

Review

Life Cycle Sustainability Assessment of Urban Wastewater Reuse: Successes, Persistent Pitfalls, and a Practical Path Forward

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Abstract

Achieving sustainable urban water management is increasingly critical amid climate change, water scarcity, population growth, and intensifying pressure on freshwater resources. Life Cycle Sustainability Assessment (LCSA) has emerged as a promising integrated framework to evaluate the holistic sustainability of municipal wastewater reuse systems by combining environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). This paper presents a critical narrative review synthesizing current evidence on LCSA applications specifically in urban municipal wastewater reuse contexts—encompassing non-potable urban, agricultural, and potable reuse—and identifying which configurations deliver genuine sustainability benefits, where major methodological shortcomings persist, and how the field can advance toward more robust, policy-relevant practice. The evidence base was assembled through structured searches in Scopus, Web of Science, and Google Scholar, screened from over 300 references to 25 peer-reviewed studies retained for in-depth analysis. Among the retained studies, positive outcomes were most often reported under low-carbon energy grids, short transport distances, and appropriate reuse-type matching: hybrid decentralized systems were associated with overall sustainability scores up to 4.8 times higher than conventional supply, while cluster-scale systems were associated with reductions in global warming potential of 15–40%. Persistent pitfalls include weak pillar integration, an underdeveloped social dimension, inconsistent system boundaries, and insufficient consideration of absolute sustainability. In response, this paper proposes the RENEW-LCSA Framework (Renewable Water-Oriented Life Cycle Sustainability Assessment Framework)—a practical six-step operational approach incorporating reuse-type-specific Social LCA indicators, explicit absolute sustainability assessment against the Water Scarcity Index (WSI) and local carbon budgets, and evidence-based integration of Nature-Based Solutions (NbSs). Three paradigmatic cases—Windhoek (Namibia), Singapore (NEWater), and Los Angeles County (USA)—illustrate the framework’s systematic application. By moving beyond optimistic narratives, this review advances the credibility of LCSA as a decision-support tool for safe, equitable, and circular urban water management, contributing to SDG 6 and the European Water Reuse Regulation (2020/741).



Academic Editor: Kourosh Mohammadi

Received: 28 May 2026

Revised: 4 July 2026

Accepted: 10 July 2026

Published: 16 July 2026

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Keywords: life cycle sustainability assessment; LCSA; municipal wastewater reuse; urban water management; circular economy; operational framework; social LCA; nature-based solutions; absolute sustainability

1. Introduction

Water reuse is increasingly promoted as a vital strategy to support sustainable development and address urban water scarcity intensified by climate change, population growth, and competing demands on freshwater resources. This paper focuses specifically on urban municipal wastewater reuse—encompassing water originating from domestic and municipal sources (toilet flushing, bathing, laundry, kitchen, and permitted industrial discharges reaching municipal treatment facilities)—as opposed to rural, industrial-only, or agricultural-irrigation-specific systems, which present fundamentally different governance, infrastructure, and social conditions. The urban versus rural distinction matters substantially: urban systems benefit from existing sewage infrastructure, higher population density enabling cluster-scale economies, and more structured governance frameworks, while rural systems face different challenges including informal sanitation and weaker institutional capacity. This paper focuses on urban municipal contexts where the LCSA literature is most developed.

By recovering water and nutrients from wastewater, reuse systems are often presented as exemplars of the circular economy in the urban water sector. However, their sustainability cannot be assumed: real performance depends on complex trade-offs across environmental, economic, and social dimensions throughout the entire life cycle—from collection and treatment to distribution, use, and resource recovery.

Although LCA has been widely applied to evaluate the environmental performance of water reuse, single-pillar approaches are inherently limited: they risk shifting burdens to economic or social domains that remain unexamined. LCSA, which integrates environmental LCA, Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), has therefore emerged as the most comprehensive framework currently available [1,2]. Yet, despite growing interest, full LCSA applications in urban municipal wastewater reuse remain relatively scarce, methodologically uneven, and frequently overly optimistic.

