Circular economy policies for water and wastewater

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Circular economy policies for water and wastewater

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ABSTRACT

The circular economy (CE) transition is a modern challenge for policymakers, utility managers, and consumers, particularly in the water and wastewater sector. It offers essential environmental benefits by reducing resource use, minimizing waste generation, and enhancing water recycling and reuse. This transition is important for addressing challenges in traditional water management, environmental and climate impacts. This editorial introduces the special issue on Circular Economy Policies for Water and Wastewater, outlining its key contributions and discussing the policy implications for sustainable water management systems. The published works of this issue offer valuable insights for evolving the concepts of circularity and sustainability in water and wastewater policymaking agendas. To complement the discussion, we performed a bibliographic investigation focusing on circular economy policies and water and wastewater, to capture works dealing with the whole water cycle. Analysis of the 307 articles located showed a wide range of topics involved with a worldwide coverage and international collaboration among authors.

Key words: Bibliometric study, Circular economy, Collaboration networks, Thematic map

HIGHLIGHTS

- Circular economy helps build collaborations among researches from different countries in classic and new topics.
- Including circular economy principles in water and wastewater management could address water scarcity and environmental impacts.
- Case studies show how local context affects the implementation and outcomes of circular water strategies.

1. CIRCULAR ECONOMY AND WATER MANAGEMENT

The Green Deal (GD) and circular economy (CE) have been introduced over the last two decades as strategies for efficient resource management, and have also been adopted in regions beyond the European Union (EU) (Smol 2022). The main assumptions of policies for the implementation of GD and CE in the water sector are to protect water resources in order to guarantee its safe supply for society, agriculture and industry. Based on numerous legal acts, recommendations and action plans for circular water management adopted on an international, national and regional scale, societies and utilities should reform to be able to implement CE principles (Frijns *et al.* 2024). It should be emphasized that many activities consistent with the CE assumptions were implemented before the CE policies were officially adopted (Tsagarakis *et al.* 2004), e.g., in the EU, CE was designated as a program for Europe for the first time in 2014 (Commission of European Communities 2014), while in China, the official CE strategy was adopted in 2008 (Circular Economy Promotion Law of the People's Republic of China 2008). In fact, numerous actions to protect water resources had been undertaken many decades earlier, as water (originating from wastewater) recycling and reuse, among the 5Rs (Kakwani & Kalbar 2024). Indeed, water recycling practices have been evidenced in the Minoan era, more than two millennia BC (Angelakis *et al*. 2020).

Water scarcity, pollution, and resource depletion underscore the need for a transition from conventional linear to a more circular and sustainable management approach. This approach has two key paths; on the one hand, it requires more sustainable management of primary water resources and, on the other hand, it promotes circular management of sewage and other waste generated in the water and wastewater sector (Smol *et al*. 2020), mainly by emphasizing the role of water reuse, but also recovering other valuable resources such as energy and nutrients, while at the same time minimizing waste. More specifically, the circular economy in water and wastewater management aims to close the loop of water flows by promoting reuse, resource recovery, and sustainable design throughout the water cycle. This approach goes beyond conventional treatment by integrating advanced technologies and policy frameworks. Alternatively, it can be said that the circular economy could offer a pathway that not only alleviates the issue of water scarcity but also reduces the carbon footprint of the water sector, thereby contributing to broader climate mitigation goals (Sauvé *et al*. 2021). For instance, recent technological advancements, including energy-efficient wastewater treatment plants, nutrient recovery systems, and decentralized water reuse schemes, reveal the potential to transform water management from a linear, consumption-based model into a regenerative and resource-efficient system. As climate pressures strengthen, the urgency of embedding circular practices into water governance becomes increasingly critical. The current editorial analyzes the progress in circular economy water and wastewater management policies, shedding light on emerging technologies, governance models, and the avenues through which a more sustainable and resilient water future might be achieved.

