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Review

From Efficiency to Circularity in the Wastewater Sector: A Review of Performance Indicators in Regulated Countries

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Abstract

The shift from traditional linear economic models to circular economy principles has gained momentum, particularly in the wastewater treatment sector. This transition relies on resource use efficiency, waste minimisation, and value creation. Nevertheless, a review of 83 articles, yielding 386 key performance indicators, reveals a significant lack of standardised methodologies for assessing circular economy performance in Wastewater Treatment Plants. This absence allows ambiguous outcomes and hinders comparative analyses across facilities and countries. There is a clear need for a universally applicable Key Performance Indicators-based framework that evaluates all environmental dimensions without forgetting the technical component while encompassing the various circularity strategies. Such a framework should not discard defined parameters' costs and data availability, avoiding abstract parameters that may lead to data manipulation and require extensive additional costs. Standardising Key Performance Indicators with explicit units of measurement is essential to ensure data comparability. In addition, they should comply with the regulatory institutions' evaluation requirements, at least while these methodologies have not yet evolved to incorporate broader circular and environmental considerations. Developing a standardised Key Performance Indicators-based framework is crucial for effectively evaluating circular economy performance in Wastewater Treatment Plants, ensuring comprehensive environmental assessment, data comparability, and alignment with regulatory standards. This approach would facilitate a more consistent and transparent evaluation of circular economy initiatives across diverse contexts.

Keywords: circular economy; circularity assessment; key performance indicators; sustainable development; wastewater treatment

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1. Introduction

With the global population projected to reach 10 billion by 2050, there will be a significant impact on water and sanitation resources. Currently, over four billion people worldwide experience severe water scarcity for at least one month every year, so technological concepts and solutions for water problems and adaptation to population growth and climate change will be one of the most crucial areas to develop [1–4]. The water and wastewater management sector faces significant challenges in adopting environmentally sustainable practices. However, this situation also presents valuable opportunities for advancement, especially in strategically managing water, energy, and raw materials [5]. Embracing these opportunities can lead to impactful improvements and drive the sector towards a more sustainable future [6].

Since the Industrial Revolution, most industries have tended to operate with linear models, where infinite resources are available to manufacture products, with little to no concern about resource depletion. However, we are now facing a growing focus on change, incorporating value creation in the business environment, and creating a clear separation between technical and resource efficiency and cost reduction. Recently, industries have included resource and process efficiency principles in production [7]. The circular economy (CE) must maximise ecosystem functioning and human well-being through the planning of both input and output [8]. As Hartley et al. [9] referred to it, the CE replaces the 'end-of-life' concept, focusing on reducing, reusing, recycling, and recovering materials within the production, distribution, and consumption processes. This way, the extraction of natural resources and waste production may be minimised, optimising the environmental, social, material, and economic values [10,11].

The limited availability of raw materials, the European economy's dependence on external raw materials, and its decline in the global economy [6] forced the European Union to introduce CE in its action plan—the Circular Economy Action Plan (CEAP) [12].

In short, the interest in circular models is intensifying in the public, business, social, and academic spheres as the environmental, social, and financial benefits are recognised [13]. However, there are unresolved gaps in this implementation. In some situations, it can be understood as a theoretical framework idea that needs to be proven to be implemented [14]. The transition to CE implies changes in the industries' business models or even the development of new models based on new visions, strategies, and the redesign of products, services, and distribution channels [15].

The transition to a CE requires actions and policies, preceded by setting objectives and targets, considering that the global economy is only 9% circular, with Europe representing 12% and China 2%, i.e., the linear model is still predominant [16]. From a macro perspective, this approach will be the right one to analyse objectives, as strategies are actions aimed at implementing CE solutions and capturing aspects of global and national levels. Finally, multiple strategies apply objectives in different contexts and conditions [17]. In 2015, the European Commission started the European Union (EU) action plan for a circular economy titled "Closing the Loop" [18], addressing the depletion of natural resources and high waste production [19], which was reviewed and updated in 2020 [20]. Analysing the resources discussed in this strategic plan, it is evident that all are influenced by linear behaviour. Among these, water stands out as a vital resource, significantly impacted by this pattern. When we look more closely at circularity, it is clear that we must also tackle the tough task of understanding what needs to be preserved and what impact our actions have in the water sector [21,22]. To move toward a circular economy in water and wastewater, we need to use water more wisely and treat wastewater in more sustainable ways [23].

The wastewater sector has significant potential and plays a crucial role in the transition to a circular economy model, not only in the field of safeguarding aquatic ecosystems and public health by eliminating water contaminants, but also in promoting resource recovery through a circular economy approach, providing environmental benefits to integrated systems [24,25].