The overarching thesis of this review is that the sustainability of urban municipal wastewater reuse is conditional rather than inherent, shaped by system scale, energy source, reuse type, and local governance capacity. Against this backdrop, the RENEW-LCSA Framework is proposed as a structured operational tool to enable more rigorous, context-sensitive, and policy-relevant sustainability assessments. The analysis is guided by three central research questions:

- What works?—Under what conditions and configurations do LCSA studies demonstrate real sustainability value for urban municipal water reuse systems?
- What are the pitfalls?—What methodological, conceptual, and contextual weaknesses limit the reliability and usefulness of existing assessments?
- How can we strengthen LCSA practice?—What methodological innovations, integration strategies, and policy linkages are needed to enhance its effectiveness as a decision-support tool for safe, equitable, and circular water management? Throughout this paper, ‘equitable’ is used in the sense of fair distributional access to the benefits and costs of water reuse systems across income groups, gender, and geographical location.

These questions are revisited explicitly in the conclusions (Section 9). The findings are particularly relevant for advancing SDG 6 (Clean Water and Sanitation) and the European Water Reuse Regulation (2020/741) [3].

The objectives of this paper are: (i) to critically synthesize the current evidence on LCSA applications in urban municipal wastewater reuse; (ii) to identify which reuse-type configurations deliver genuine sustainability benefits and under what conditions; (iii) to document persistent methodological pitfalls; and (iv) to propose the RENEW-LCSA Framework as a practical operational tool to overcome identified limitations. The remainder of this article is structured as follows: Section 2 presents the conceptual foundations of

LCSA. Section 3 examines successes by reuse type. Section 4 analyses persistent pitfalls. Section 5 discusses performance across contextual conditions. Section 6 introduces the RENEW-LCSA Framework. Section 7 presents barriers and enabling conditions. Section 8 outlines a research and policy agenda. Section 9 presents limitations and conclusions.

1.1. Approach to Evidence Synthesis

This paper presents a critical narrative review and interpretive synthesis of the LCSA literature on urban municipal wastewater reuse, complemented by conceptual framework development. Unlike systematic reviews, the objective is not exhaustive coverage or quantitative meta-analysis, but rather to identify cross-cutting patterns of success and persistent limitations, while advancing a forward-looking operational framework. This article type—a critical narrative review with framework development—is well established in sustainability science for identifying gaps and proposing methodological advances [4,5].

The evidence base was assembled through targeted searches in Scopus, Web of Science, and Google Scholar using keyword combinations including: ('life cycle sustainability assessment' OR 'LCSA') AND ('water reuse' OR 'wastewater reuse' OR 'reclaimed water' OR 'municipal wastewater' OR 'water recycling'). Searches were supplemented by backward and forward snowballing. The temporal scope covered peer-reviewed publications primarily from 2010–2026, with foundational methodological references [1]. (ISO 14040/14044) [6] was included regardless of date. Language was restricted to English and Portuguese. This language restriction may introduce bias by excluding relevant studies published in other languages, including Spanish, French, Chinese, and Arabic, and is acknowledged as a limitation of this review (see Section 9.1). Searches were conducted in Scopus (final search date: 15 March 2026), Web of Science (final search date: 15 March 2026), and Google Scholar (final search date: 15 March 2026). Full search strings are provided in Supplementary Table S1. Duplicates identified across databases were removed prior to screening ($n = 47$ duplicates removed). Screening was performed independently by both authors, yielding an inter-reviewer agreement of 89% (Cohen's $\kappa = 0.76$), with remaining disagreements resolved by consensus.

A PRISMA-style flow diagram is provided in Supplementary Figure S1. The initial search returned over 300 references. After title and abstract screening against relevance to LCSA (requiring coverage of at least two of three pillars) applied to urban municipal wastewater reuse, approximately 80 studies were subjected to full-text review.

Of these, 28 studies (25 peer-reviewed articles and three institutional grey literature sources (Singapore NWater programme reports, Windhoek operational data, LADWP/OCWD documentation)) were retained for in-depth synthesis. Studies were excluded if they: (a) focused on regions or systems outside the urban municipal wastewater scope; (b) addressed only one LCSA pillar without cross-pillar analysis; or (c) lacked sufficient empirical or methodological grounding for critical synthesis. Because this is a critical narrative review rather than a systematic review, PRISMA 2020 reporting was not fully followed; however, transparent reporting of search and selection criteria is provided in Supplementary Table S1.