Initially, we employ a bibliometric technique that emphasizes, through network analysis, the possible contributions between and within research groups, providing a more precise understanding of the relationship between circular economy policies and wastewater issues. We rely on the Scopus database and use the keywords 'circular economy policies' and 'wastewater' or 'water' to identify relevant research publications in order to capture insights from the entire water cycle. After that, we eliminate non-relevant publications, excluding unrelated studies as proposed by Page *et al*. (2021). The exclusion criteria include duplicates, non-English language articles, conference materials, editorials, and letters to maintain focus on in-depth research.

Subsequently, we utilize the R-biblioshiny package tools (Aria & Cuccurullo 2017), which can leverage a diverse set of bibliometric information and serve as visualization tools for conducting information analysis and generating visualizations related to the intersection of circularity and wastewater management. Moreover, this package facilitates efficient data processing and transformation, ensuring accuracy and consistency and provides advanced functions for constructing and analyzing bibliographic networks, enabling us to explore the intricate relationships within the literature on circularity and wastewater management.

Figure 1 presents a snapshot of the academic research on the relationship between the circular economy and wastewater management over the period 2006–2024. In particular, it provides a bibliometric overview of 307 (Scopus) documents from 160 sources, indicating a notable expansion in scholarly work. The field exhibits a strong annual growth rate of 26.9%, reflecting the increasing academic and research interest in this topic. It is also noteworthy to highlight that the analysis involved 1,287 unique authors, with an average of 4.48 co-authors per document, suggesting a strong collaborative research practice. Only 21 authors contributed single-authored publications (6.8% of the papers), which highlights the predominance of co-authored work. Furthermore,

Fig. 1 | Scientific output based on scopus database.

36.5% of the publications involved international co-authorship, underscoring the global nature of research collaborations.

Figure 2 presents a Sankey diagram illustrating the interconnection among the publication sources (SO), the authors' keywords or research themes (DE), and the countries of author affiliation (AU_CO) in the analyzed body of literature. This three-part relationship offers insight into thematic collaborative trends and the geographical distribution of research. The central node (DE) lists the authors' keywords, with 'circular economy,' 'sustainable development,' 'sustainability,' 'life cycle assessment,' and 'recycling' emerging as the most prominent research topics. On the right side (AU_CO), the diagram reveals that countries such as the United Kingdom, Italy, and China are central contributors to research on circular economy and sustainable wastewater management. This visualization highlights the diversity of topics and the global collaboration patterns that characterize current research at the intersection of circular economy and water management, demonstrating how research themes bridge multiple countries and academic sources.

