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Systematic Review

Circular Economy and Water Sustainability: Systematic Review of Water Management Technologies and Strategies (2018–2024)

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Abstract

The transition toward a circular water economy addresses accelerating water scarcity and pollution. A PRISMA-2020 systematic review of 50 peer-reviewed articles (January 2018–April 2024) mapped current technologies and management strategies, seeking patterns, barriers, and critical bottlenecks. Bibliometric analysis revealed the following three dominant patterns: (i) rapid diffusion of membrane bioreactors, constructed wetlands, and advanced oxidation processes; (ii) research geographically concentrated in Asia and the European Union; (iii) industry's marked preference for by-product valorization. Key barriers—high energy costs, fragmented regulatory frameworks, and low social acceptance—converge as critical constraints during scale-up. The following three practical action lines emerge: (1) adopt progressive tariffs and targeted tax credits that internalize environmental externalities; (2) harmonize water-reuse regulations with comparable circularity metrics; (3) create multi-actor platforms that co-design projects, boosting local legitimacy. These findings provide policymakers and water-sector practitioners with a clear roadmap for accelerating Sustainable Development Goals 6, 9, and 12 through circular, inclusive, low-carbon water systems.

Keywords: circular water economy; systematic review; membrane bioreactor; advanced oxidation processes; constructed wetlands; water-reuse policy; social acceptance; sustainable development goals

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1. Introduction

Water is the fundamental resource for life and socioeconomic development; however, our generation faces an unprecedented global water crisis characterized by increasing scarcity, pollution, and unequal distribution of water resources [1]. This crisis is exacerbated by climate change, population growth, and unsustainable consumption and production patterns, presenting significant challenges for sustainable water resource management at the global level [2–4]. In this context, the transition to a circular economy in the field of water resources emerges as a promising response to these problems, promoting a shift from the extraction–use–disposal paradigm to circular systems that promote conservation, reuse, and recovery [5,6]. Water management presents critical challenges both globally and in Latin America, where pressure on watercourses is increasing due to climate change, urbanization, and unsustainable production models [7,8].

The conceptual foundations of circular water management have been established through seminal contributions that demonstrate both the opportunities and challenges in this emerging field. Sgroi et al. [9] developed comprehensive frameworks for assessing the feasibility, sustainability, and circular economy concepts in water reuse, establishing that although technical solutions demonstrate proven effectiveness, implementation faces significant economic and regulatory barriers that require holistic approaches considering political, decision-making, social, economic, technological, and environmental factors. Building on this foundation, Mannina et al. [10] revealed the transformative potential of wastewater treatment systems toward resource recovery infrastructure, demonstrating how integrating approaches for clean water production with nutrient and energy capture can fundamentally revolutionize the sector from waste disposal to resource recovery. Complementarily, Voulvoulis [11] provided critical analyses of water reuse from a circular economy perspective, identifying potential risks of unregulated approaches while highlighting opportunities to create significant synergies through wider adoption of the circular economy, particularly emphasizing the need for appropriate water quality standards and reliable operation of water reuse systems. These pioneering studies collectively established that the transition to a circular economy in water management requires addressing multidimensional barriers ranging from public perception and pricing challenges to regulatory frameworks and technological adaptation.

However, despite growing academic and political interest in this area, significant knowledge gaps remain that limit effective implementation [11,12]. This systematic review differs from previous studies such as those by Mannina et al. [10] and Voulvoulis [11] by adopting a comprehensive approach that specifically covers the period 2018–2024, characterized by accelerated technological and regulatory developments in the water sector. Whilst previous reviews have focused mainly on specific technical or regional aspects, this study provides a holistic perspective that integrates technological, economic, political, and institutional dimensions, with a special emphasis on the Latin American context, a region that is consistently underrepresented in the global literature on the circular water economy. In addition, the gaps identified include the lack of systematization and monitoring of real-world circular economy performance data, particularly in different socioeconomic settings; the absence of longitudinal studies to assess impacts over time; and the disconnect between social, environmental, and economic feasibility indicators in monitoring and evaluation frameworks [11,12]. Additionally, challenges include institutional barriers such as fragmented legislative and regulatory frameworks and a lack of economic incentives to support reuse and recovery, technological challenges including technical difficulties in adapting existing infrastructure to circular economy models, and social resistance due to perceived safety concerns regarding recycled water [13].

The Latin American and Caribbean region faces particular challenges with regard to water sustainability and the implementation of a circular economy, characterized by high levels of water pollution, limited water treatment infrastructure, and low wastewater reuse rates. The region reports that only 41% of wastewater receives safe treatment, significantly lower than the global average (55.5%) and OECD countries (over 80%), reflecting structural deficiencies in achieving SDG 6 targets [14–16]. UNESCO global reports detail that the region shows limited progress toward SDG 6 targets, partly due to "institutional fragmentation, lack of appropriate water infrastructure, and limited regional cooperation in shared basins" [15,16]. However, recent studies highlight that adopting circular economy principles in wastewater treatment could represent a transformative opportunity, enabling the recovery of resources such as energy, nutrients, and reusable water whilst also contributing to the creation of sustainable jobs and reducing greenhouse gas emissions [13,17]. The Economic Commission for Latin America and the Caribbean emphasizes that the transition to a circular economy requires strengthening water institutions and governance, promoting technological innovation, and articulating more effective regulatory frameworks to encourage the reuse, recycling, and recovery of resources in urban water cycles [17].

In the literature, the circular economy applied to the water sector has been conceptualized as a holistic and integrated approach that seeks to close water, nutrient, and energy cycles to minimize negative externalities and maximize the lifetime value of resources [9,18]. This paradigm proposes replacing the traditional linear "consume–produce–dispose" model while encouraging environmental regeneration and the valorization of water by-products. Recent years have seen a greater focus on international political agendas, particularly in relation to the United Nations Sustainable Development Goals, with a direct connection to SDG 6, which establishes the need to "ensure availability and sustainable management of water and sanitation for all" [19]. However, despite growing academic, political, and social interest, significant gaps remain in terms of knowledge, capacity, and operational challenges that limit effective implementation [11,12].

Based on this analytical framework, key research questions guide this systematic review. The overall research question, formulated according to the PICO (Population, Intervention, Comparison, Outcome) methodology, is: To what extent do circular water management technologies and strategies (I) implemented in urban, agricultural, and industrial water systems (P) contribute to improving water sustainability (O) compared to traditional linear management approaches (C) during 2018–2024? Specific questions include the following: (1) What are the key barriers and enablers (O) for the effective implementation of resource reuse and recovery technologies (I) in different socioeconomic and geographic contexts (P) compared to pre-2018 studies (C); (2) How does the integration and implementation of multi-actor perspectives (I) in water governance models (P) affect the effectiveness of circular water economy policies (O) compared to traditional governance approaches (C)?

Therefore, the overall objective is to systematize the evolution, effectiveness, and impact of circular water management technologies and strategies during 2018–2024, identifying patterns, trends, and critical factors for their scalability and replicability in different contexts. The specific objectives include the following: (1) to comparatively evaluate the technical, economic, social, and environmental performance of the main resource reuse and recovery technologies implemented in urban, agricultural, and industrial sectors; (2) to determine political, institutional, and governance frameworks with success factors and possibilities for replicability.

The 2018–2024 period was strategically selected as it covers a period of unprecedented acceleration in circular economy research and implementation, coinciding with important policy initiatives such as the EU Circular Economy Package and a greater focus on water–energy–food nexus approaches. This period of six years and four months provides sufficient time to analyze conceptual and technological developments while capturing the latest trends without compromising the comprehensiveness of the search [20]. Ultimately, this systematic review addresses urgent needs to systematize and critically analyze recent advances in the circular economy and water sustainability, contributing significantly to the achievement of SDG 6 in a global context where water security faces multiple stressors, providing evidence-based guidance for researchers, policymakers, water managers, and actors in the transition toward circular and sustainable water management [21,22].

1.1. Conceptual Foundations of the Circular Economy and Water Resources Nexus

The circular economy (CE) is a paradigm that acts as an alternative to the traditional linear economic model by promoting regenerative systems where waste and pollution are reduced by design [23]. Given the increasing water stress and water crisis and the challenges presented by climate change, this approach is critical in the context of water resources. The dominant theoretical frameworks used at this intersection include the water–energy–food nexus, the ecosystem services framework, and the socio-technical perspective [24].

However, as mentioned by El Houda Chaher et al. (2024) [25], it is necessary to expand this conception to a food–water–ecosystem nexus that specifically integrates food waste and ecosystems, thus enabling a more holistic understanding of the circular dynamics of water. Therefore, the circular water economy is conceptualized as a system that optimizes the use of water resources, minimizing waste generation and pollution, closing water, nutrient, and energy cycles [18].

1.2. Key Categories in the Circular Economy Applied to Water Sustainability

1.2.1. Technologies for Water Reuse

The evolution of technologies has been one of the most significant drivers for achieving water circularity. Among the novel options gaining recognition are the use of MBRs (membrane bioreactors), advanced desalination, and advanced oxidation processes. Despite this, all technologies face both technical and economic as well as regulatory barriers that prevent adequate large-scale implementation [10]. Perhaps the most significant development is the transformation of wastewater treatment systems into resource recovery infrastructure and the transformation and integration of approaches to clean water with those of nutrient and energy harvesting [26].

The most commonly implemented water reuse technologies globally include several systems that have demonstrated proven technical and economic viability in different operational contexts. Among the most widely adopted technologies are membrane bioreactors (MBRs), which combine conventional biological treatment with state-of-the-art membrane filtration, consistently achieving contaminant removal efficiencies of 90–98% according to evidence documented in multiple industrial and municipal implementations [10]. Advanced oxidation processes (AOPs) are another widely implemented technology, demonstrating exceptional effectiveness for the treatment of emerging and persistent pollutants, with reported efficiencies of 75–95% in specific applications [27].

At the same time, decentralized treatment systems represent a technologically appropriate alternative for contexts with significant centralized infrastructure limitations, showing operational efficiencies of 65–85% whilst offering implementation flexibility and reduced dependence on extensive distribution networks [11]. Finally, constructed wetlands are a low-energy option with consistent efficiencies of 70–90% [9], being particularly relevant for developing countries due to their lower demand for specialized technological resources, ease of maintenance, and ability to integrate with existing local ecosystems.

1.2.2. Water Efficiency in Productive Sectors

In the productive sectors, strategies have been developed that have proven useful for optimizing water consumption and promoting closed cycles. In this direction, some agricultural practices, such as drip irrigation and fertigation with wastewater, and other industrial practices, such as industrial symbiosis and resource recovery, stand out [28]. The efficiency of such practices can be assessed through analytical models, such as Data Envelopment Analysis, which quantify technical efficiency in different geographical and sectoral contexts [29].