The circular economy policy framework goals, such as resource recovery, are closely linked to wastewater treatment processes and wastewater sludge management [26,27]. Almeida et al. [28] identified several barriers that complicate the transition to circularity, particularly in transforming Wastewater Treatment Plants (WWTPs) into Water Resource

Recovery Facilities (WRRFs). These barriers include the limited large-scale application of advanced treatment technologies, challenges in developing a market for recovered resources, regulatory constraints on reusing these resources, and others [29]. Figure 1 presents a SWOT analysis of the implementation of the circular economy in the wastewater sector.

	Internal factors	**External factors**
Positive	**Strengths** • Benefits from By -Products/Waste Stream • Constant availability of wastewater • Decrease of pressure on natural resources • Reduce tariff pressure on the consumer	**Opportunities** • Considerable initial financial outlay • Little experience in large -scale implementation • The price of non -circular products is higher than circular/valorised products (Taxes?) • Lack of trust and awareness of recycled/recovered products
Negative	**Weaknesses** • The global trend to promote green processes • Due to water scarcity, wastewater reclamation and reuse as a Quick Tool • The quick development of new technologies • New Market Space	**Threats** • Political and legislation changes • General distrust towards the use of reclaimed water and other resources • Recovery costs for some substances might end up being higher than their synthesis or extraction • Economical Environment/Infrastructure level: developing countries vs developed countries

Figure 1. SWOT analysis of the wastewater sector regarding the implementation of circular economy (adapted from Guerra-Rodríguez et al. and Kathi et al. [29,30]).

The presented SWOT analysis provided a comprehensive evaluation of the strengths, weaknesses, opportunities, and threats associated with implementing circular economic approaches in the wastewater sector. This analysis allows for outlining potential pathways for implementation; strengths and weaknesses pertain to the internal environment, while opportunities and threats relate to external factors, such as assessing the availability of raw materials and their valorisation potential, identifying obstacles to resource recovery, and highlighting emerging market opportunities as well as political and legislative challenges. Combining all the information mentioned, this review's common conclusion is that water and wastewater represent an important role in the transformation towards a CE in the European Union (EU), and more concretely, Wastewater Treatment Plants can provide valuable resources such as clean water, energy, fuels, and nutrients, contributing to sustainable development goals and facilitating a transition to a circular economy [31]. In the new EU directive on urban wastewater treatment [Directive (EU) 2024/3019], the emphasis on increasing circularity has become a fundamental principle. This directive introduces specific requirements to significantly improve the recovery of valuable components, such as nutrients, organic matter, and energy, from both wastewater and sewage sludge. By implementing innovative technologies and practices, municipalities will be better equipped to transform wastewater into a resource, promoting sustainability and reducing environmental impact. This approach not only assists in meeting regulatory standards but also encourages the development of a more efficient and sustainable urban water management system. Although there is a big set of indicators to assess this transformation, its evaluation strategy and methodology are not yet well defined or standardised.

Facing the noteworthy inexistence of reviews about this topic in the global context, this study aimed to construct a thorough literature review of the scientific literature published in the last five years since the release of the new CE Action Plan (2020), which allows us to enumerate the KPIs that have been used to assess the circularity of the wastewater sector and evaluate its transition from a linear to a circular model. This study presents itself as a first step towards a potential universal and applicable KPI-based framework. This KPI analysis will cover the four main dimensions of sustainable goals: technical, environmental, economic, and social [32,33] while highlighting the good practices in European-regulated countries and the gaps that need to be developed.

2. Methods

To reach the mentioned aim, the literature review was based on the approach proposed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement to ensure data and information quality [34]. This procedure involves several standard steps: the definition of search parameters (database and registers—Web of Science and SCOPUS), eligibility criteria (inclusion and exclusion), characterisation of the information sources, enumeration of search strategies and selection approach, description of the data collection process, enumerating the risks, and undertaking the review. These steps create a coherent database of publications and the subsequent literature analysis. Table 1 shows the search engines and eligibility criteria developed to implement the PRISMA methodology and conduct the literature review.

Table 1. Eligibility criteria used for literature review (for title and abstract filter).

Research Question		
Are there KPIs that can assess the potential of the wastewater sector's transition from a linear to a circular model?		
Eligibility Criteria		
• Specifically, assess the circular economy and/or sustainability of wastewater systems; • Specifically, the assessment needs to have a list of KPIs; • May fully or partly cover the following dimensions/categories: technical, environmental, economic, and social, on the assessment; • The text must constitute a peer-reviewed original article, review, or book chapter; • Only documents written in English were accepted; • The full text must be provided; • It must be published after 2020—New CE Action Plan.		
Specified search terms	**Web of Science search records**	**SCOPUS search records**
The selection of the articles was conducted based on the following identified query: (Topic): "circular economy" and " wastewater treatment" and "key performance indicators" or "assessment" or "sustainable development" or "resource recovery"; (Publication Year): 2020 or 2021 or 2022 or 2023 or 2024 or 2025; (Document Types): Book Chapters or Article or Review Article; (Languages): English; (Open Access): All Open Access. The results of this step of research are presented in Figure 2.	N = 213	N = 326

Using the raw data retrieved from the Scopus and Web of Science databases and the search query presented in Table 1, it was possible to create a graph (Figure 2) which presents the increasing trend in publications about a circular economy in wastewater systems, in the last five years.