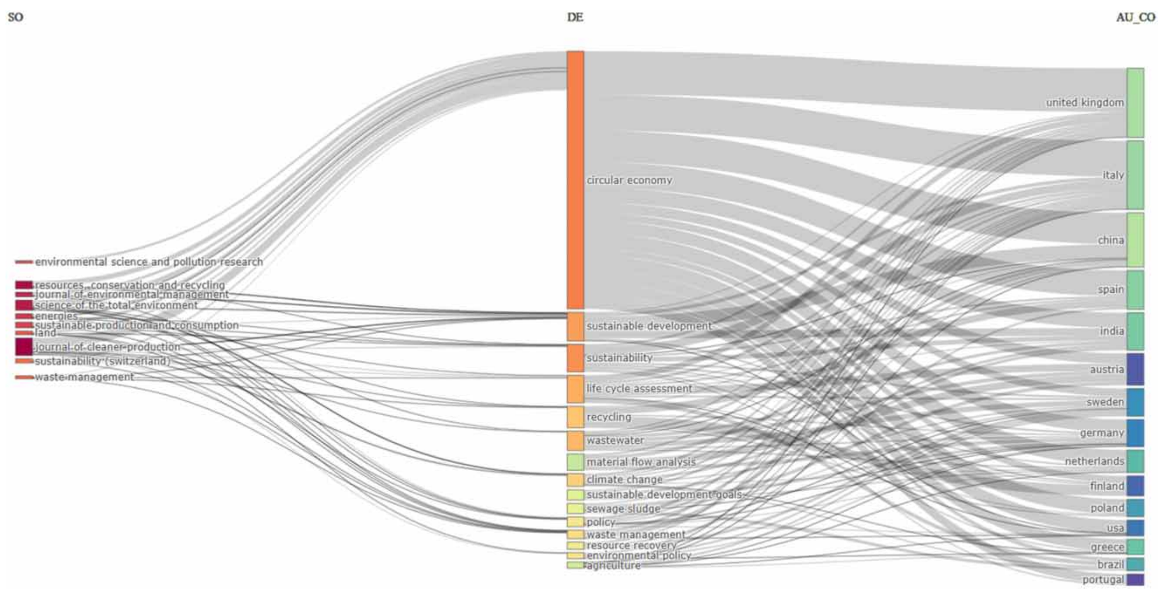

Fig. 2 | Interconnections among the publication sources (SO), the authors' keywords/research themes (DE), and the countries of author affiliation (AU_CO).

Fig. 3 | Word cloud with the most frequent keywords of the bibliometric search.

Thereafter, Figure 3 presents a word cloud of the most frequently used author keywords (with the principal words of the special issue title omitted) in the analyzed literature on circular economy and water-related sustainability. The dominant keywords – 'sustainable development,' 'recycling,' and 'environmental impact,' – 'indicate the strong emphasis on linking waste management practices with broader sustainability goals. Other frequently occurring terms include 'sustainability,' 'life cycle assessment,' 'climate change,' 'economic aspect,' and 'environmental policy,' highlighting the multidisciplinary nature of the field. The importance of these terms suggests a research focus that integrates environmental, economic, and policy dimensions into circular economy and resource recovery frameworks.

Figure 4 illustrates a keyword co-occurrence density map generated from the analyzed dataset, showing how frequently keywords co-occur within the same documents. The visualization employs a heatmap-style overlay,

Fig. 4 | Keywords co-occurrence network.

with darker red areas indicating regions of higher co-occurrence density and signaling thematic clusters with strong interconnections. The most prominent and central terms include 'waste management,' 'sustainable development,' 'recycling,' 'environmental impact,' and 'economic aspect,' reflecting the thematic centrality and interdisciplinary nature of research in this field. On the left side, keywords such as 'life cycle,' 'life cycle assessment,' 'food waste,' and 'agriculture' form a notable cluster related to resource efficiency and environmental sustainability. Meanwhile, terms like 'climate change,' 'decision making,' and 'water pollution' appear in adjacent areas, bridging environmental policy and management themes. Overall, the figure highlights interconnected knowledge domains that combine technological, environmental, and policy-oriented approaches, underscoring the trend toward integrative, systems-based thinking in circular economy and water-related sustainability research.

Thereafter, Figure 5 presents a geographical distribution map of the countries contributing to the scholarly literature on circular economy and wastewater-related research. The countries are shaded in varying intensities of blue, where darker shades represent higher publication output. Grey indicates no recorded publications in the analyzed dataset. China exhibits the highest volume of publications within the dataset. Other major contributors include the United Kingdom (UK), Italy, Spain, and India, all of which are shaded in relatively dark blue, suggesting robust research activity. Conversely, large regions in Africa, Central Asia, and parts of the Middle East appear grey, highlighting gaps in research participation from those areas. This map underscores the global but uneven distribution of academic achievements in the field while providing valuable insights into the leading countries that drive the research agenda as well as regions that remain under represented. International collaborations and capacity-building efforts could be further encouraged to achieve a more balanced and inclusive knowledge base.