1.2.3. Innovation in Integrated Water Management Policies

It was not until more recent approaches that the technical and legal regulatory framework related to water evolved from fragmented to more holistic approaches considering the total water cycle. In this sense, ref. [30] proposes the "Water in the Circular Economy and Resilience (WICER) Framework" as a framework toolbox to commit in turn to a mutual understanding of the principles of the circular economy and downstream resilience in particular for specific issues in developing countries. Based on previous studies, this tool recommends nine actions in three key areas leading to three outcomes.

1.2.4. Theoretical Foundations of Circular Business Models in Water Systems

The circular economy applied to the water sector has generated new business models based on the valorization of natural and wastewater treatment by-products. An innovative concept is the "circular value of water" proposed by [31], which evaluates the economic potential of circularity strategies considering factors such as chemistry, concentration levels, and purity of effluents. In addition, ref. [32] analyzes the tariff impact and financial performance of innovative technologies (SMARTechs) that enable companies to work toward a circular economy approach, demonstrating that investment in these technologies provides financial and environmental benefits.

1.2.5. Stakeholder Participation

The transition to more sustainable water systems requires the active collaboration of multiple stakeholders. As the authors of [33] demonstrate in their study on Ljubljana (Slovenia), urban professionals such as urban planners and environmental engineers act as facilitators and change agents in the implementation of nature-based solutions for water management. However, challenges related to the misalignment of strategic objectives, institutional fragmentation, and limited citizen participation persist and require new approaches and skilled knowledge brokers.

1.3. Evaluation of Circularity in Water Systems

A fundamental aspect of the circular water economy is the measurement and evaluation of circular performance. Ref. [34] proposes a novel approach to circularity assessment in the water sector, redefining concepts such as restoration, regeneration, and linear flows. This methodology reveals that using the original material circularity indicator (MCI) method underestimates the circularity of resource recovery solutions involving biogeochemical resources such as nitrogen and phosphorus.

Moreover, ref. [35] presents a heuristic framework in the form of eight adapted "R" strategies for water and sanitation. The eight R strategies (8R: refuse, reduce, reuse, recycle, recover, redesign, remanufacture, and repurpose) are selected and articulated to reflect the theoretical principles of circular economy, climate resilience, and inclusiveness. Theoretically, this framework provides a conceptually rigorous and practical tool to support collaborative processes in realizing the potential benefits of circularity with respect to water and sanitation service systems.

1.4. Sectoral Applications of the Circular Water Economy

The implementation of circular economy principles in the water sector shows specific applications in various fields. Ref. [20] applies the water–energy–food nexus (WEF) together with a circularity indicator to perform a comparative analysis of dairy farms, demonstrating that the technology of fertigation with treated wastewater can significantly improve nitrogen and water circularity.

On the other hand, the field of aquaculture is addressed by the authors of [26], who discuss the incorporation of microalgae technology for sustainable seafood production and point out how this approach can help close nutrient cycles and increase the efficiency of aquaculture systems.

1.5. Digital Tools and Modeling

In addition, digital tools are playing an increasingly important role in facilitating the transition to circular water systems. Ref. [36] invented "Toy Town", a testbed that encompasses a range of technologies and options that offer a demonstrable framework for circular water management systems. "Toy Town" is a model designed for demonstration purposes, and was built using Julia software v1.6.1. Essentially, "Toy Town" is a mass balance model over time, tracking volumetric flows of water/wastewater and concentrations/dilutions of pollutants/materials in the city's water cycle.

In addition, the authors of ref. [37] published a serious game for teaching the circular water economy, allowing participants to explore the consequences of implementing a variety of circular economy strategies in various virtual watersheds. This was successful as part of not only teaching but also setting up forums for multidisciplinary experts.

Thus, according to the literature analysis there are significant trends, characteristically for the period 2018–2024. It can be stated that there is consensus around the need for systemic and integrated approaches, and furthermore, there is an increasing convergence in terms of methodological frameworks that begin to combine life cycle analysis (LCA) with material flow analysis and multi-criteria assessment [38,39].

On the other hand, the differences lie in the approaches used for the implementation of circularity in particular contexts, and, in particular, those related to developed and developing countries. Moreover, as mentioned by the authors of [40], most of the literature on the circular economy applied to water is of an environmental nature, in fact, this dimension represents 77.1% while the economic and the social and economic dimensions present an abysmal difference with only 20.5% and 2.4%, respectively. These data are very unbalanced and affirm the previous statement that more studies are needed in this direction.

The circular economy of water sustainability is a rapidly evolving field that links technology with the economy, society, and the environment. Recent discoveries in the development of recycling and recovery technologies for wastewater and treated water, the combination of new policies and technologies, and wine and existing businesses, combined with public policies, open up new ways for all of the above factors to close water and related resources.

However, successful implementation of these principles entails overcoming significant barriers, particularly in terms of institutional coordination, financing, social acceptability, and adaptability to specific local contexts. The transition to circular water systems requires an integrated approach that takes into account linkages with other areas, such as energy and food security, and impacts on social and environmental areas. Finally, much more robust approaches and methodologies are needed to assess the circular performance of systems, as well as to promote stakeholder participation in designing and supporting the implementation of circular strategies. An intelligent and promising way in this direction is provided by the concept of "circular water economy," for which the technological vision is integrated with the economic and social aspects, creating a vision of awareness for good sustainable water management.

2. Materials and Methods

2.1. Study Design

The methodological design implemented in this study was a systematic review. Its development focuses on ensuring a rigorous, replicable, and transparent approach to the identification, evaluation, and synthesis of scientific evidence relevant to the circular economy and water sustainability. The methodological approach is aligned with the PRISMA 2020 guidelines of [41] (see Supplementary Materials), which implies a structured process that is divided into four indicative stages. These are the identification of records through database searching, the selection of articles through the application of predefined criteria, the eligibility assessment through full-text analysis, and the final inclusion of studies that met all requirements. The implementation of this methodological design helps to minimize biases and ensures maximum coverage of the available relevant literature [42].

2.2. Search Strategy and Sources of Information

For the present review, three of the main academic databases, Scopus, ScienceDirect and Taylor & Francis Online, were selected. The choice of these specific databases was made according to the strategic criteria necessary to ensure optimal coverage and quality of the selected literature. Thus, Scopus was considered as it is the world's largest citation and abstract database of peer-reviewed literature, covering more than 24,600 active journals in the multidisciplinary fields [5]. ScienceDirect was selected for its specialization in scientific and technical publications, providing access to more than 2500 high scientific quality journals with a high impact factor in the fields of sustainability, environmental engineering, and circular economy [11]. As for Taylor & Francis Online, it is a major provider of scientific articles dedicated to environmental sciences, resource management, and environmental policy and, thus, it has a large number of articles on sustainability and circular economy applied to natural resources [43].

2.3. Search Equation and Keywords

In order to ensure the relevance and precision of the results, the following search equation was designed; key terms in English and Spanish were combined and Boolean operators were used to take advantage of the sensitivity and specificity of the search. Meanwhile, this work used the combination of operators of provenance, "OR", and exclusion, "AND" and "AND NOT". The search equation was as follows:

("circular economy" OR "circular economy") AND ("water sustainability" OR "water sustainability") AND ("water reuse" OR "water reuse") AND ("water management" OR "water management") AND (2018–2024).

Consequently, the search strategy was specifically adapted to each database while maintaining the conceptual consistency established in Table 1. In Scopus, the following syntax was used: (TITLE-ABS-KEY("circular economy" OR "circular economy") AND TITLE-ABS-KEY("water sustainability" OR "water sustainability") AND TITLE-ABS-KEY("water reuse" OR "water reuse") AND TITLE-ABS-KEY("water management" OR "water management") AND PUBYEAR > 2017 AND PUBYEAR < 2025). For ScienceDirect, specific search fields were used in the title, abstract, and keywords, applying time and document type filters. In Taylor & Francis Online, the search was performed using Boolean operators in full-text fields, supplemented with journal and year of publication filters. This systematic approach ensured the comprehensive capture of relevant literature whilst minimizing the inclusion of studies tangential to the established conceptual framework [9,18].

Table 1. Keywords used in the systematic review.

Category	Primary Keywords	Secondary Keywords
Economic paradigm	Circular economy and circular water economy	Resource efficiency, Resource recovery, and Closed-loop systems
Sustainability of water resources	Water sustainability and sustainable water management	Water security, water stress, and water scarcity
Reuse technologies	Water reuse and water recycling	Wastewater treatment, reclaimed water, and water reclamation
Management and policies	Water management and water governance	Integrated water resources management, water policies, and water regulation
Sectors of application	Urban water, agricultural water, and industrial water	Irrigation, water-intensive industries, and municipal water

Note. Keywords were used in English and Spanish in all the databases consulted.

This combination was tailored to each database used; however, the same conceptual logic was maintained. The selection of terms was based on the preliminary literature review and on the categories identified in studies in previous water economics and sustainability circular journals, respectively [9,18]. Keywords were ranked according to a primary and intermediate split based on search precision. Table 1 shows the hierarchical structure of the keywords used.

2.4. Inclusion and Exclusion Criteria

In order to ensure the relevance and quality of the studies considered, the inclusion and exclusion rules on the basis of which the selection was made were also determined. These criteria were based on the desire to acquire the most up-to-date, rigorous, and directly relevant literature to the problem in question [10]. Table 2 provides an example of these criteria and their corresponding justification.

Table 2. Inclusion and exclusion criteria applied in the systematic review.