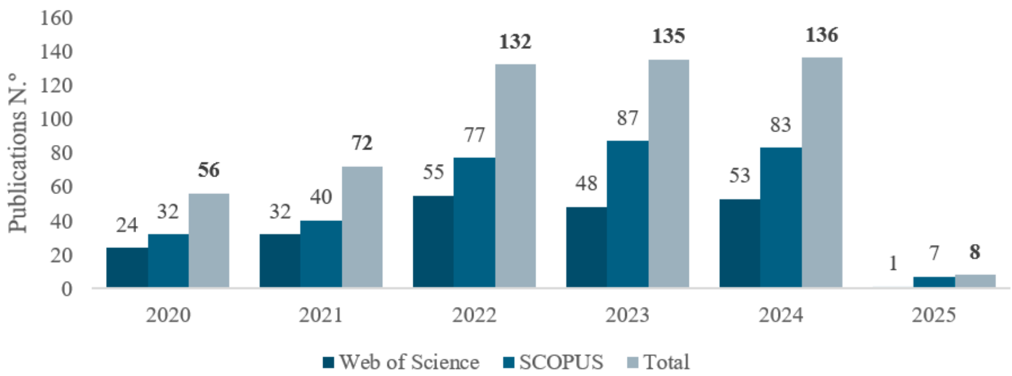

Figure 2. Results of the Scopus and Web of Science Query Search by year (retrieved from the Scopus and Web of Science database).

The search results were analysed using VOSviewer software (Visualizing scientific landscapes, V 1.6.20), which constructed a robust keyword density network from the retrieved documents. This network effectively identifies related subjects, as illustrated in Figure 3. The size of the circles in the figure represents the density of specific keywords, with larger circles signifying a higher keyword density. This comprehensive analysis not only informed our decisions regarding the implementation of the PRISMA methodology but also enhanced the results, allowing us to improve and expand the final sample by incorporating valuable additional studies.

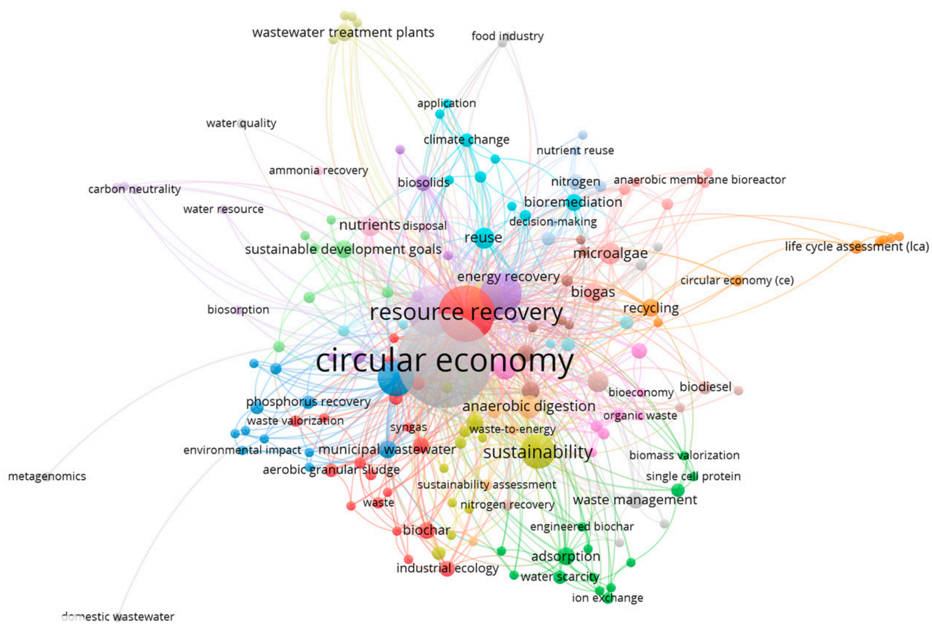

Figure 3. Keyword density network from the retrieved documents (VOSviewer).

After identifying all potentially relevant articles, a selection process was undertaken to determine which documents fulfilled the eligibility criteria. This evaluation was based on a thorough analysis of titles, abstracts, and authors' keywords, as depicted in Figure 4.