Figure 6 presents a thematic map categorizing key research themes in circular economy and water-related sustainability studies according to their centrality (importance within the field) and density (level of development). In the upper-right quadrant, 'waste management,' 'economic aspect,' and 'waste disposal' are positioned as

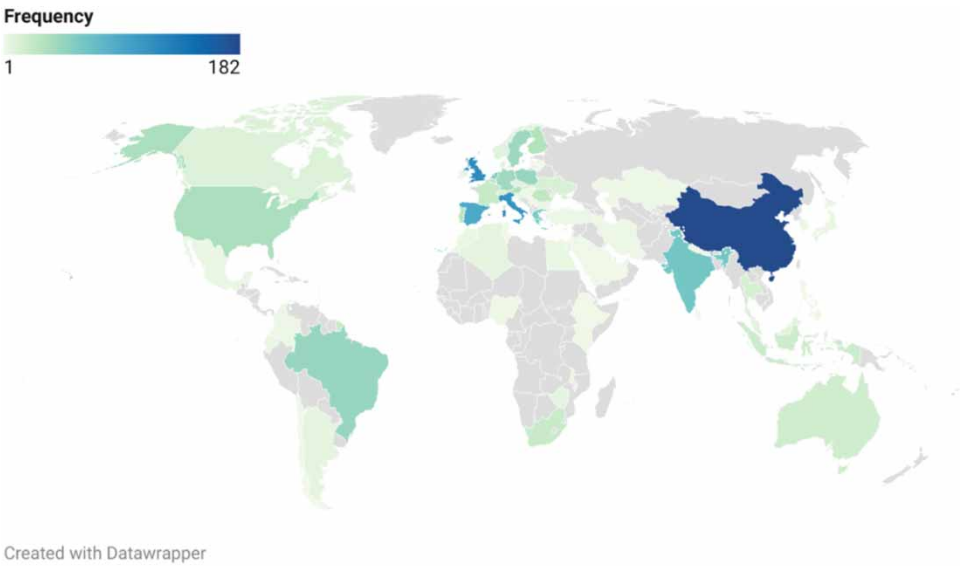

Fig. 5 | Country scientific production in number of documents.