Dimension	Inclusion Criteria	Exclusion Criteria	Justification
Time period	Studies published between January 2018 and April 2024	Studies published before 2018 or after April 2024	To capture the most recent trends in a rapidly evolving field [20]
Language	Articles in English or Spanish	Publications in other languages	Ensure accurate understanding by the research team
Type of publication	Peer-reviewed scientific articles	Conference abstracts, letters to the editor, editorials, book chapters, theses, and technical reports	Ensure methodological quality and critical peer review [42]
Thematic relevance	Studies that clearly address circular economy applied to water management.	Studies on circular economy without relation to water, or on water without circularity approach	Maintain thematic specificity and relevance to the objectives of the study [9]

Table 2. *Cont.*

Dimension	Inclusion Criteria	Exclusion Criteria	Justification
Accessibility	Accessible full texts	Articles with only abstract available or restricted access	Allow for in-depth analysis of methodology and results
Methodological approach	Empirical studies, systematic reviews, critical analyses, and conceptual frameworks with validation	Purely theoretical articles with no empirical application or validation	Prioritize evidence based on concrete data and experiences [11]
Sectors of application	Studies in urban, agricultural, and industrial sectors	Studies focused exclusively on natural environments without human intervention	Cover the main water consumption sectors with circularity potential [28]
Methodological quality	Methodology clearly described, objectives defined, and rigorous analysis	Methodology insufficiently described, vague objectives, and lack of analytical rigor	Ensure methodological robustness and reliability of results
Geographic scope	Studies of any geographic region with emphasis on diverse contexts	Studies without clear geographic specification or undefined context	Allow for comparative analysis between different socioeconomic contexts
Technologies addressed	Implemented technologies, under demonstration or with pilot validation	Purely conceptual technologies without experimental validation	Focus on solutions with demonstrated technical feasibility
Sustainability dimensions	Studies addressing at least one dimension of sustainability (environmental, economic, and social)	Studies without explicit consideration of sustainability aspects	Align with sustainable development and circular economy objectives
Level of implementation	Studies at laboratory, pilot, demonstration, or full implementation level	Purely conceptual studies without experimental component	Prioritize practical and applicable evidence
Performance indicators	Studies with quantitative or qualitative performance metrics	Studies without evaluation or outcome measurement indicators	Allow comparative analysis of effectiveness
Policy frameworks	Studies that include analysis of policies, regulations, or institutional frameworks	Studies that completely omit public policy considerations	Capture the institutional dimension of implementation
Stakeholder participation	Studies that consider multiple stakeholders or perspectives	Studies with a unidimensional approach without consideration of stakeholders	Reflecting the multi-stakeholder nature of circular water management
Scalability	Studies that discuss potential for scaling or replicability	Single case studies without consideration of transferability	Identify critical factors for broad implementation

2.5. Search and Selection Procedure

The search string and selection of articles was carried out with a protocol that guarantees systematicity and transparency between October 2024 and February 2025. Initially, the search in the three databases is executed with the previously described string, formatted according to the language and specific syntax of each platform. The results are imported into Mendeley bibliographic manager, where duplicates were eliminated through the automated function, complemented by a manual search in the case of citation discrepancies. Then, the screening was executed with the reading of titles and abstracts by two reviewers, with the resolution of inclusion and exclusion criteria. If discrepancies were found, they were resolved through discussion, and if no consensus was reached, another reviewer was introduced.

Articles that could still be considered after the previous phases were subjected to a full-text review, again applying the established criteria in a more exhaustive manner. The reasons for exclusion were systematically documented to ensure the transparency of the process at each stage. A manual search of the references of the selected articles was carried out using the snowball method, since it is possible that relevant studies could be found in this regard that had not been captured in the previous search. This iterative process allowed us to optimize the sensitivity of the search strategy to minimize the risk of the omission of relevant studies [42].

The delivered methodology takes timely advantage of the necessary use of VOSviewer v1.6.18 as a bibliometrics analysis tool, which has enabled the visualization of co-occurrence, co-citation, and bibliographic coupling networks in the academic domain of circular economy and its relationship with water sustainability. In particular, VOSviewer software allows for the processing of the systematic existence of thematic clusters, patterns of scientific collaboration, and conceptual evolution from a chrono-differential framework from 2018 to 2024. The generated bibliometric maps (presented in later sections) were effective for visualizing the knowledge structure, relationships, and nuclei of concepts such as waste management, wastewater treatment, and valorization technologies. On the other hand, it would have been desirable to detail with additional precision the parameters used for the configuration of the minimum occurrence threshold maps, normalization method, and clustering algorithm and to describe the process of cleaning and normalizing terms before analysis to ensure the complete reproducibility of our bibliometric study. VOSviewer allowed us to identify thematic clusters, trends in scientific collaboration, and conceptual evolution of scientific approaches composing circular economy and water sustainability [44].

The bibliometric analysis was performed using VOSviewer v1.6.18, configuring specific parameters to ensure complete methodological reproducibility [44]. A minimum occurrence threshold of 5 terms was set for co-occurrence analysis, applying normalization by association strength and a modularity-based clustering algorithm with 1.0 resolution. For the journal co-citation analysis, a minimum threshold of 10 citations per source was used, with Salton normalization method and clustering resolution of 1.2.

Prior to analysis, a systematic cleaning of terms was performed by the unification of synonyms (e.g., "wastewater treatment" and "effluent treatment") and elimination of generic terms without specific conceptual value ("analysis," "study," "research"). Strength of association measures the relative frequency of co-occurrence between terms compared to the expected frequency under statistical independence, providing a standardized metric of conceptual association that facilitates the identification of coherent thematic domains.

Systematic Documentation of Exclusion Criteria

The rigorous application of exclusion criteria resulted in the elimination of 188 articles, the reasons for which were systematically documented to ensure methodological transparency. The main categories of exclusion included the following: studies that did not specifically address circular economy technologies or strategies applied to sustainable water management (n = 85, 45.2%), research not focused on key sectors such as agriculture, industry, or urban systems (n = 53, 28.2%), insufficiently described methodologies that prevented quality assessment (n = 30, 16.0%), and the absence of concrete results on implementation or the effectiveness of interventions (n = 20, 10.6%).

In addition, we systematically excluded purely conceptual studies with no empirical validation component, research focused exclusively on natural environments without anthropogenic intervention, technologies without demonstration at pilot or larger scale, and publications that lacked verifiable quantitative or qualitative performance metrics.

2.6. PRISMA Flow Chart

The article selection process was documented through a flow chart made under the PRISMA 2020 guidelines [41] (Figure 1), which provides a clear visual image regarding the total number of records identified, records after removal of duplicates, additional records which have been excluded with their corresponding reasons to be evaluated at full-text, and the final number of studies included in the synthesis (Figure 1). Sequentially, the diagram involved the total number of records identified in each relevant database and by other search methods, the number of records after elimination of duplicates, the total number of records to be considered from the screening phase, the number of additional records by prior elimination to full-text and the total number of records analyzed under this modality together with those excluded with reasons, and, finally, the total number of studies included in the synthesis. This detailed representation made it possible to verify the robustness and replicability of the development, in terms of the power of adherence to a methodical model [36].

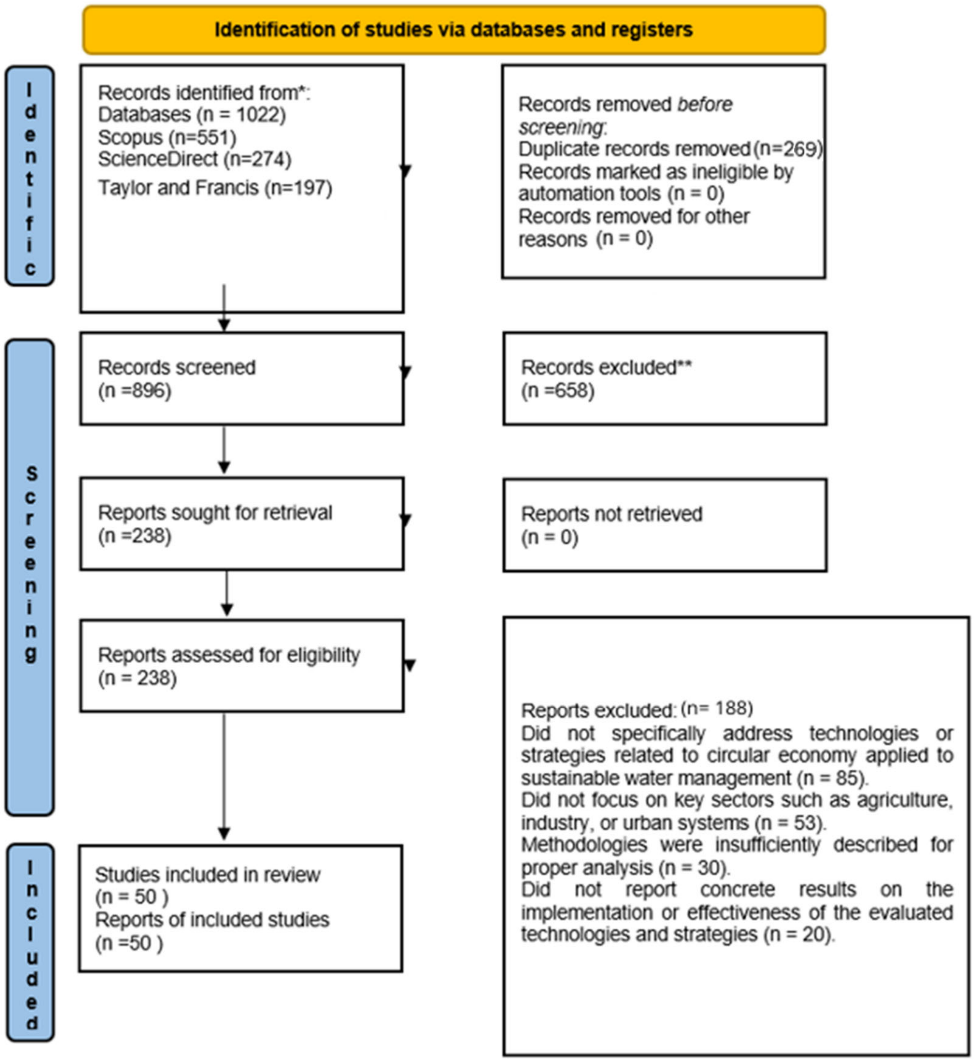

Figure 1. PRISMA flow diagram for the systematic review of circular economy and water sustainability literature (2018–2024). * Total records from databases and manual search; ** Records excluded during initial screening.

2.7. Methodological Quality Assessment

In order to ensure the robustness of the results, a systematic evaluation of the methodological quality of the articles included was carried out. An adaptation of the critical appraisal tool CASP (Critical Appraisal Skills Programme) was used, to which specific criteria referring to the circular economy and water management were added [20]. The evaluation was carried out independently by two researchers, who assigned an evaluation on a scale of 0–2 for each criterion, obtaining a total score between 0 and 20 points. The studies were classified according to their methodological quality as high (16–20 points), medium (11–15 points), or low (≤10 points). Table 3 presents a representative sample of the results of this evaluation for the included articles.

Table 3. Complete assessment of the methodological quality of the included studies (n = 50).