1.2. Analytical Framework: Coding and Categorization of Studies

To ensure methodological transparency and reproducibility, each retained study was qualitatively coded using a structured analytical matrix applied independently by both authors, yielding an inter-reviewer agreement of 91% (Cohen's $\kappa = 0.79$), with disagreements resolved by discussion. Studies were categorized along four main dimensions:

- Implementation scale: building-level, cluster, centralized, or hybrid decentralized;

- Reuse type: non-potable urban (toilet flushing, urban irrigation, industrial cooling), agricultural, indirect potable, or direct potable;
- LCSA pillar coverage: which of the three pillars (LCA, LCC, S-LCA) were included, and how they were integrated;
- Geographical and socio-economic context: region, income level, climate zone, and local water alternatives.

Evidence on successes and pitfalls was organized thematically within and across these categories. Directional assessments are explicitly derived from this coding procedure and should be interpreted as heuristic, qualitative syntheses based on patterns in the retained literature rather than as statistical outputs. This coding framework underpins the design of the reuse-type-specific Social LCA indicators and the contextual factor analysis in Section 5. Supplementary Table S2 lists all included studies and provides reasons for exclusion of borderline full-text articles reviewed for potential inclusion.

1.3. Case-Comparison Protocol and Scoring Rubric

To ensure transparency of the case comparison in Section 6.3, a structured case-comparison protocol was developed. Data were extracted following a source hierarchy: (1) peer-reviewed publications; (2) official programme reports and government documentation; (3) grey literature and operational data. Where data were directly measured in primary sources, this is indicated; where inferred from secondary sources, this is noted; missing data are reported as such. Radar chart scores were assigned on a 1–5 scale: 1 = very poor; 2 = below average; 3 = moderate; 4 = good; 5 = excellent. Scores were assigned independently by both authors, yielding an inter-reviewer agreement of 93% (Cohen's $\kappa = 0.84$), and discrepancies resolved by consensus.

2. Conceptual Foundations of LCSA

2.1. Life Cycle Sustainability Assessment (LCSA): Core Concept, Evolution, and Pillar Linkages

Life Cycle Sustainability Assessment (LCSA)—this acronym is used consistently in uppercase throughout—emerged as a response to the limitations of traditional single-pillar approaches. It integrates three complementary methodologies—LCA for environmental impacts, LCC for economic performance, and S-LCA for social implications—to provide a holistic evaluation of products, technologies, or systems across their entire life cycle [1,2]. The UNEP/SETAC Life Cycle Initiative has been instrumental in promoting LCSA, recommending that the three pillars be applied in parallel using consistent functional units and system boundaries, with results interpreted jointly [4].

Despite its conceptual strength, LCSA faces significant implementation challenges. LCA is the most mature pillar, supported by extensive databases (ecoinvent, GaBi) and standardized methods (ISO 14040/14044). In contrast, LCC and especially S-LCA suffer from data scarcity, methodological inconsistencies, and difficulties in capturing context-specific impacts [5,7,8]. Integration efforts range from simple parallel assessments to advanced multi-criteria decision analysis (MCDA) and Circular LCSA (C-LCSA) approaches [9]. A recurring criticism is that most studies treat the three pillars as largely independent exercises with weak feedback loops. Transparency issues are particularly acute in the aggregation step: weighting schemes across pillars are frequently arbitrary, undisclosed, or applied without stakeholder input—for example, assigning equal weights to all three pillars without justification, or deriving AHP weights from a non-representative expert panel—constituting a fundamental problem for reproducibility and stakeholder legitimacy [2,9]. Additionally, conventional LCSA tends to focus on relative sustainability (comparing alternatives) rather than absolute sustainability (assessing whether a system operates within planetary boundaries)—a critical gap addressed in this review. Table 1 summarizes the historical

development of Life Cycle Assessment approaches toward integrated LCSA from 1990 to 2026.

Table 1. Development of Life Cycle Assessment approaches toward LCSA (1990–2026).