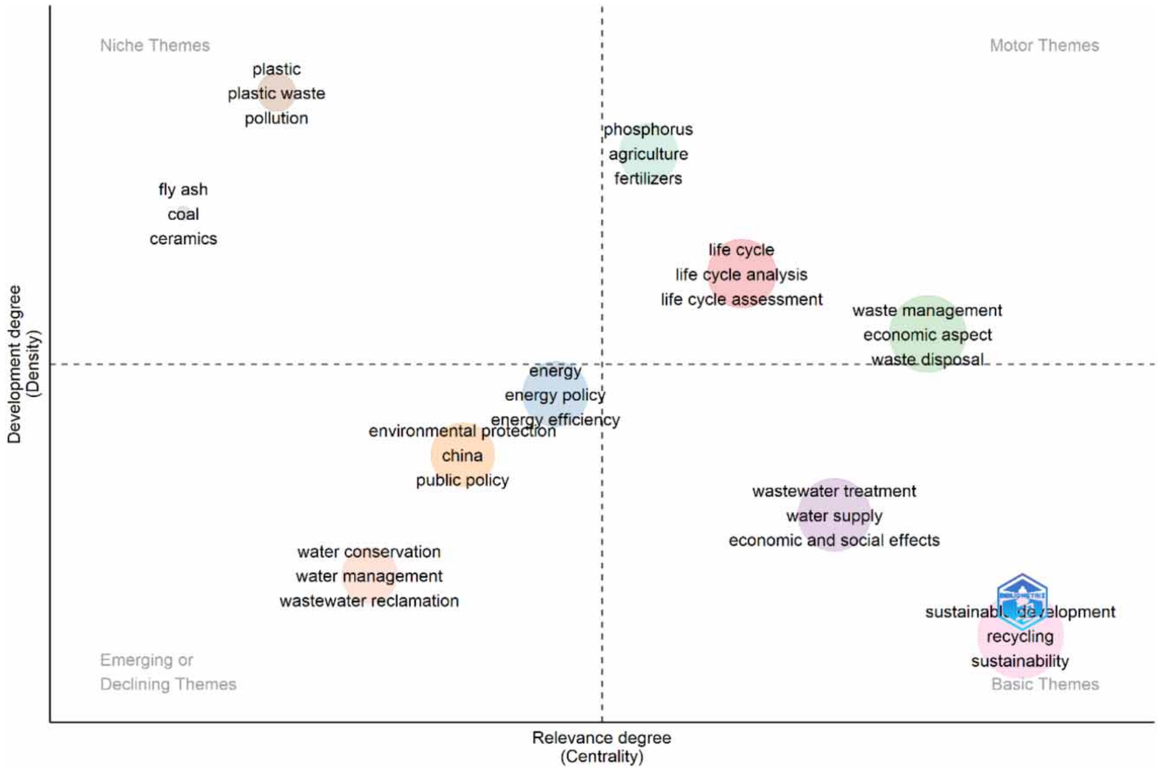

Fig. 6 | Thematic map.

motor themes — highly relevant and well developed – indicating their strong influence on the research landscape. The lower-right quadrant, representing basic themes, includes 'sustainable development,' 'recycling,' 'sustainability,' 'wastewater treatment,' and 'water supply.' These topics are central to the field but have relatively lower density, suggesting they remain fundamental research anchors with potential for further development. In the upper-left quadrant, niche themes such as 'plastic waste,' 'pollution,' and 'ceramics' exhibit high internal development but lower overall centrality, indicating their specialized yet less connected nature. Finally, the lower-left quadrant contains emerging or declining themes, including 'water management,' 'wastewater reclamation,' and 'water conservation,' which may represent either emerging areas of interest or topics that are declining in over time.

Figure 7 presents the 10 most highly cited documents in dataset, based on citation data. Each entry includes the author(s), publication year, and the journal name. The x-axis represents the number of global citations, while bubble size indicates the citation volume, with larger bubbles corresponding to higher counts. Leading the list is the paper by Jones *et al.* (2021) published in *Earth System Science Data*, with 489 global citations. The study provides consistent estimates of wastewater production, collection, treatment, and reuse at both country and gridded levels, reflecting its significant impact on the field. Moreno *et al.* (2016) followed, publishing in *Sustainability* and achieving 407 citations. The authors presented a framework for circular design, showing how products can be created to support reuse, recycling, and closed loops. Thereafter, Chen *et al.* (2020) in *Science of the Total Environment* had 392 citations. The paper showed how green chemistry and circular economy

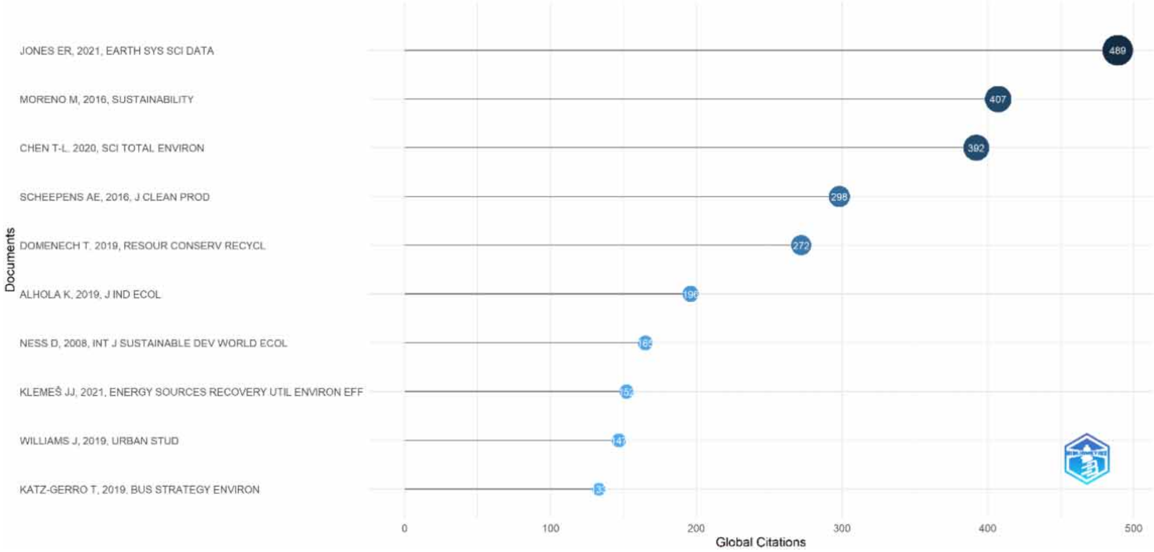

Fig. 7 | Most cited documents.