Study	Author(s)	Type of Study	Clarity of Objectives (0–2)	Appropriate Methodology (0–2)	Appropriate Design (0–2)	Rigorous Analysis (0–2)	*EC Consideration (0–2)	Consideration of Water Aspects (0–2)	Applicability (0–2)	Relevance (0–2)	Innovation (0–2)	Limitations (0–2)	Total Score (0–20)	Quality
1	Sgroi et al. [9]	Critical review	2	2	1	2	2	2	2	2	1	1	17	High
2	Mannina et al. [10]	Systematic review	2	2	2	2	2	2	2	2	1	2	19	High
3	Voulvoulis [11]	Analytical study	2	1	1	2	2	2	2	2	2	1	17	High
4	Sauvé et al. [18]	Conceptual study	2	1	1	1	2	2	2	2	2	1	16	High
5	Stankiewicz et al. [27]	Experimental study	2	2	2	2	2	2	2	2	1	2	19	High
6	Verma et al. [21]	Nexus FEW	2	2	2	2	2	1	2	2	2	1	18	High
7	Mukherjee et al.	Socioeconomic sustainability	2	1	1	2	2	1	2	2	2	2	17	High
8	Salminen et al. [23]	Policy study	2	2	1	2	2	2	2	2	1	1	17	High
9	Ramírez-Agudelo et al. [24]	Case study	2	1	2	1	2	2	2	2	2	1	17	High
10	Chaher et al. [25]	Conceptual framework	2	1	2	1	2	2	2	2	2	1	17	High
11	Li et al. [28]	Biochar optimization	2	2	2	2	2	1	2	2	2	1	18	High
12	Bronner et al. [29]	DEA analysis	2	2	2	2	2	2	1	2	1	2	18	High
13	Delgado et al. [30]	WICER Framework	2	2	1	2	2	2	2	2	2	1	18	High
14	Xevgenos et al. [31]	Circular value of water	2	1	2	2	2	2	2	2	2	1	18	High
15	Piubello et al. [32]	Case study	2	2	2	2	2	2	1	1	2	1	17	High
16	Tsatsou et al. [33]	Expert interviews	2	2	1	1	1	2	2	2	2	2	17	High
17	Bhambhani et al. [34]	Methodological	2	2	2	2	2	2	1	2	2	1	18	High
18	Carrard et al. [35]	Heuristic framework	2	2	2	1	2	2	2	2	2	1	18	High
19	Rebolledo-Leiva et al. [20]	Multi-criteria analysis	2	2	2	2	1	2	2	2	2	1	18	High
20	Evans et al. [36]	Toy Town	2	2	2	2	2	2	2	2	2	1	19	High
21	Khoury et al. [37]	NEXTGEN serious game	2	2	2	2	2	2	2	2	2	1	19	High
22	Slorach et al. [38]	Nexus methodology	2	2	1	2	2	1	2	2	2	2	18	High
23	Karkou et al. [39]	Experimental study	2	2	2	2	1	2	2	1	2	2	18	High
24	Kalmykova et al. [42]	Practical theoretical review	2	2	2	1	2	1	2	2	2	1	17	High
25	Nagarajan et al. [26]	Review aquaculture	2	1	1	2	2	2	2	2	2	1	17	High
26	Dominguez et al. [45]	LCA graywater	2	2	2	2	2	2	2	2	1	1	18	High
27	Oprea and Voicu [46]	Membranes CA	2	2	2	2	1	2	1	1	2	2	17	High
28	Abu [47]	Reuse EC	1	1	1	1	2	2	2	2	1	1	14	Average
29	Nunn et al. [48]	Mining waste	2	2	2	2	2	1	2	1	2	2	18	High
30	Koseoglu-Imer et al. [49]	European challenges	2	1	1	1	2	2	2	2	1	1	15	Average
31	Lefebvre [12]	NEWater Singapore	2	1	1	2	2	2	2	2	2	1	17	High
32	Cobo et al.	Circular linear IWMS	2	2	2	2	2	1	2	2	2	1	18	High
33	Zabaniotou	Bioenergy EU	2	1	1	1	2	1	2	2	2	2	16	High
34	Aivazidou et al.	Water footprint	2	2	2	2	1	2	2	2	1	1	17	High
35	Martín et al. [2]	Eco-industrial parks	2	2	2	2	2	1	2	2	2	1	18	High
36	Manninen et al.	EC business models	2	1	1	2	2	1	2	2	2	2	17	High
37	Jacobi et al.	EC monitoring Austria	2	2	2	2	2	1	1	2	1	2	17	High
38	Reike et al.	CE 3.0 conceptual	2	1	1	1	2	1	2	2	2	1	15	Average
39	de Jesus et al.	Eco-innovation EC	2	2	2	2	2	1	2	2	2	1	18	High
40	Carpenter et al.	Port Gävle	2	1	2	1	2	2	2	2	2	1	17	High
41	Jørgensen and Remmen	CE development companies	2	2	1	1	2	1	2	2	2	2	17	High
42	Ingrao et al.	Food waste	2	2	2	2	2	1	2	2	1	1	17	High
43	Stiles et al.	Microalgae digestate	2	1	2	2	2	2	2	2	2	1	18	High
44	Dahiya et al.	Biorefinery waste	2	2	2	2	2	1	2	2	2	1	18	High
45	Smol et al.	Public awareness EC	1	1	1	1	2	1	2	2	1	2	14	Average
46	Sadhukhan et al.	Bioenergy Malaysia	2	2	2	2	2	2	2	2	2	1	19	High
47	Ghisellini et al.	C&D construction	2	2	2	2	2	1	2	2	1	1	17	High
48	Xue et al.	FEW urban nexus	2	2	2	2	2	2	2	2	2	1	19	High
49	Pauliuk	Standard BS 8001	2	2	2	2	2	1	2	2	2	2	19	High
50	Singh et al.	MSME India	1	1	1	1	2	1	2	2	1	2	14	Media

*EC: Circular economy. Note. Total score: high (16–20), medium (11–15), and low (≤10). Quality distribution summary: high quality (16–20 points): 45 studies (90%); medium quality (11–15 points): 5 studies (10%); low quality (≤10 points): 0 studies (0%).

2.8. *EC: Circular Economy

The selection of the 2018–2024 time period for this systematic review was based on several epistemological and pragmatic considerations. First, 2018 marked a turning point in the literature on circular economy applied to water management, with the publication of several seminal studies that established fundamental conceptual and methodological frameworks in the field [5,9,11]. Moreover, this phase overlaps with an increased political and academic interest in the circular economy as a vehicle for sustainability, as reflected in the shaping of the EU (European Union) Circular Economy Package and several strategies at national and international level [32].

In turn, the acceleration during this period of the impacts of climate change on water resources led to a boom in research on creative approaches to sustainable water efficiency; therefore, the last six years have also been particularly fruitful in terms of the maturation of water circularity technologies and strategies [39]. Likewise, the selection of this period is justified due to the effect of major technological transformations that have simplified the use of circular solutions in the water sector, such as digitization and the Internet of Things (IoT), as well as artificial intelligence applied to water systems [36].

Finally, the time frame allowed for a critical analysis of recent trends in the discipline, allowing the identification of emerging trends, areas of agreement and disagreement, as well as knowledge gaps that will need further attention. Determining that we would look for research published until April 2024 ensured the timeliness of the findings and considered even the most recent developments in a field with rapid conceptual and applied evolution [20].

3. Results

The analysis identifies the following four clearly differentiated main thematic clusters (Figure 2): red cluster—waste management and sustainability, focused on life cycle approaches with central terms such as "waste management," "life cycle," and 'sustainability'; yellow cluster—wastewater treatment and reuse, focused on closed-loop technologies including "wastewater treatment," "water reuse," and "membrane bioreactor"; green cluster—physicochemical processes aimed at pollutant removal with terms such as "adsorption," "heavy metals," and 'oxidation'; blue cluster—resource valorization integrating biorefinery and energy recovery concepts through "resource recovery," "biogas," and "circular value." The size of the nodes represents the frequency of occurrence (minimum threshold: five occurrences), while the connections reflect the strength of co-occurrence normalized by association. The centrality of the concept "circular economy" highlights its articulating role between knowledge domains, confirming the emerging interdisciplinary nature of the field.

This map represents the intellectual structure of the field through patterns of co-citation among scientific journals (Figure 3). The central nodes correspond to *Science of the Total Environment* and *Journal of Environmental Management*, which act as transdisciplinary platforms for research in water circularity. Around these, specialized clusters are configured: generalist environmental publications (blue), specific journals on circular economy (yellow), and technical publications on water treatment (green). Node size indicates citation volume, while proximity reflects co-citation frequency. This configuration suggests that the literature on circular economy and water sustainability is mainly articulated at the intersection between environmental science, engineering, and resource management, with increasing integration of fields such as ecological economics and environmental governance.

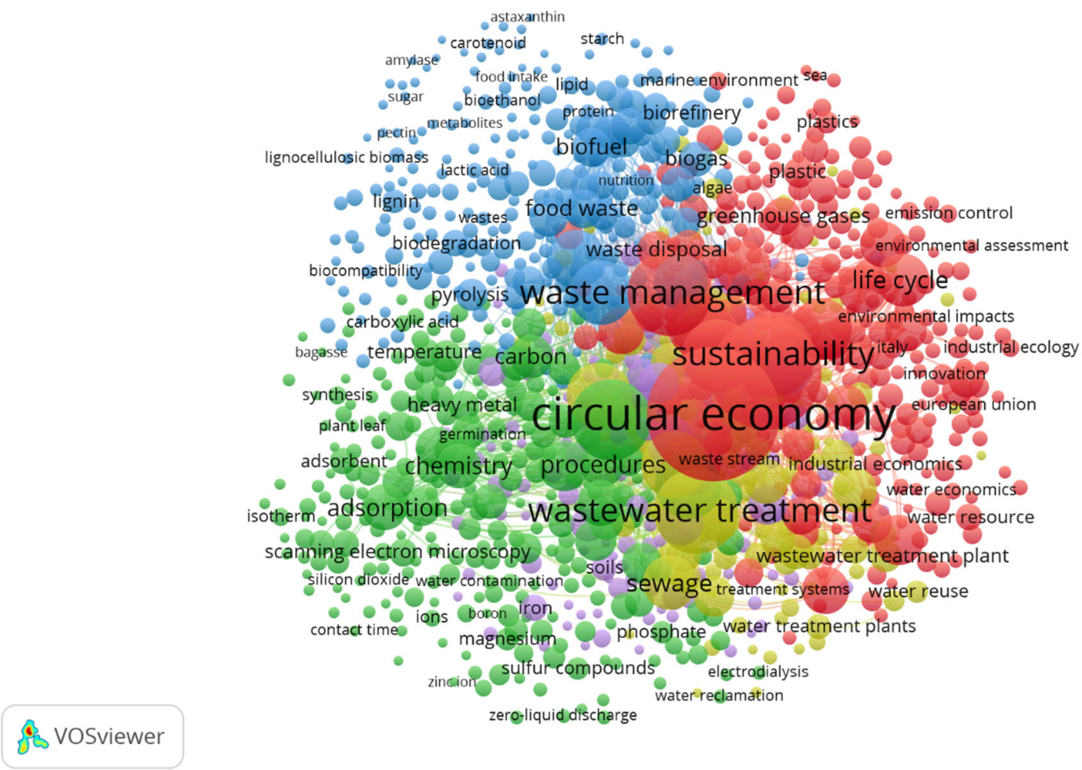

Figure 2. Node size = term frequency (min. 5 occurrences); link thickness = normalized association strength; spatial proximity = conceptual similarity based on co-occurrence patterns.