From the total of 539 articles from the global picture, 36 articles were selected that were closely aligned with the established criteria. Additionally, four documents were included, which involved identifying further relevant papers via the reference lists and citations of key articles. They provided valuable complementary information that enhanced the overall accuracy of the information structure. In total, 83 documents were ultimately selected for this research analysis (Supplementary Materials S3 shows the details of the selected articles).

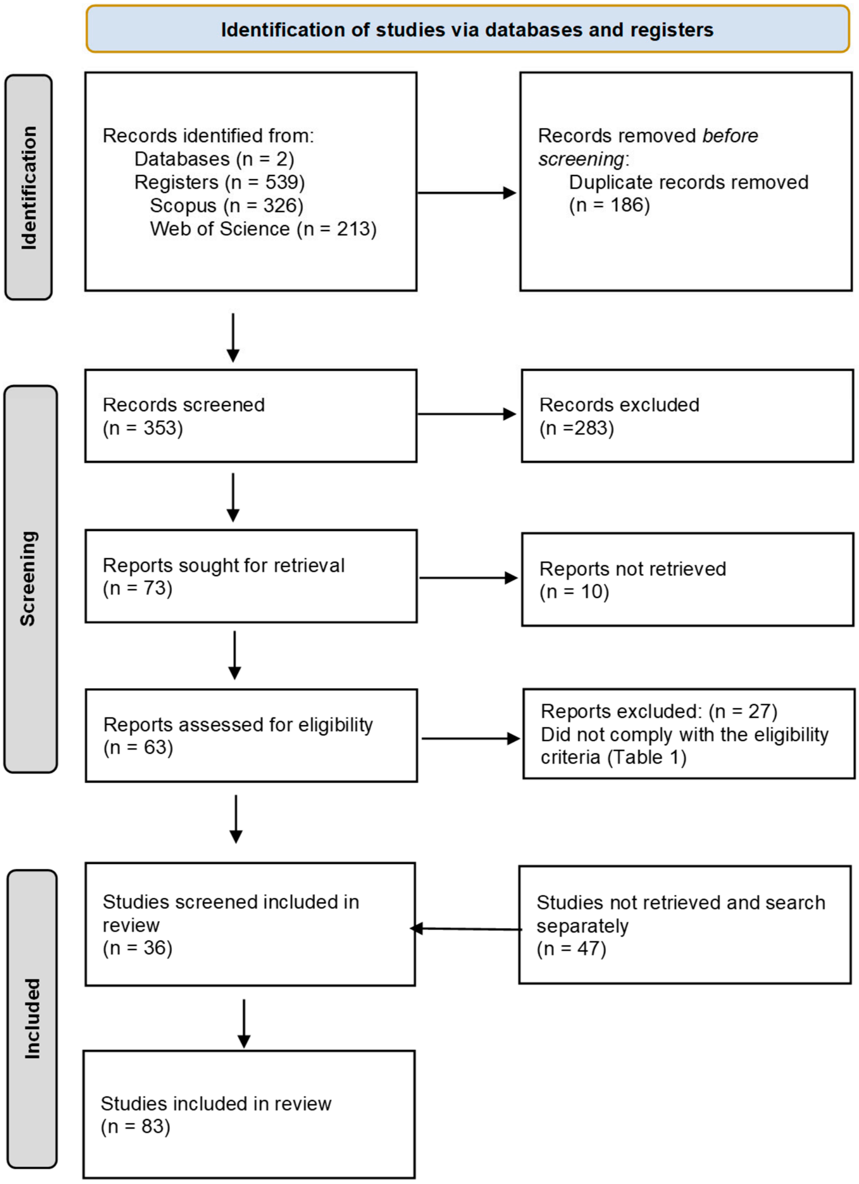

Figure 4. PRISMA methodological approach results.

3. Results and Discussion

According to the Organisation for Economic Co-operation and Development (OECD), the principles of Water Governance need to cover three main dimensions: Effectiveness, Efficiency, and Trust and Engagement [35]. These OECD Water Governance principles relate to the analysed four dimensions (technical, environmental, economic, and social) since reaching effectiveness and efficiency relies, for obvious reasons, on the technical, environmental, and economic dimensions, while the trust and engagement aims to promote a more developed social dimension. To monitor, control, and act, it will be necessary to measure and compare an organisation's performance against others in the same industry; the best way is to implement and use an evaluation methodology, using a matrix with clear, concise, and standard KPIs [36]. In Europe, some countries' national regulators are organised in an association—such as the Association of European Regulators in the drinking water and wastewater sector (WAREG)—which permits acceleration and helps countries to follow and implement the best practices that are clearly defined in Directive 2000/60/EC of the European Parliament and Council, where it can be seen the framework for water policy for the community globally. This association was established in 2014, and it is the best way to exhibit the European public perspective on water services. Table S1 (Supplementary Materials S1) characterises the European Members and Observers and the management model in which the country is organised. Figure 5 shows the geographic dispersion of WAREG members and observers.