principles can support wastewater treatment, recovery, and reuse, guiding sustainable water policies. Then follow papers by Scheepens *et al.* (2016) and Domenech *et al.* (2019) with 298 and 292 citations, respectively. Scheepens *et al.* (2016) applied LCA-based methods to assess and plan sustainable business models for water-based tourism. Domenech *et al.* (2019) mapped the development of industrial symbiosis across Europe, including how shared wastewater treatment and resource exchanges between industries can support circular economy policy goals. Finally, papers by Alhola *et al.* (2019), Ness (2008), Klemeš *et al.* (2021), Williams (2019) and Katz-Gerro & López Sintas (2019) follow closely, with citation counts ranging from 133 to 196 works. Particularly, Alhola *et al.* (2019) explored how public procurement can be leveraged to foster circular economy practices, including wastewater-efficient products and services, by integrating sustainable and green criteria into policies. Ness (2008) argued that holistic, integrated infrastructure systems, including water and wastewater services, are vital to improving resource productivity and supporting sustainable urban development in China. Klemeš *et al.* (2021) proposed a novel plastic waste footprint metric that incorporates water use and wastewater considerations across plastics' life cycle to support policymaking for sustainable circular economy practices. Williams (2019) advocated for a holistic, circular approach to managing urban resources to reduce resource consumption, mitigate urban challenges such as flooding and pollution, and inform integrated water-related policymaking in cities. Katz-Gerro & López Sintas (2019) demonstrated circular economy practices among European SMEs, revealing that roughly one-third of firms have adopted water-efficiency policies and wastewater recovery efforts, underlining the role of water-related strategies in circular initiatives. Overall, the figure highlights the seminal and influential studies that continue to guide research directions and inform policy discussions in the intersection of circular economy and sustainable water management.

Figure 8 presents a trend topic analysis of the most frequently used terms in the literature on circular economy and water-related sustainability over time. The visualization shows both the temporal span of each term and its relative prominence, with larger bubbles indicating higher frequency of occurrence. In recent years, there has been sustained and growing interest in topics such as 'sustainable development goal,' 'climate change,' 'food