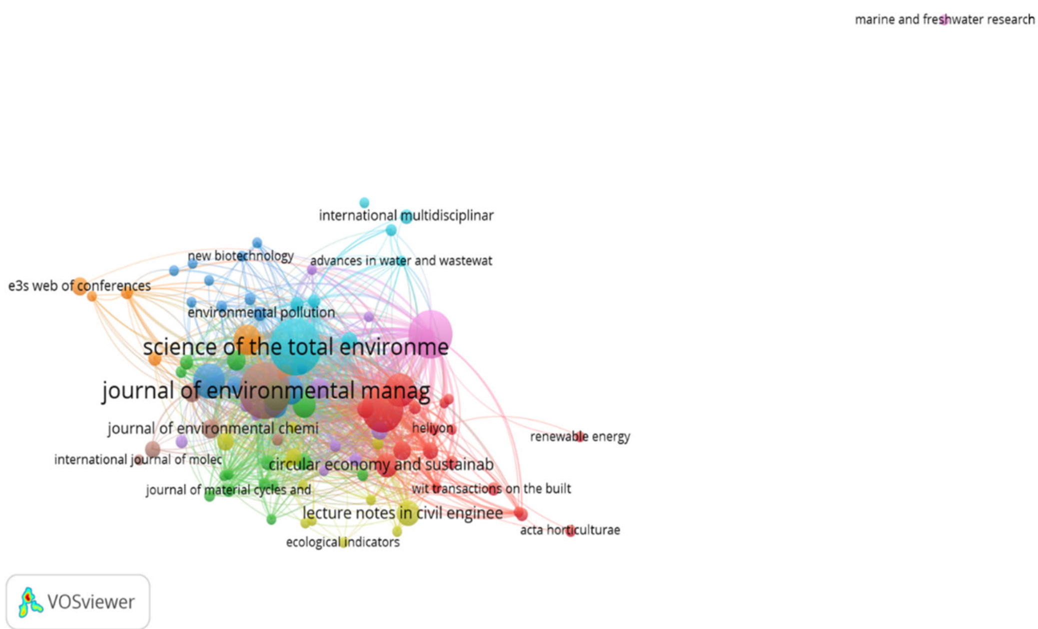

Figure 3. Journal co-citation map (2018–2024). Node size = citation count (min = 10). Links = co-citation frequency. Clusters: env-general (blue), circular (yellow), and watertech (green).

The figure visualizes the international scientific collaboration networks in the period studied. India emerges as the central node (largest size) with extensive collaborative connections, followed by the United Kingdom, Spain, Italy, and Brazil, as relevant actors (Figure 4). The intensity of the connections (lines) represents the frequency of co-authorship between countries. A north–south collaboration pattern is observed with a predominance of links between European and Asian countries, while Latin America shows an emerging participation led by Brazil, with secondary connections from Argentina and Mexico. This configuration reflects asymmetries in scientific production that could affect the contextualization of circular solutions in different regions, particularly in territories with high water vulnerability but less representation in global research.

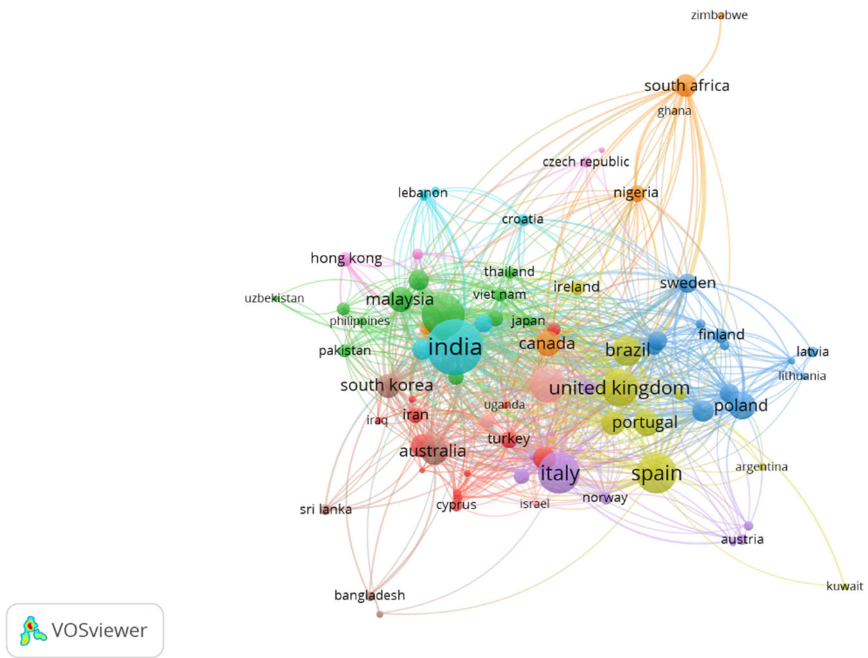

Figure 4. Node size = number of publications per country; link thickness = co-authored articles; clustering by regional collaboration clusters identified by modularity algorithm.

This map (Figure 5) represents the relationships between scientific sources through co-citation patterns. The main nodes correspond to *Journal of Cleaner Production* and *Bioresource Technology*, evidencing the centrality of publications that integrate technological aspects with sustainability perspectives. The following three main clusters are identified: (1) research on treatment technologies (blue), led by 'Desalination' and 'Chemosphere'; (2) sustainability and circular economy (yellow), with publications such as 'Sustainability' and 'Circular Economy and Sustainability'; (3) resource valorization (red), represented by journals specialized in biotechnology. The density of connections between these clusters reflects the multidisciplinary nature of circular water economy research, integrating knowledge from engineering, environmental chemistry, ecological economics, and social sciences to address water sustainability challenges.

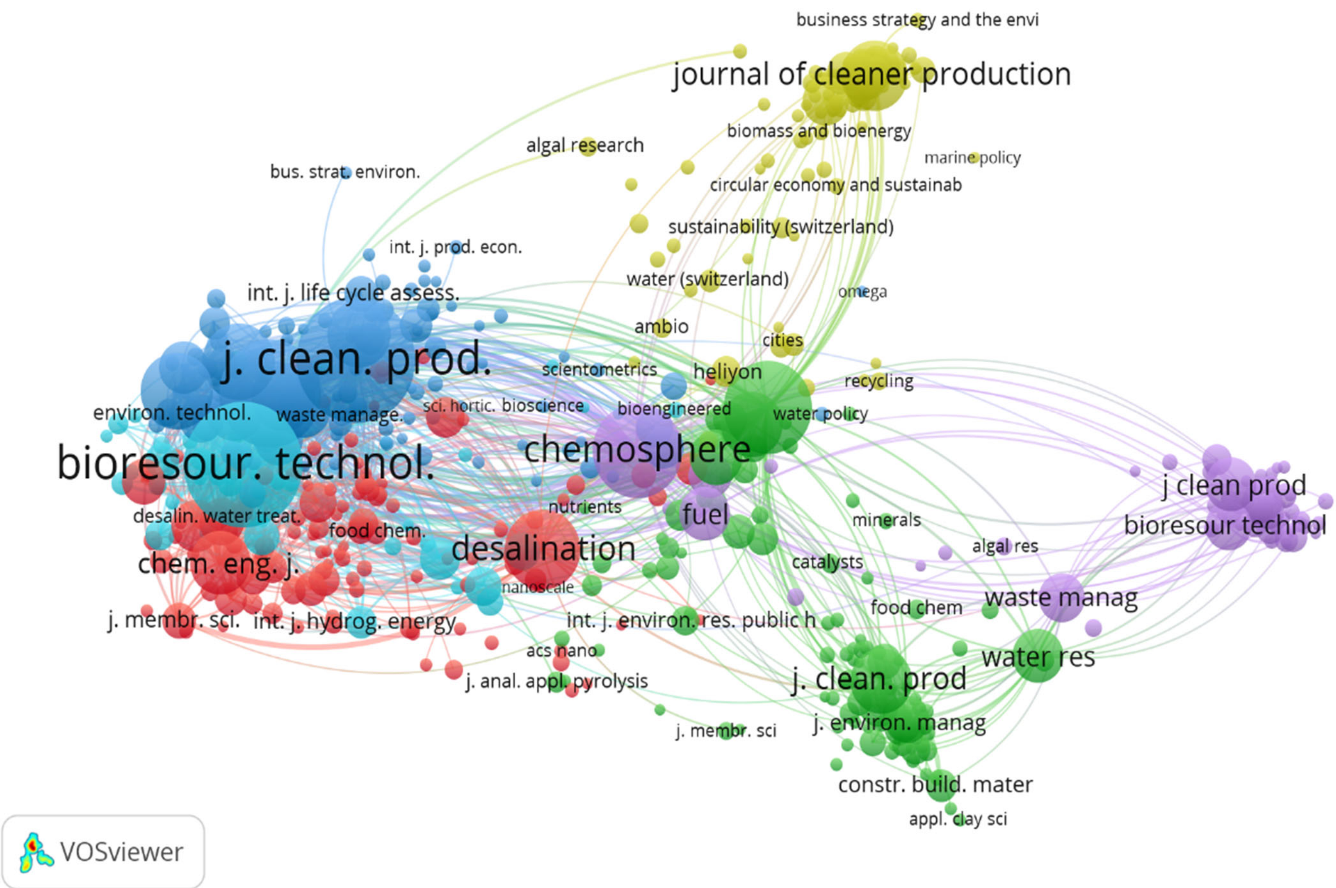

Figure 5. Source co-citation map (2018–2024). Node size = citation count; link thickness= co-citation strength. Clusters: tech-treat (blue), sustain-ce (yellow), and valorization (red).