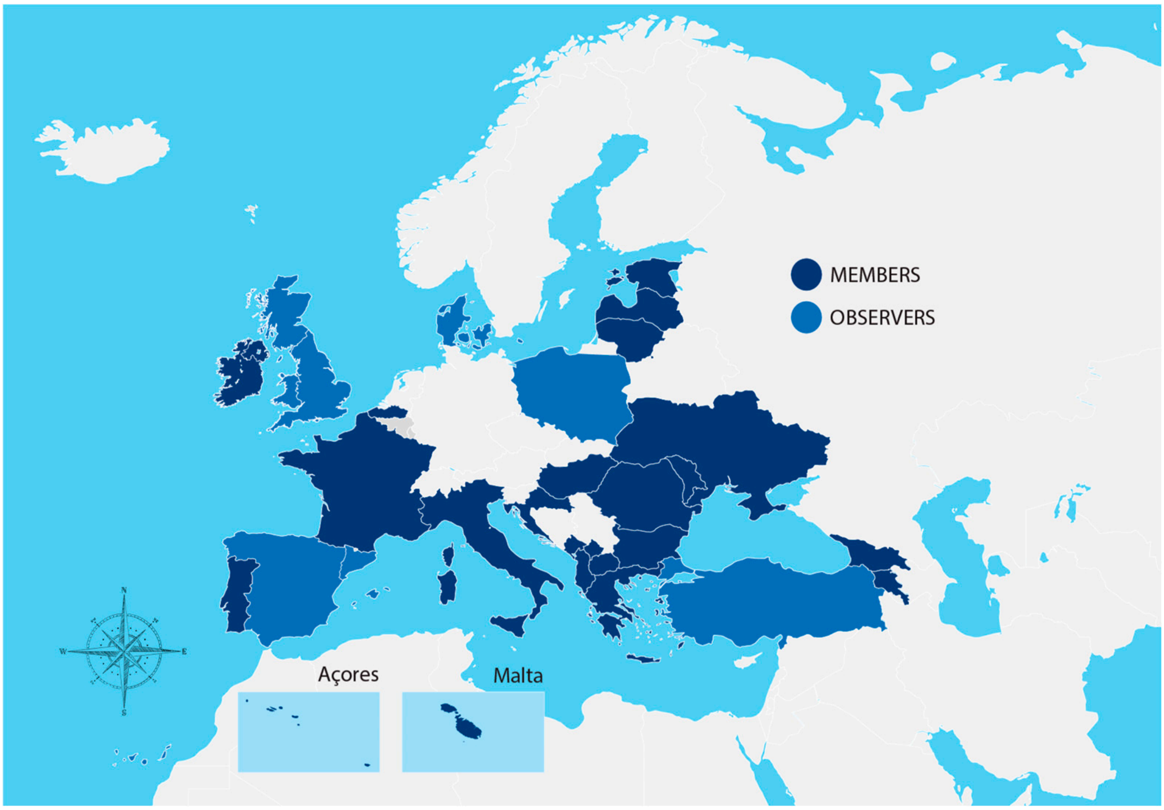

Figure 5. WAREG members and observers [37].

Unfortunately, the last European directives and taxonomies—Directive 2000/60/EC, Directive 98/83/EC, Directive 91/271/EEC, Directive 2000/60/EC, Directive (EU) 2020/2184, and the EU Taxonomy Climate Delegated Act of 4.6.2021—do not clearly state legal requirements regarding performance indicators [38]. Nevertheless, these regulatory documents recommend that water and wastewater operators make data publicly available and assess the performance indicators. Yet, the problem remains; there is no defined set of KPIs. To cover this existing gap, to measure/evaluate the performance of the operators in the same sector, various organisations, like the International Water Association (IWA), the World Bank (with International Benchmarking Network for Water and Sanitation Utilities (IB-NET)) and a wide range of national regulators have defined a standard way to evaluate the performance of water utilities with the support of a matrix of KPIs [10,39–41]. Nevertheless, most existing frameworks only really evaluate technical performance; and in some countries, not even a simplified version of an assessment procedure, listing the analysed KPI, has been published. Therefore, incorporating CE principles with an associated strategic framework is an opportunity for improvement in the sector [42,43]. For sure, there exist some good practices promoting CE approaches. For instance, the use of wastewater sludge as agricultural fertiliser, the reuse of treated wastewater, or measures undertaken by most regulators to reduce water leakage. However, the regulators need to define clearly how to assess CE from a global point of view [44]. The development of metrics, instruments, and evaluation approaches is not a common practice within the circular economy, as actions that derive from this model focus more on the short term, neglecting the analysis of potential long-term effects [45]. The implementation of circular economy-promoting actions is a continuous improvement process, adapting to environmental, social, technical, and economic conditions that occur under high uncertainty. Strategies for progressing towards a circular economy and maintaining inherent sustainability need regular evaluation and optimisation to stay on track towards the core values of environmental quality, social equity, and economic prosperity, i.e., the whole-system perspective is needed—as outlined in the United Nations Sustainable Development Goals (UN SDG).