Period	Milestone	Key Development
1990s	Environmental LCA standardization	ISO 14040 (1997) and ISO 14044 [6] establish standardized LCA methodology; ecoinvent and GaBi databases developed
Late 1990s–2000s	LCC integration	Life Cycle Costing recognized as economic pillar; shadow pricing of externalities introduced
2009	S-LCA Guidelines	UNEP/SETAC publish first Guidelines for Social Life Cycle Assessment of Products
2008	LCSA concept	Kloepffer [1] proposes LCSA as integration of LCA+LCC+S-LCA; framework formally conceptualized
2020	S-LCA revision	UNEP/SETAC publish revised S-LCA Guidelines with strengthened stakeholder and governance dimensions
2021	LCSA principles	Valdivia et al. [2] publish principles for LCSA application endorsed by UNEP Life Cycle Initiative
2022–2024	Advanced integration	C-LCSA (Luthin et al. [9]); absolute sustainability frameworks (Hackenhaar et al. [8]); multi-criteria aggregation advances
2025–2026	Water-sector specificity	Growing LCSA applications in water reuse (this review); calls for reuse-type-specific S-LCA indicators and absolute sustainability operationalization

Note: This table presents key milestones in the evolution toward integrated LCSA. LCA = Life Cycle Assessment; LCC = Life Cycle Costing; S-LCA = Social Life Cycle Assessment; LCSA = Life Cycle Sustainability Assessment; C-LCSA = Circular LCSA.

The three LCSA pillars are linked through shared functional units and system boundaries (Step 2 of the RENEW-LCSA Framework), and their outputs are integrated through multi-criteria synthesis (Step 5). The iterative feedback among pillars—where, for example, S-LCA findings on public acceptance influence the feasibility assumptions entering LCC—is an essential feature of genuine LCSA integration that is frequently absent in practice.

2.2. LCSA in the Context of Urban Municipal Wastewater Reuse

Urban municipal wastewater originates mainly from domestic sources (toilet flushing, bathing, laundry, kitchen) and permitted industrial discharges reaching centralized or decentralized treatment facilities. After secondary or tertiary treatment—including biological nutrient removal, membrane filtration (ultrafiltration, nanofiltration, reverse osmosis), UV disinfection, and advanced oxidation processes—reclaimed water can be applied for non-potable urban uses (irrigation of urban green spaces, toilet flushing, industrial cooling), agricultural irrigation, indirect or direct potable reuse, or resource recovery. Water quality requirements vary substantially by intended end-use and must comply with applicable standards including EU Water Reuse Regulation (2020/741), WHO Guidelines for the Safe Use of Wastewater in Agriculture [10], and national regulations [11,12].

Beyond water, wastewater is increasingly recognized as a resource matrix. Nutrient recovery (struvite precipitation for phosphorus; ammonia stripping for nitrogen) converts waste streams into agricultural inputs, supporting circular economy objectives. Bio-gas and bioenergy recovery from anaerobic digestion of primary and secondary sludge provides energy self-sufficiency for treatment plants. Emerging technologies include advanced membrane-based processes for simultaneous water reclamation and resource

recovery [13,14], water–energy nexus applications integrating heat recovery from wastewater [15], and desalination brine valorisation applicable in coastal reuse contexts [16]. These emerging dimensions are currently underrepresented in LCSA studies but are directly relevant to the circular water economy agenda addressed in this review.

Typical functional units include 1 m³ of reclaimed water delivered for a specific end-use or annual water supply per capita [11,12]. System boundaries ideally follow a cradle-to-cradle approach, encompassing wastewater collection, advanced treatment, distribution, use phase, and resource recovery. However, many analyses remain limited to cradle-to-gate, omitting important downstream impacts and resource recovery credits—a persistent methodological weakness addressed in the RENEW-LCSA Framework.

3. Successes: What Works Under Favourable Conditions

While LCSA studies have identified promising outcomes, the evidence of genuine sustainability advantages remains conditional and context-specific. Positive results emerge only under particular configurations and favourable local conditions. Conclusions differ substantially by reuse type, which is why this section is organized accordingly—drawing directly on the studies coded for each respective reuse category (Section 1.2).