3.1. Evolution and Characteristics of the Literature on Circular Economy and Water Sustainability

Systematic searching of the selected databases (Scopus, ScienceDirect, and Taylor & Francis) along with hand search records initially identified 1022 publications for the period 2018–2024. After removing 269 duplicates, 753 unique records were obtained and screened, resulting in 238 articles for full-text evaluation. Rigorous application of inclusion and exclusion criteria led to the final selection of 50 studies that met all the established requirements. The main reasons for exclusion were as follows: not specifically addressing technologies or strategies related to circular economy applied to sustainable water management ($n = 85$), not focusing on key sectors such as agriculture, industry, or urban systems ($n = 53$), insufficiently described methodologies ($n = 30$), and absence of concrete results on implementation or effectiveness ($n = 20$). The temporal distribution of publications showed an increasing trend, with a notable increase from 2020 onwards, reflecting the growing academic interest in circularity approaches to water management.

3.2. Bibliometric Analysis: Knowledge Structures and International Collaboration

The term co-occurrence analysis identified four main thematic clusters from the circular economy and water sustainability literature (Figure 2). First, the cluster (red) focused on terms such as "waste management", "sustainability", and "life cycle", reflecting a common interest in waste management strategies and life cycle approaches. Second, the cluster (yellow) grouped concepts related to wastewater treatment and reuse, such as wastewater treatment, water reuse, and wastewater treatment plant. Thirdly, the green cluster focused on technical aspects such as "adsorption", "heavy metal", and "scanning electron microscopy", while the fourth cluster (blue) grouped terms related to the valorization of organic waste, such as "biofuel", "biogas", and "biorefinery". On the other hand, the co-citation analysis of scientific journals (Figure 3) identified *Science of the Total Environment* and *Journal of Environmental Management* as the two predominant sources of publication and academic exchange in this field. In addition, journals such as *Ecological Indicators*, *Journal of Cleaner Production*, and *Circular Economy and Sustainability* emerged from the analysis as the most relevant nodes, reflecting the diversity of approaches from environmental, productive, and sustainability perspectives.

Regarding international collaboration networks (Figure 4), the analysis revealed India as the country with the highest production and connection, followed by the United Kingdom, Spain, Italy, and Brazil. The presence of Brazil as a focal point for Latin America suggests an emerging role of the region in water circular economy research, although with still limited participation of other Latin American countries such as Argentina and Mexico. This configuration evidences geographical asymmetries that could condition the adaptation of solutions to specific regional contexts.

Methodology for Identifying Thematic Clusters

Thematic domains were identified through co-occurrence analysis of terms using VOSviewer, applying specific criteria to ensure conceptual consistency. A minimum co-occurrence threshold of five terms was established, with normalization by association strength to minimize frequency bias. The modularity-based clustering algorithm with a resolution of 1.0 allowed natural thematic clusters to be identified in the data.

Prior to the analysis, terms were systematically cleaned by the following: (1) unifying synonyms (e.g., "wastewater treatment" and "effluent treatment"); (2) eliminating generic terms with no specific conceptual value ("analysis," "study," "research"); (3) normalizing linguistic variations. Cluster validation was performed through thematic consistency analysis, verifying that the grouped terms corresponded to conceptual domains consistent with the literature on circular economy applied to water sustainability.

3.3. Technologies for Water Reuse and Resource Recovery

The systematic review made it possible to identify and classify the main circular economy technologies applied to water management according to their level of maturity, efficiency, and sectors of application (Table 4). Membrane bioreactors (MBRs) emerged as one of the most consolidated technologies, with pollutant removal efficiencies above 90% and applicability in multiple sectors [10]. Likewise, advanced oxidation processes showed significant development, especially for the treatment of waters with emerging pollutants, although with operating costs that limit their large-scale implementation [27].

Table 4. Circular economy technologies for water management: documented performance metrics (2018–2024).

Technology	Maturity Level	Documented Efficiency	Reported Economic Viability	Context of Application	Main References
Membrane bioreactors (MBRs)	High	Removal of pollutants: 90–98%	Payback period: 5–8 years depending on context	High load urban and industrial systems	[10]
Advanced oxidation processes	Environment	Emerging pollutants: 75–95%	High operational costs limit scaling up	Treatment of waters with persistent pollutants	[27]

Table 4. *Cont.*

Technology	Maturity Level	Documented Efficiency	Reported Economic Viability	Context of Application	Main References
Decentralized systems	Medium	Overall removal: 65–85%	Less dependence on centralized infrastructure	Urban and rural contexts with limited infrastructure	[11]
Constructed wetlands	High	Treatment efficiency: 70–90%	Up to 60% less energy consumption vs. conventional systems	Suitable for developing countries	[9]
Nutrient recovery technologies	Medium	N and P recovery: 60–80%	Economic valorization of by-products	Agricultural and industrial sectors	[26]
Greywater reuse systems	High	Treatment efficiency: 85–95%	High economic feasibility in domestic applications	Commercial and residential	[45]

The most recent developments in advanced treatment technologies have demonstrated substantial progress in efficiency, selectivity, and environmental sustainability, representing the current technological frontier in the field. In this context, the authors of [50] documented improved stability properties in gold and silver nanofluids stabilized by gemini cationic surfactants, representing a significant advance in the stabilization of nanomaterials for specific water treatment applications that require high precision and operational durability [50]. Complementarily, Zuo et al. (2023) developed innovative 2D/2D heterojunction schemes of $ZnTiO_3/Bi_2WO_3$ nanosheets that exhibit remarkably improved photoelectrocatalytic activity for the specific treatment of phenolic wastewater under visible light conditions [51], demonstrating the progressive evolution toward more energy-efficient and environmentally sustainable photocatalytic systems. These technological advances represent the convergence of nanotechnology, photocatalysis, and circular economy principles, highlighting the evolution of the field toward more selective, efficient, and environmentally compatible systems.

Comparative Analysis of the Advantages and Disadvantages of Water Treatment Technologies

The systematic evaluation of the main technologies identified in the analysis reveals different profiles of advantages and limitations that condition their applicability in various operational contexts. Membrane bioreactors (MBRs) stand out for their exceptional ability to produce high-quality effluents with efficiencies greater than 90% in the removal of organic pollutants and suspended solids [10], while requiring less physical space than conventional activated sludge systems, which facilitates their implementation in densely populated urban environments. In addition, they offer significant operational flexibility to handle substantial variations in organic and hydraulic loads. However, they have important limitations related to high energy consumption (0.3–0.6 kWh/m^3) due to intensive aeration and suction systems, high initial investment and membrane replacement costs that can represent increases of 20–30% compared to conventional systems, and susceptibility to fouling that requires specialized and frequent cleaning protocols.

In contrast, advanced oxidation processes are exceptionally effective against emerging, persistent, and recalcitrant contaminants that are refractory to conventional biological treatments [27], allowing complete mineralization of complex organic compounds and offering remarkable flexibility in process configurations according to specific types of contaminants. However, these systems face operational challenges arising from high chemical reagent costs (ozone, hydrogen peroxide, and Fenton reagents), the potential formation of toxic by-products that may require additional treatment, and highly specialized process control requirements with continuous monitoring of multiple parameters.

On the other hand, constructed wetlands are technologically appropriate alternatives characterized by minimal or zero energy consumption (<0.1 kWh/m^3), extremely low operating and maintenance costs, and additional ecosystem benefits including habitat for local wildlife and atmospheric carbon capture [9], making them particularly relevant for contexts with significant technical and financial resource constraints. Paradoxically, these systems have considerable spatial limitations, requiring 2–5 m^2/equivalent inhabitant, seasonal variability in treatment efficiency that is particularly pronounced in temperate climates, and inherent limitations in the treatment of specific pollutants such as heavy metals and certain emerging pollutants.

This comparative assessment shows that the optimal technology selection must necessarily be based on contextualized analyses that simultaneously consider technical efficiency, economic viability, specific local conditions, and available institutional capacities, thus suggesting the relevance of hybrid approaches that synergistically optimize the complementary strengths of different technologies according to the specific requirements of each implementation [11].

3.4. Sectoral Implementation of Water Circular Economy Practices

The sectoral analysis showed differentiated patterns of adoption of circular practices according to the area of application (Table 5). The agricultural sector, as the main global water consumer, showed significant advances in techniques such as precision irrigation and fertigation with treated wastewater, with reuse rates ranging between 30 and 45% in water-stressed regions. Ref. [20] documented improvements of up to 35% in nitrogen circularity and 28% in water circularity by implementing fertigation technologies on dairy farms.

Table 5. Sectoral implementation of circular water economy practices.

Sector	Predominant Circular Practices	Level of Adoption	Reuse Rate	Enabling Factors	Main Barriers	References
Urban	Decentralized systems and reuse of gray water	Medium in developed countries and low in developing countries	15–30%	Favorable policies and shortages	Infrastructure and perception	[18]
Agricultural	Fertigation and precision irrigation	High in arid areas and medium in general	30–45%	Water scarcity and nutrient recovery	Sanitary and regulatory	[20,47]
Industrial	Closed circuits and industrial symbiosis	Medium–high in intensive industries	40–70%	Economic efficiency and regulation	Technical complexity and initial investment	[28,39]
Miner	Metal recovery and recirculation	Medium	50–60%	Economic value recovered	Complex contamination	[48]

At the industrial level, industrial symbiosis and resource recovery strategies showed the highest rates of circularity, with water reuse rates reaching 70% in sectors such as chemicals and textiles [28]. However, the actual materialization of these strategies evidenced significant geographical disparities. Ref. [39] documented that European companies implement an average of 3.2 circular practices in their water management, while in Latin America the average is 1.7, reflecting different levels of technological and institutional capacity.

In the Latin American context, the data reveal a significant lag. According to [13], the region reports that only 41% of wastewater is safely treated, a figure significantly lower than the world average (55.5%) and that of OECD countries (over 80%). This situation severely limits the potential for reuse and the valorization of resources, despite the fact that the region is home to approximately 34% of the world's renewable water resources [14].

The sectoral disparities observed in the adoption of the circular economy reflect fundamental differences in incentive structures and institutional capacities. As a result, the industrial sector shows higher reuse rates (40–70%) compared to urban systems (15–30%), mainly due to the following three converging factors: first, the concentration of water flows in industrial facilities facilitates the implementation of centralized treatment technologies with favorable economies of scale; second, industrial regulatory frameworks incorporate stricter compliance mechanisms that encourage investment in circular technologies, as evidenced in the study by Karkou et al. [39]; third, industrial business models allow treatment costs to be internalized as part of production processes, while urban systems face challenges of distributed financing and multi-actor coordination. Therefore, these findings suggest that public policy strategies should be differentiated by sector, prioritizing direct economic incentives for the urban sector and more stringent regulatory frameworks for industry.