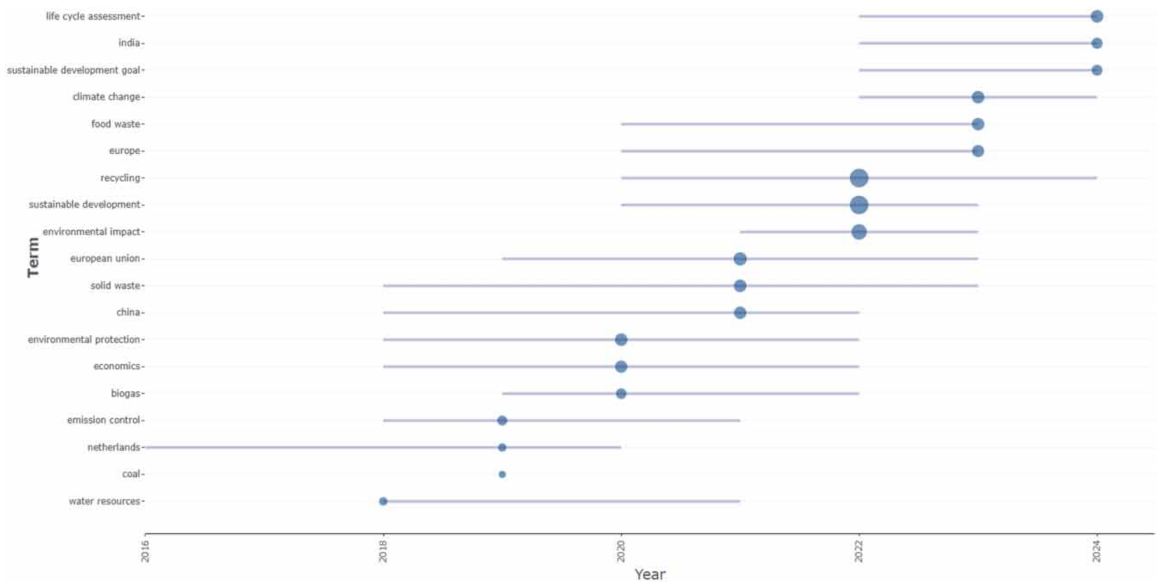

Fig. 8 | Trend topics.

waste,' 'Europe,' and 'recycling,' each showing longer durations and larger bubble sizes. More recent terms, including 'life cycle assessment,' 'India' and 'sustainable development,' have emerged strongly since 2022, reflecting expanding geographical focus and alignment with global policy agendas such as the Sustainable Development Goals (SDGs). In contrast, earlier topics like 'coal,' 'emission control,' and 'biogas' appeared between 2018 and 2020 but have since declined in importance, possibly indicating a shift in thematic priorities. This analysis illustrates the evolving research landscape, highlighting both the persistence of core sustainability-related themes and the emergence of new frontiers likely to influence future scholarship and policymaking.

2. OVERVIEW OF THE CONTRIBUTIONS OF THE SPECIAL ISSUE

A solid idea of circular wastewater management begins with understanding the foundational conditions that can lead to a shift. Frijns *et al.* (2024) set the stage for that transition. Real-world pilot projects are essential for proving that circular water technologies can be viable in the long term. A shift is needed from the conventional cost-based assessments that have been used for so long to business models that put circular value creation at their heart. Public acceptance and the right regulatory tools, such as end-of-waste standards, are also crucial for facilitating the entry of recovered resources into the market. This study offers empirical insights from illustrative cases, highlighting the technological, economic, socio-cultural, and regulatory elements that either support or hinder the broader implementation of circular practices in the water sector. It concludes that a coordinated approach is necessary to reframe water systems within a circular context and to establish the legitimacy of circular water practices within society and the economy.

Balkrishna *et al.* (2024) examine the Namami Gange initiative in India. One of the standout discourses is how conflicting national goals, like boosting industrial output and energy generation, can work against water quality goals. Despite its intentions, the program is struggling because of fragmented governance and overlapping objectives. That reinforces the notion that successful water circularity demands integrated strategies aligning economic development with environmental stewardship. They found that efforts to increase energy production, irrigation, and manufacturing, as well as developing the river as an inland waterway, conflict with initiatives to clean the Ganga, as both sets of goals are integral to the government's broader growth agenda. Progress is also necessary to be achieved at the regional governance level.

Riazi *et al*. (2025) investigate how inter-municipal cooperation can promote circular water practices in Portugal. This article introduces and applies a framework to evaluate the role of inter-municipal cooperation (IMC) in advancing water circular economy (WCE) strategies, focusing on three core aspects: IMC's engagement in WCE promotion, the establishment of robust WCE governance, and the alignment of WCE with territorial characteristics and spatial considerations. While legislative frameworks are in place to support these collaborations, the study finds that numerous challenges remain, including limited funding, infrastructure gaps, and a shortage of skilled personnel. However, overcoming these challenges and improving integration between water management and spatial planning are crucial for inter-municipal cooperation to play a more significant role in promoting water reuse and circular economy strategies. Kakwani & Kalbar (2024) introduce the Water Circularity Indicator (WCI-2.0), a tool designed to help cities prioritize key actions under the 5Rs framework (Reduce, Reuse, Recycle, Reclaim, and Restore). By applying this tool in Pimpri-Chinchwad, India, they demonstrate how city governments can make more informed, targeted decisions regarding water infrastructure and resource allocation. They concluded that achieving efficient urban water management requires shifting the focus from treatment and disposal toward distributed and decentralized approaches for water and wastewater management. While significant infrastructure investments are planned for the coming decades, the priority should be reducing water consumption and losses, followed by promoting localised reuse, particularly in the context of a highly industrialised city. Emphasising local reuse and recycling can eliminate the need for large-scale water supply and sewerage infrastructure to handle freshwater and wastewater demands. This analytical approach directly addresses the limitations of previous studies in governance and planning.