The conditions and scenarios to be considered in assessing the sustainability of circular economy practices should take into consideration: the stakeholders (academia, non-governmental organisations, community), the level of ambition, the level of analysis (macro, meso, and micro), the type of resource (material, component, product, service), the scale (local or global), the time scale (short term or long term), the phases of implementation, and finally, the multidimensional indicators (environmental, social, technical, and economic) [11]. By considering all these dimensions, assessments become more holistic, actionable, and aligned with real-world complexity, ultimately enabling more effective and fair circular economy transitions.

The definitions and quantification of indicators used in the literature are often not detailed enough to consistently evaluate technologies or treatment facilities for resource recovery and, in most cases, not sufficiently complete to conduct an overall integrated assessment [46]. The integration of methods, models, and metrics is necessary to adequately describe the behaviour of the treatment system and enable the evaluation of circularity. The intrinsic goal of circularity is to reduce resource usage, increase their reuse (i.e., closing resource loops), and increase recovery, which requires quantification. Assessing circularity implies a complex and multi-sectoral analysis, managing different resources and considering feedback loops and interdependencies, so using KPIs simplifies this procedure [21].

By reviewing the 83 articles, it was possible to assess a list of 386 KPIs and their appearance frequency, which was summarised in Table 2. It is possible to observe the extensive listing of all the analysed KPIs in Table S2 (Supplementary Material). Due to the extent of the list, it was not possible to present it in the main body of the article.

Table 2. Organisation of the 386 KPIs per sustainable dimension and circularity strategy.

R Strategy	Sustainable Dimension				
	Economical	**Environmental**	**Social**	**Technical**	**Total**
Recovery	38	58	5	36	137
Recycle	7	6	6	5	24
Reduce	25	40	23	78	166
Reuse	24	11	9	15	59
Total	94	115	43	134	386

Nevertheless, it is important to mention that some KPIs may fall under repetition within different dimensions/strategies due to different authors' categorisation of the same KPI. The goal of the research is to conduct the mentioned KPI review, in the concrete case of wastewater operations in regulated countries. This study examines the KPIs that have been published as research articles, including case studies, and presents a comprehensive summary of the state of the art for CE evaluation on WWTP. The retrieved articles were scrutinised and analysed according to their categorisation proposal on sustainability dimensions: environmental, economic, and social [11], and their circularity strategy within the 4R policy (reduce, recovery, reuse, and recycle) [47]. Within the sustainability dimension, a technical dimension was also added to accommodate regulatory institution requirements.

Considering the concept of CE adopted in 2014 in the European Community "Towards a circular economy: a zero-waste program for Europe", special attention should be paid to practices in the treatment of effluents, as it is part of the waste management chain value, so a circular economy model structure for the water and wastewater sector must be based on waste prevention rules [3]. Some waste prevention methods are available, summarised as the so-called "Rs". Several authors come across the various R's (framework) to implement CE, being the main core of it. Initially, the 3R model (reduce, reuse, recycle) was the most prominent framework in places like China, yet in Europe, the 4R model was the core one, introducing "Recover" as the fourth R [47]. Several authors proposed extensions of the 4R model, such as the 6Rs or even 9Rs [3,47,48], although they ended up not following a broad application, mostly due to their complexity and the R's ambiguity and interchangeability.

The evaluation of the extracted KPIs allows the understanding that, as expected, most of the KPIs are still falling within the technical component (134 KPIs). Although CE is based on an equal combination of its four dimensions, the social (43 KPIs) and environmental (115 KPIs) dimensions fall short in the KPIs used for the CE evaluation. The economic dimension (94 KPIs) is still one of the dimensions that is more commonly evaluated, being strongly leveraged by the circularity strategy in the recovery pillar. When analysing the KPI per circularity strategy, it is visible that reduce (166 KPIs), recovery (137 KPIs), and reuse (59 KPIs) are those with more impact and concern, which is aligned with environmental awareness. Lastly comes recycling (24 KPIs), whose low number of KPIs may be explained by the technical difficulties of implementing these policies, such as treated wastewater for potable use or aquifer recharge [49,50]. Figure 6 also shows the weight of the acceleration strategies to promote circularity on WWTPs.