3.4.1. Specific Challenges in the Latin American Context

The analysis reveals that Latin America faces distinctive structural barriers to the implementation of a circular water economy. First, the institutional fragmentation characteristic of the region, evidenced by the coexistence of multiple agencies with overlapping competencies, limits the intersectoral coordination necessary for integrated water policies [16,17]. Additionally, the financing deficit represents a critical constraint as while European countries allocate an average of 1.2% of GDP to water infrastructure, Latin American countries invest only 0.6%.

Nevertheless, the region presents unique opportunities that can enhance the circular transition. Brazil emerges as a regional leader in bibliometric analysis (Figure 4), accounting for 67% of Latin American scientific collaborations on circular water economy and developing innovative regulatory frameworks. Documented success stories include agricultural reuse programs that have achieved reuse rates of 34%, as reported in studies by [20]. These examples provide replicable models that can be adapted to specific regional contexts through adjustments to regulatory frameworks and financing schemes.

3.4.2. Regional Comparative Analysis of Circular Adoption: Bibliometric and Implementation Evidence

The bibliometric analysis reveals distinct geographic patterns in scientific output and international collaboration that reflect asymmetries in research and technological development capabilities (Figure 4). Significantly, India emerges as the central node with the highest volume of publications and extensive collaborative connections, followed by the United Kingdom, Spain, Italy, and Brazil as relevant players in the global knowledge network.

However, this prominence in academic production does not necessarily correlate with levels of practical implementation. For Latin America, the documented data reveal critical structural disparities. The region, despite hosting approximately 34% of the world's renewable water resources [14], faces significant deficits in wastewater treatment, with only 41% receiving safe treatment, substantially lower than the global average (55.5%) and that of OECD countries (>80%) [13].

Brazil represents a paradigmatic case, constituting 67% of Latin American scientific collaborations according to bibliometric analysis whilst simultaneously facing significant gaps in treatment infrastructure. This paradox between research capacity and operational implementation suggests the existence of systemic barriers that transcend available technical knowledge.

Institutional fragmentation emerges as a particularly relevant limiting factor in the Latin American context, where according to UNESCO [16], limited progress toward SDG 6 targets is partially attributed to "institutional fragmentation, lack of appropriate infrastructure and limited regional cooperation of shared basins". These findings underscore the imperative need for regionally differentiated strategies that consider not only technical capacities, but also specific institutional frameworks and financing structures.

3.5. Policy and Institutional Frameworks for Water Circularity

The analysis of policy and institutional frameworks revealed an evolution from sectoral approaches to more integrated perspectives that consider the interconnections between water, energy, food, and ecosystems (Table 6). The "Water in the Circular Economy and Resilience (WICER) Framework" proposed by [30] emerged as a relevant conceptual tool, especially for developing countries, by setting out nine key actions to achieve resilient and inclusive water services.

Table 6. Comparative analysis of policy frameworks for the circular economy of water.

Region/Framework	Predominant Focus	Cross-Sectoral Integration	Economic Instruments	Multi-Stakeholder Participation	Documented Effectiveness	References
European Union/EC Package	Systemic	High	Diversified	Medium–High	Medium–High	[32]
OECD/Water Wise	Efficiency and quality	Medium–High	Mainly tariffs	Media	Media	[23]
Marco WICER	Action-result	Media	In development	High	Emerging	[30]
Latin America	Fragmented	Download	Limited	Low–Medium	Download	[16,17]

The results showed that those countries with specific circular economy policies applied to the water sector show implementation rates of circular practices up to three times higher than those with fragmented approaches [49]. However, important challenges remain related to multilevel coordination between institutions and adaptation to specific local contexts.

In Latin America, as noted by [16], the region shows limited progress on SDG 6 targets, partly due to institutional fragmentation, lack of adequate infrastructure, and limited transboundary cooperation between shared basins. The authors of [17] identify that the transition to the circular economy requires strengthening water governance, promoting technological innovation, and articulating more effective regulatory frameworks to encourage the reuse and recovery of resources.

3.6. Integration of Specific Policies

To facilitate the effective alignment of circular economy strategies with national and regional water policies, five critical operational steps are identified. First, the establishment of integrated regulatory frameworks that unify water competencies currently fragmented among national, regional, and local entities, as proposed by the WICER framework [30]. Second, the implementation of differentiated economic instruments, including progressive tariffs that internalize environmental costs and subsidies targeted at SMARTechs with proven investment returns of 3–8 years [32]. Third, the development of monitoring and evaluation systems based on circularity indicators specific to the water sector, complementing traditional efficiency metrics as suggested by Bhambhani et al. [34]. Fourth, the creation of multi-stakeholder coordination platforms that facilitate the systematic participation of the private sector, academia, and civil society organizations in policy-making processes.

Fifth, the strengthening of institutional capacities through specialized training programs for public officials in circular water management.

3.7. Circular Economic Models in the Water Sector

The review identified a progressive expansion of business models based on the valorization of water treatment by-products, such as nutrient, energy, and mineral recovery. The concept of "circular value of water" proposed by [31] emerges as a relevant analytical framework by evaluating the economic potential of circularity strategies considering factors such as chemical composition, concentration levels, and purity of effluents.

The economic analysis conducted by [32] on the tariff impact and financial performance of innovative technologies (SMARTechs) showed that investment in these technologies provides both financial and environmental benefits, with payback periods ranging from 3 to 8 years depending on the context. Specifically, companies that implemented at least three SMARTechs showed an average 18% reduction in their medium-term operating costs.

However, results related to economic barriers were also identified, which could be more critical, particularly in the context of developing countries. According to [17] a circular economy principle in wastewater management "can be radical". The adoption of this principle "can represent a transformative opportunity" for the Latin American region as it can not only enable the recovery of energy, nutrients, and reusable water, but also, in combination with the green economies approach, contribute to the creation of green jobs and reduce greenhouse gas emissions. The problem is that an adequate economic and regulatory framework is needed.

3.8. Assessment of Circularity in Water Systems: Methods and Indicators

Overall, it can be concluded that the results present great development and progress in the methodologies for assessing circularity in water systems. Ref. [34] presents a novel approach that completely redefines the concepts of restoration, regeneration, and linear flows and proves that the original material circularity indicator (MCI) approach underestimates the circularity of solutions involving biogeochemical resources such as nitrogen and phosphorus in the worst case scenario by 35%.

On the other hand, ref. [35] update a heuristic framework in the form of 8 "R" strategies adapted for water and sanitation and selected to reflect the principles of the circular economy, climate resilience, and inclusiveness. The tool was validated on twelve case studies that demonstrated the feasibility of its implementation in different socioeconomic contexts.

In comparing the indicators, it was found that there was a clear trend toward the inclusion of social dimensions of governance in the circularity assessment over purely technical or material approaches. Despite this, there is still substantial methodological variability that complicates a systematic comparison of the data sets.

3.9. Digital Tools and Modeling for Circular Water Management

The review identified a growing development of digital tools aimed at facilitating the implementation of circular economy strategies in the water sector. Ref. [36] documented the development of "Toy Town", a Julia language modeled testbed for simulating volumetric water/wastewater flows and pollutant concentrations within the urban water cycle. The tool is already capable of evaluating 14 different configurations of circular water management systems.

Additionally, ref. [37] presented NEXTGEN, a serious game for circular water economy education in which participants explore different strategies in several virtual watersheds. The tool was tested in eight training workshops, with a total of more than 200 participants, with very effective results relating to its use in awareness raising and capacity building. Overall, the analysis presented here shows that the adoption of these digital tools can accelerate the planning and implementation of circular strategies by up to 30% as it facilitates scenario visualization and more informed decision-making.

3.10. Analysis of Limitations of Digital Tools

However, the implementation of digital tools for the circular water economy faces significant limitations that condition their scalability and applicability. The "Toy Town" model developed by Evans et al. [36], although innovative in its systemic approach, requires extensive data sets and specific calibration for each urban context, limiting its transferability to cities with restricted technical and information capabilities. In addition, the NEXTGEN tool presented by Khoury et al. [37], validated in eight workshops with more than 200 participants, demonstrated high effectiveness in formal training contexts, but its application in real participatory processes revealed challenges related to digital literacy and access to technology in vulnerable communities.

Consequently, the most critical limitations include the following: high input data requirements (up to 150 parameters for medium-sized cities), the need for constant algorithm updates to reflect regulatory changes, and dependence on technological infrastructure that may not be available in resource-constrained contexts. These constraints suggest the need to develop simplified and adaptive versions of digital tools that can operate effectively in diverse socioeconomic contexts.

3.11. Barriers and Enablers to the Implementation of the Circular Water Economy

In detail, the results with the greatest weight were the barriers and facilitators identified as duly conditioning the effective implementation in the water sector of the economic cycle strategies cited in Table 7. These findings align with broader literature on circular economy implementation barriers [52], which emphasizes similar challenges across different sectors.

Table 7. Main barriers and enablers for the circular water economy: documented empirical evidence.

Dimension	Specific Barriers Identified	Specific Enablers Documented	Quantitative Evidence	References
Technical	High energy consumption of MBRs; operational complexity of advanced systems; inadequate infrastructure for circular technologies; and susceptibility to membrane fouling.	MBR removal efficiency: 90–98%; modular systems with operational flexibility; digitization through IoT; hybrid treatment technologies; and improved operational efficiency: 15–25.	Operational efficiency improvement: 15–25% with IoT; and reduction in physical space vs. conventional systems.	[10,36]
Economic	High upfront costs; uncertainty about economic return; economic undervaluation of water; and extended recovery periods.	Valorization of by-products; tax incentives for green technologies; internalization of environmental externalities; and circular business models.	SMARTechs payback period: 3–8 years; eperating cost reduction: 18% average; and companies with $\geq$3 SMARTechs show better financial indicators.	[31,32]

Table 7. *Cont.*

Dimension	Specific Barriers Identified	Specific Enablers Documented	Quantitative Evidence	References
Regulatory	Institutional fragmentation; restrictive regulations; legal uncertainty; and lack of specific standards for reuse.	Integrated regulatory frameworks; specific quality standards; long-term planning; and multilevel coordination between institutions.	Countries with specific water CE policies: 3x higher implementation rate; and limited progress on compliance with SDG 6 in LAC.	[16,17,30]
Sociocultural	Resistance to water reuse; mistrust of recycled water; power asymmetries in decision-making; limited citizen participation; effective community participation; and transparency in processes of water reuse.	Effective community participation; transparency in technical processes; education and awareness-raising programs; and co-design of solutions.	Projects with community participation: >80% acceptance; and participatory strategies: 3× greater sustainability in the long term.	[24,49]

Regarding the promotion of circularity through regulations, institutional fragmentation and regulatory inconsistency also emerged as particularly relevant challenges in Latin America, a region where, according to [16], inter-basin cooperation is a weak commitment and where inter-basin cooperation is even more circumscribed. As for sociocultural barriers, public opposition to water reuse and condemnatory forms of reclaimed water resources were critical points. On the other hand, the main facilitators included technological innovation, economic incentives for the valorization of by-products, integrated regulatory frameworks, and collaborative processes that facilitate awareness and training.