Wadwekar & Kapshe (2024) also focus on urban-level challenges, using Bhopal, India, as a case study. This study seeks to determine whether urban water resources are being utilised efficiently and sustainably to meet residents' needs, while proposing wastewater reuse as a potential strategy to enhance water use efficiency. Their research evaluates the city's reliance on external water sources and advocates for more robust policies to promote the reuse of treated wastewater. Their findings complement the WCI-2.0 framework and support the call for institutional mechanisms that enable sustainable water-use practices within the context of the urban circular economy.

However, tools and metrics alone do not resolve the deeper social and institutional hurdles that hinder implementation. Matos *et al*. (2025) explore these barriers through co-creation processes in cities across Southern Europe and the Middle East. They found that stakeholder resistance, outdated regulations, and limited awareness significantly hinder the adoption of circular water practices. Addressing the challenges linked to implementing new water loops, even when they are technical, often requires non-technical solutions within the institutional context. Co-creation processes highlight the importance of prioritising institutional structures and raise stakeholder awareness during the rollout of new water loops, supporting the development of symbiotic territories that align with policy objectives as well as the strategies of producers and users. Their study underscores that inclusive governance models and adaptive institutional frameworks are just as crucial as technological solutions for achieving lasting change.

Riediger *et al*. (2025) explore how coordinated investment in sanitation and water reuse can deliver broader environmental and financial benefits. Focusing on Brazil's Jundiaí River Basin, they demonstrate that aligning water and sanitation planning improves long-term water security while reducing costs and generating income from resource recovery. Their findings indicate that while deferring investments can reduce immediate costs, it also delays and reduces the benefits, including lower water treatment expenses, energy savings, and potential income from selling reclaimed water. Delays in sanitation investments lead to a declining benefit-to-investment ratio, whereas wastewater treatment and reuse can generate substantial revenue. These results underscore the importance of aligning water resource management with sanitation planning to enhance water security and promote circular economy practices. Their macro-level analysis aligns with earlier calls for systemic planning that transcends sectoral silos.

Finally, Sun *et al.* (2024) investigate the relationship between industrial expansion and water sustainability across Chinese cities using a coupling coordination model. The results indicate that from 2010 to 2019, there was a general improvement in the level of coordination between industrial development and water resource security in China. Their findings reveal that industrial development places more stress on water resources than the reverse, underscoring the need for differentiated regional strategies. Balancing economic ambitions with sustainable water practices emerges as a vital priority for achieving circularity on a national scale.

3. CONCLUDING REMARKS

The circular economy fosters collaborations among researchers from different countries and disciplines, encompassing both traditional and emerging topics, as illustrated by the preceding bibliometric analysis. Incorporating circular economy principles into water and wastewater management can help address water scarcity and mitigate environmental impacts. In particular, as demonstrated by the studies discussed in this paper, creating a circular water system requires a multifaceted approach that combines technological innovation, regulatory reform, stakeholder engagement, cross-sector collaboration, and data-driven tools. At the same time, addressing economic, environmental, and institutional factors is crucial to making these systems scalable and sustainable, even at the local level. Case studies from large developing countries demonstrate how local context shape the implementation and outcomes of circular water strategies.

Overall, this special issue takes a significant step forward in understanding how circular economy principles can be effectively integrated into water and wastewater governance. It provides researchers and policymakers with the tools, evidence, and strategic pathways they need to support the sustainable transformation of water systems. These contributions can inspire further dialogue, innovation, and coordinated action toward advancing water sustainability and progressing toward the Sustainable Development Goals.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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