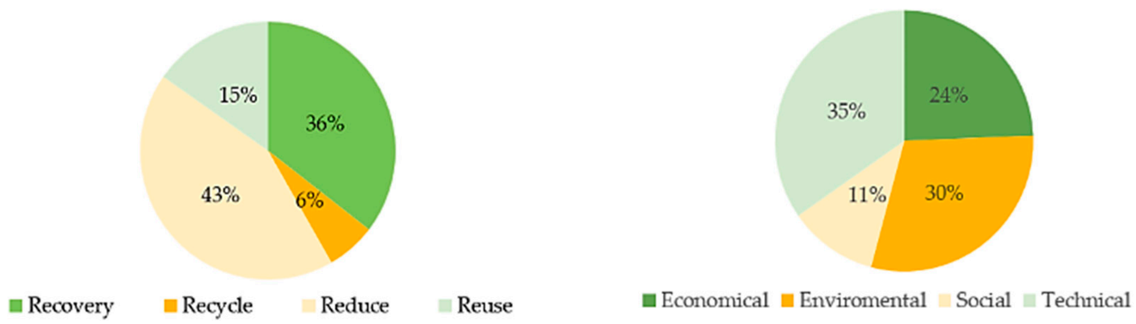

Figure 6. Percentage of KPI per circularity strategy or sustainable dimension for Wastewater Treatment Plants application.

Analysis of Figure 6 reveals that the strategies which have been extensively developed within the scientific community are as follows: reduce and recovery; as previously stated. The focus on reduction stems from the historical goal of operators to lower operational expenditure (OPEX) and reduce the consumption of raw materials. Recovery is emphasised because Water Resource Recovery Facilities (WRRF) possess significant resources that can be extracted and marketed; however, this approach primarily depends on the treatment technology available (CAPEX and OPEX are crucial to accelerating to the next steps). On the other hand, the reuse and recycling strategies are influenced by the differences in administrative procedures, legislative constraints, and community perspectives.

The KPIs were also statistically analysed and grouped into key areas of protection (Figure 7). The most frequently mentioned areas include resource market penetration, energy efficiency, costs, economic efficiency, global warming, reclamation and removal, nutrient uptake and removal, resource recovery, and complexity [24,33,51–59]. Besides, more articles have been consulted and analysed to clearly define groups and other analyses, which can be observed on the SM [60–84].