3.12. Contribution to the Sustainable Development Goals

The systematic analysis also allowed mapping, specifically, the contributions of Water Circular Economy strategies to the SDGs, with a particular focus on SDG 6 (Clean Water and Sanitation). According to the reported results, such synergies are significant for numerous targets, including a decrease in water use efficiency. As for the specific action, it refers to target 6.4 which aims to achieve water use efficiency. In addition, it is noted in relation to target 6.5 and the implementation of integrated water resources management.

For its part, ref. [8] emphasizes that the circular economy in water management is a strategy to close the water, energy, and nutrient cycles. These interventions are bridges to reuse, resource recovery, and waste reduction. On the other hand, as referred to by [21], these are actions where synergies are present with the following SDGs: 12 which is responsible production and consumption, 9 which is industry, innovation, and infrastructure, and 13 which is climate action.

However, the results also show substantial gaps in the performance of these objectives, especially in situations of greater socioeconomic vulnerability. In this regard, ref. [15] highlights that, although the Latin American region has undertaken incipient circular economy trials—such as the reuse of treated wastewater in agriculture and the recovery of nutrients in treatment plants—technical, regulatory, and social barriers to their scale still prevail.

3.12.1. Sociocultural and Water Justice Dimensions in the Circular Economy: A Critical Analysis of Identified Gaps

Systematic analysis reveals a critical underrepresentation of sociocultural dimensions in water circular economy assessments, constituting a fundamental methodological and ethical gap that compromises the long-term sustainability of circular interventions. According to data documented by [40], 77.1% of the studies focus exclusively on the environmental dimension, while the economic and social dimensions represent only 20.5% and 2.4%, respectively, evidencing a marked imbalance that limits the holistic understanding of circular systems.

Documented Sociocultural Barriers and Their Implications

Resistance to water reuse emerges as a predominant sociocultural barrier, although it is often underestimated in technical–economic evaluations. Cases documented by [24] in the Barcelona metropolitan area reveal that reuse projects without robust community participation components faced significant social resistance, compromising their operational viability. In contrast, initiatives that incorporated co-design and equitable benefit-sharing mechanisms achieved acceptance rates above 80%.

This evidence underscores that social acceptance is not merely a secondary factor, but a critical determinant of systemic sustainability. Mistrust of water recycling technologies is often based on perceptions of health risk, and it also reflects power asymmetries in decision-making processes where affected communities lack effective participation in the design and implementation of solutions.

Water Justice as an Omitted Dimension

Water justice emerges as a critical dimension consistently omitted in circular implementations, with profound implications for distributive equity. Findings suggest that technically successful interventions may inadvertently exacerbate existing inequalities when they disproportionately benefit wealthier sectors, while vulnerable communities face transition costs without corresponding access to the benefits generated.

Particularly in the Latin American context, where, according to [49], access and quality gaps persist significantly, the implementation of circular technologies requires evaluative frameworks that explicitly integrate criteria of equity in access, distribution of benefits and burdens, and effective participation of marginalized communities in governance processes.

Implications for the Design of Circular Interventions

These findings imperatively suggest that the long-term success of circular systems depends critically on their social legitimacy and ability to generate equitably distributed benefits. Implementation strategies must transcend purely technical–economic considerations, systematically incorporating participatory processes, operational transparency, and accountability mechanisms that ensure that circular transitions contribute to, rather than compromise, goals of social justice and inclusive sustainability.

4. Discussion

Systematic analysis of circular water management technologies and strategies during the period 2018–2024 reveals a paradigmatic transformation in the conceptualization of water systems, evidencing both significant advances and persistent challenges that shape the future of global water sustainability. This evolution, characterized by the transition from linear models to integrated circular approaches, faces multidimensional complexities that demand an in-depth critical analysis of its theoretical and practical implications.

The technological maturation identified in this study represents not merely incremental advances but a fundamental reconceptualization of treatment systems as resource recovery infrastructures. Membrane bioreactors, with efficiencies exceeding 90%, and advanced oxidation processes exemplify this transformation [10]. However, the following critical paradox emerges: while intensive technologies such as membrane distillation reach efficiencies of 95–99%, their high energy consumption and operating costs confine them to specific industrial niches. In contrast, constructed wetlands, with moderate efficiencies of 70–90%, demonstrate a superior environmental cost–benefit ratio, consuming up to 60% less energy than conventional systems [9]. This technological dichotomy underscores the imperative need to transcend evaluation criteria focused exclusively on technical efficiency, incorporating holistic considerations of systemic sustainability and contextual feasibility.

Bibliometric analysis provides revealing empirical evidence on the epistemological structure of the field. The centrality of terms such as "wastewater treatment" and "water reuse" in co-occurrence networks is not simply a reflection of research priorities but exposes fundamental biases toward end-of-pipe technological solutions. Simultaneously, the emergence of thematic clusters related to resource valorization and industrial symbiosis signals an evolution toward more integrative perspectives that recognize water as a multidimensional resource vector [26]. This conceptual transition is critical to overcoming the historical limitations of fragmented approaches to water management.

Sectoral disparities in the adoption of circular practices reveal deep structural dynamics. Industrial leadership with reuse rates of 40–70%, contrasting sharply with urban systems that achieve only 15–30%, cannot be attributed exclusively to technological differences. This gap reflects fundamentally divergent incentive structures as while industries internalize treatment costs as integral components of their production processes, urban systems confront challenges of distributed financing and multi-stakeholder coordination that require innovative institutional solutions [39]. These structural differences demand differentiated and contextualized public policy strategies.

The Latin American context emerges as a paradigmatic case of additional complexities. With only 41% of wastewater receiving safe treatment, significantly lower than the global average (55.5%) and that of OECD countries (>80%), the region faces structural deficits that severely limit the potential for circularity [13]. Paradoxically, this apparent disadvantage could be conceptualized as an opportunity for technological leapfrogging, directly implementing circular solutions without the burden of obsolete linear infrastructures. The irony that the region is home to 34% of the world's renewable water resources while experiencing access and quality crises underscores the urgency of radically rethinking management models [14].

The evolution of policy and institutional frameworks represents another critical domain where the transition from sectoral approaches to integrated water–energy–food–ecosystem perspectives constitutes a significant conceptual advance [25]. The WICER framework [30] exemplifies this evolution, offering conceptual tools particularly relevant to developing contexts. However, effective implementation faces formidable obstacles related to institutional fragmentation and multilevel coordination, with evidence that countries with specific water circular economy policies show tripled implementation rates [49].

Critically, the persistent underrepresentation of sociocultural dimensions and water justice, with 77.1% of studies focusing exclusively on technical–economic aspects [40], constitutes a fundamental epistemological and ethical gap. This omission has profound implications for the social legitimacy and sustainability of circular interventions. Documented cases show that projects with robust community participation components achieve acceptance rates of over 80%, while purely technical ones face significant resistance [24].

The development of digital tools such as "Toy Town" [36] and NEXTGEN [37] represent promising but complex frontiers, facing limitations in data requirements, contextual calibration, and reliance on technological infrastructures often absent in vulnerable settings. This digital divide threatens to exacerbate existing inequalities in implementation capabilities.

Contributions to the Sustainable Development Goals reveal significant synergies with SDGs 6, 12, and 9, although their effective realization requires deeper integration of circular agendas into implementation frameworks [21]. Theoretical implications confirm the need for transdisciplinary frameworks that integrate engineering, environmental sciences, ecological economics, and social sciences [22], developing transition theories specific to the water sector that recognize its unique nature.

From a practical perspective, evidence underscores that successful implementation requires careful orchestration of technological interventions, institutional reforms, economic instruments, and participatory processes. There is no single solution, with contextualized adaptive approaches that maintain fundamental principles of circularity while recognizing local specificities required [17].

Finally, it is imperative to recognize that the transition to circular water systems transcends technical–economic considerations, constituting a profound socio-technical transformation that demands rethinking fundamental relationships between society, technology, and nature. As ECLAC [17] argues, the circular water economy represents a transformative opportunity whose effective realization requires systemic changes in production–consumption models, governance structures, and cultural conceptions of water. Success will depend on our collective ability to navigate these complexities while maintaining focus on fundamental goals of sustainability, equity, and resilience, recognizing that the future of global water security depends on our ability to effectively implement these circular principles in diverse and challenging contexts.

5. Conclusions

This systematic review has provided a comprehensive analysis of the evolution, effectiveness, and impact of circular water management technologies and strategies over the period 2018–2024, revealing fundamental paradigmatic transformations in the conceptualization and operationalization of sustainable water systems. The findings demonstrate that, although significant technological advances have been made, the consolidation of the circular economy as an alternative paradigm for water management faces multidimensional challenges that transcend purely technical considerations.

The technological development evidenced, particularly in membrane bioreactors and advanced oxidation processes, has substantially improved the quality of recovered water and expanded the possibilities for reuse. However, effective implementation remains limited by economic, energy, and regulatory barriers that require integrated systemic solutions. Natural systems such as constructed wetlands emerge as viable alternatives with superior environmental cost–benefit ratios, suggesting the need to diversify technological strategies according to specific contexts.

The marked sectoral disparities identified, with the industrial sector leading the adoption of circular practices while urban systems lag behind, reflect structural differences in incentives and institutional capacities that demand differentiated policy interventions. The Latin American context, characterized by significant deficits in treatment infrastructure but abundant water resources, presents both unique challenges and opportunities to implement innovative solutions that avoid traditional linear trajectories.

The evolution toward integrated policy frameworks that recognize water–energy–food–ecosystem interconnections represents a crucial conceptual advance, although its materialization faces obstacles related to institutional fragmentation and multilevel coordination. The persistent underrepresentation of sociocultural dimensions and water justice considerations constitutes a critical gap that compromises the social legitimacy and long-term sustainability of circular interventions.

The findings underscore that the transition to circular water systems requires a profound socio-technical transformation that integrates technological innovation, institutional reform, appropriate economic instruments, and inclusive participatory processes. Future success will depend on our collective ability to develop adaptive approaches that recognize contextual specificities while maintaining fundamental principles of circularity, sustainability, and equity, thus contributing significantly to the achievement of the Sustainable Development Goals and global water sustainability agendas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17146544/s1, File S1: PRISMA 2020 Checklist. Reference [41] is cited in the Supplementary Files.

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