3.1. Non-Potable Urban Reuse (Toilet Flushing, Urban Irrigation, Industrial Cooling)

Non-potable urban reuse consistently shows the most favourable outcomes across LCSA studies. Cluster-scale and hybrid decentralized systems stand out by balancing economies of scale with reduced transport distances. Hybrid systems combining grey-water treatment with rainwater harvesting can deliver up to 4.8 times higher overall sustainability scores than conventional water supply under favourable conditions [12]. Significant reductions in eutrophication (−50 to −100%) and ecotoxicity have been reported in high-water-stress urban contexts [17]. Cluster-scale configurations reduce global warming potential (GWP) by 15–40% compared to conventional supply [11]. These advantages are most consistent for non-potable applications, which avoid the high energy demands of potable-grade treatment.

3.2. Agricultural Reuse

Agricultural irrigation shows clear sustainability benefits when reclaimed water replaces high-impact alternatives such as desalination or over-exploited groundwater. Studies report reduced GWP, lower freshwater depletion, and improved economic performance when environmental externalities are internalized via shadow pricing [18,19]. Performance depends on crop selection, soil conditions, salinity tolerance, and adequate treatment levels to minimize health risks for field workers and consumers. Benefits are most pronounced in water-scarce Mediterranean and semi-arid contexts where avoided water depletion impact is largest.

3.3. Potable Reuse (Indirect and Direct)

Direct potable reuse shows more limited and conditional successes. While technically feasible in extreme scarcity contexts (Windhoek, Namibia, since 1968), it requires highly energy-intensive advanced treatment and faces greater social challenges related to public acceptance and institutional trust. Benefits are more evident in indirect potable reuse schemes when high-quality reclaimed water displaces imported or desalinated water in dense urban settings. Even in optimistic scenarios, environmental benefits can reverse under fossil-heavy energy sources [17].

Table 2 indicates that positive sustainability outcomes were most often reported for cluster-scale and hybrid decentralized configurations under favourable local conditions—particularly low-carbon energy supply, short transport distances, and

appropriate reuse-type matching. Non-potable urban applications offered the most consistent benefits among the retained studies. Even these advantages remain highly context-dependent, reinforcing the need for site-specific assessments.

Table 2. Summary of key LCSA studies showing positive outcomes, by reuse type.

Study	Scale	Reuse Type	Key Quantitative Outcomes	Favourable Conditions	Limitations/Caveats
Opher et al. [11]	Cluster	Non-potable urban	GWP: −15% to −40% Best overall balance	Short transport distances; urban context	Sensitive to energy mix
Souza et al. [12]	Hybrid decent.	Non-potable urban	Up to 4.8× higher overall sustainability score GWP: −20% to −60% (with renewables)	Low-carbon energy; greywater + rainwater	Specific to Brazil/Germany contexts
Gilboa et al. [20]	Model city	Non-potable urban	Environmental benefits in dynamic scenarios	Low-carbon electricity	Results vary significantly with assumptions
Kalboussi et al. [18]	Field	Agricultural	Reduced impacts vs. desalination; significant water depletion reduction	High water scarcity; suitable quality matching	Limited social assessment
Canaj et al. [19]	Field	Agricultural	Better economic performance when externalities internalized	Internalization of environmental costs	Context-specific to Mediterranean crops
Negi & Chandel [17]	Urban	Non-potable/Direct potable	Eutrophication: −50% to −100% (non-potable) GWP: +5% to +34% (direct potable)	High water stress; urban context (non-potable)	High energy intensity for potable reuse

Note: Results are highly context-sensitive. Advantages may diminish or reverse under fossil-heavy energy grids, long transport distances, stricter treatment requirements, or different reuse types. Readers should consult primary studies for full quantitative detail. GWP = global warming potential. All figures relative to conventional water supply alternatives as defined in each primary study.

4. Pitfalls: Persistent Methodological and Conceptual Weaknesses

Despite conditional successes, a closer examination reveals substantial methodological, conceptual, and contextual weaknesses that significantly limit the reliability, comparability, and practical usefulness of most LCSA studies.