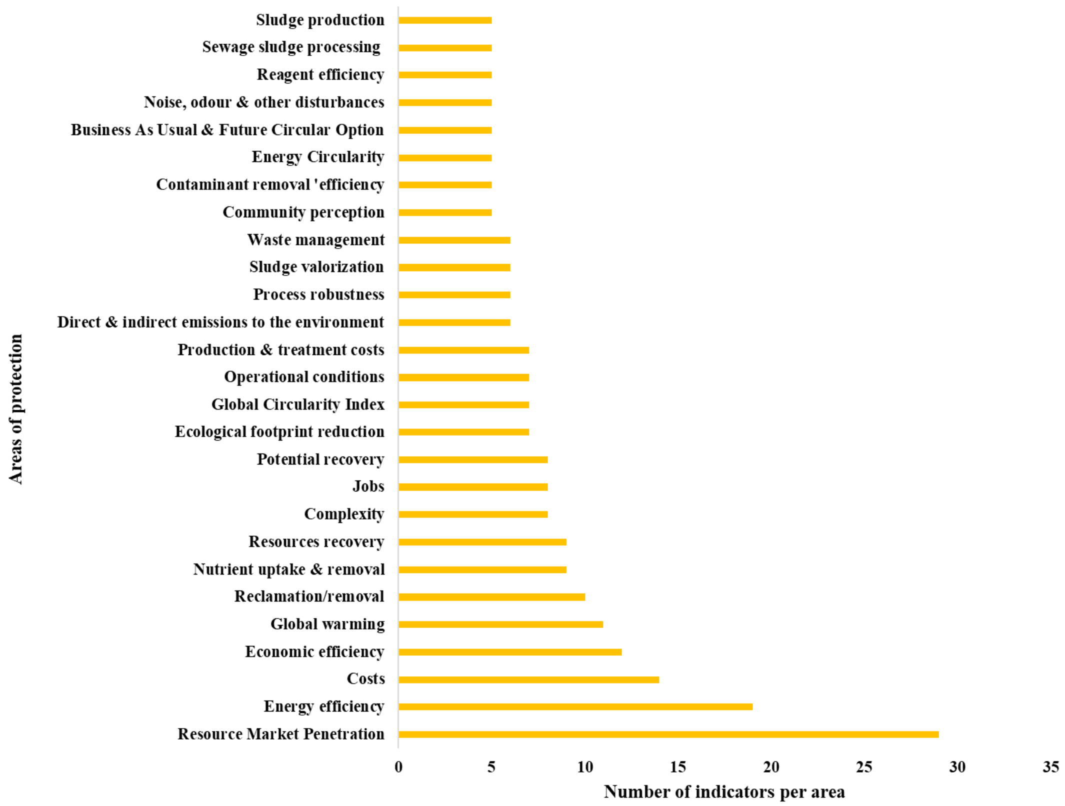

Figure 7. Circularity indicators areas of protection (more than five definitions per area).

More than 113 KPIs were capable of being classified in the 27 aforementioned clusters, highlighting how these key areas relate to environmental challenges, solutions, and opportunities in resilience, sustainability, innovation, and emerging markets. The rest of the KPIs were not possible to aggregate in clusters with more than five KPIs and were therefore disregarded for organisational purposes.

In conclusion, the analysis of 83 articles, yielding 386 KPIs, reveals the significant absence of a standardised methodology for assessing the CE performance of WWTP due to the dispersion of used KPIs. This deficiency leads to ambiguous CE outcomes and hinders comparative analyses across different facilities and nations. Consequently, there is an evident need for a universally applicable framework that comprehensively evaluates all sustainable dimensions and encompasses the various circularity strategies. Yet, it is imperative to recognise that parameter assessment entails cost and it highly depends on the availability and quantifiability of data. Selecting abstract or complex parameters not only increases the risk of data manipulation but also necessitates additional time for internal definition, opening the door for mistakes and unequal evaluations. Therefore, standardising a CE KPI-based framework with explicit and well-defined units of measurement is essential to ensure data comparability with WWTP and countries. Moreover, this selection process should also consider the requirements of regulatory institutions, at least while these bodies enhance their evaluation methodologies to incorporate broader circular and environmental considerations.

4. Conclusions

The consistent application of legal and governance policies delivers key insights and recommendations essential for community advancement, thereby strengthening the circularity policy aims in the European water sector. The EU policy directives have established significant priorities for policymaking, including adaptation to the Urban Wastewater Treatment Directive (UWWTD) Directive (2024/3019), sewage sludge management, and bathing water quality, among others. In accordance with these directives, new initiatives such as the Zero Pollution Strategy, the Green Deal, the Circular Economy Action Plan, national recovery plans, digitalisation efforts, and reuse regulations must be aligned effectively. The SWOT analysis highlights the critical need for cohesive alignment of all these policies and legal tools to facilitate the swift transition to a circular economy within the water sector, with special emphasis on the wastewater sector, which holds considerable potential for development. To implement this operational plan, it is essential to first assess the maturity of each country's wastewater management systems. This assessment will enable a comparison of development levels across countries. Various promising approaches to evaluating the performance of wastewater services have already been developed in Europe's regulated countries. In some instances, this can involve using a KPI matrix to measure efficiency. However, there are still some gaps still existing in this field. This research showcases those exactly by showing the lack of concise use of KPIs, or classification of each KPI, making them be used for assessing multiple different levels. To expedite the use of a KPI-based framework for assessing circularity, it is required to first establish a clear evaluation methodology. This will facilitate straightforward testing and implementation across countries. A circular approach must encompass goals for reducing, recovering, reusing, and recycling resources, which will help reframe WWTP as WRRF. An integrated approach should consider these goals within economic, environmental, technical, and social dimensions to engage all stakeholders effectively. This dynamic and adaptive strategy will catalyse the circular transition of WWTPs by assessing the current situation, identifying key improvement measures needed to meet set goals, and evaluating implementation strategies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17152226/s1, Supplementary Materials S1: European countries profile water utility; Supplementary Materials S2. Circularity assessment of wastewater treatment plants—KPIs by technical, environmental, economic and social categories according to R strategies; Supplementary Materials S3: Selected Articles - PRISMA Methodological Approach.

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Abbreviations

The following abbreviations are used in this manuscript:

CE	Circular Economy
WWTP	Wastewater Treatment Plants
KPI	Key Performance Indicator
CEAP	Circular Economy Action Plan
WRRF	Water Resource Recovery Facilities
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
OECD	Organisation for Economic Co-operation and Development
WAREG	Association of European Regulators in the drinking water and wastewater sector
IWA	International Water Association
IBNET	International Benchmarking Network for Water and Sanitation Utilities
UN SDG	United Nations Sustainable Development Goals
NGO	Non-Governmental Organization
UWWTD	Urban Wastewater Treatment Directive

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