cross-sectoral coordination and regulatory alignment, alongside integrating renewable energy into resource recovery, can help mitigate trade-offs between circularity and environmental performance. Ultimately, socio-economic and behavioural factors such as public acceptance, equity and stakeholder engagement will play a pivotal role in determining the long-term success of circular economy strategies in the water sector. Finally, this review is subject to methodological limitations, as reliance on a single search string and database may have excluded using alternative terminology or indexed elsewhere, indicating that future reviews would benefit from broader search vocabularies and multiple databases.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: Brindusa Sluser reports that financial support was provided by COST Association (CA23157). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgements

This article is based on work from COST ACTION CA 23157 "European Network for Multiple View Life Cycle Sustainability Assessment – MultiViewLCSA" supported by COST (European Cooperation in Science and Technology).

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- •• of outstanding interest

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The study introduces a structured framework to evaluate how coherently Water-Energy-Food-Ecosystem policies align across sectors and governance levels. Applying it to a river-basin case, it shows that fragmented objectives and uncoordinated measures frequently undermine nexus integration, while consistent cross-sectoral targets strengthen policy synergies. By identifying where misalignments occur and how they affect basin-scale sustainability, the work highlights the need for coordinated, multi-level governance to support effective nexus implementation.

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A combined circularity assessment, LCA and LCC approach was applied to an upgraded wastewater treatment plant to evaluate its sustainability and resource-recovery performance. The study shows that advanced treatment stages increase circularity but also raise environmental impacts and operational costs due to high energy demand. It highlights the trade-offs involved in circular economy transitions and the need for optimised design and supportive policy frameworks.

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