4.1. Integration and Methodological Pitfalls

Weak integration across the three pillars remains a central problem. Although many studies claim to adopt an LCSA approach, LCA, LCC, and S-LCA are often conducted as largely independent exercises with minimal cross-analysis or feedback loops. When integration is attempted (typically via MCDA or AHP), weighting procedures are frequently applied without sufficient justification, stakeholder participation, or sensitivity testing [2,9]. Inconsistent functional units and system boundaries further undermine comparability across non-potable urban, agricultural, and potable reuse applications.

4.2. The Underdeveloped Social Pillar (S-LCA)

The S-LCA remains the weakest component across all reuse types and geographical contexts. Most studies either omit it entirely or limit it to generic worker-focused indicators

from secondary databases. Critical dimensions—public acceptance, risk perception, distributional equity, governance capacity, and gender—receive marginal or no attention [21–23]. This is particularly serious because social factors frequently determine the practical viability of reuse schemes. Without structured inclusion of social indicators, LCSA assessments risk being technically sophisticated but socially uninformed—and therefore of limited practical value in contested governance contexts.

Table 3 responds directly to this gap by presenting a structured set of priority S-LCA indicators differentiated by reuse type, each with a concrete measurement approach. These indicators should be adapted to local contexts and complemented by qualitative methods such as participatory mapping, focus groups, and deliberative polling.

Table 3. Priority S-LCA indicators by water reuse type (for use in Step 3 of the RENEW-LCSA Framework).

Indicator Category	Non-Potable Urban Reuse	Potable Reuse (Direct/Indirect)	Agricultural Reuse
Public Acceptance & Trust (Measurement: surveys, willingness-to-pay studies, media analysis)	Community awareness; dual-pipe acceptance rate	Risk perception surveys; institutional trust indices	Food safety perception surveys; cultural acceptance assessment
Distributional Equity (Measurement: access mapping, affordability indices)	Equitable access to dual infrastructure across income groups	Fair pricing mechanisms; access for low-income users	Smallholder access; equitable cost/benefit distribution
Worker Health & Safety (Measurement: exposure assessments, incident rates)	Operator training coverage; exposure to reclaimed water	Advanced treatment operator training; monitoring frequency	Field worker pathogen exposure; PPE provision rate
Governance & Participation (Measurement: stakeholder mapping, co-design audits)	Community co-design; local government capacity	Regulatory oversight quality; institutional coordination	Farmer participation in scheme design; extension service coverage
Gender Equality (Measurement: gender-disaggregated data)	Women’s role in water management decisions	Gender-inclusive governance structures	Women farmers’ access to reuse schemes
Employment Quality (Measurement: employment quality indices)	Local job creation rates; fair wage compliance	Skilled employment opportunities in advanced treatment	Rural employment stability; seasonal labour conditions

Note: Indicators should be selected and weighted in consultation with local stakeholders. Quantitative metrics should always be complemented by qualitative approaches. Not all indicators will be equally relevant in all contexts; the table provides a reuse-type-specific structured starting point. These indicators are applied in Step 3 of the RENEW-LCSA Framework.

4.3. Conceptual and Analytical Gaps

Most studies focus exclusively on relative sustainability—comparing alternatives against each other—rather than absolute sustainability, which asks whether a system operates within local and planetary carrying capacity thresholds [8,24]. Additional gaps include: limited incorporation of circularity metrics; predominantly static analyses that fail to account for future uncertainties (climate change, energy transition, population dynamics); and insufficient explicit acknowledgement of cross-study comparability limitations when quantitative results from studies with different system boundaries and functional units are synthesized.

4.4. Geographical Representativeness and Underrepresented Contexts

The evidence base is heavily concentrated in Europe, China, Israel, and a few Global South countries. Large water-scarce regions in sub-Saharan Africa and South Asia remain severely underrepresented [25,26]. This geographical bias has six specific methodological implications for LCSA in underrepresented contexts:

- Data scarcity forces reliance on non-representative generic databases (e.g., European ecoinvent data applied to African or South Asian systems);
- Informal and non-sewered sanitation systems common in LMIC contexts are incompatible with standard LCSA functional units (which assume formalized collection infrastructure);
- Regulatory gaps and weaker institutional structures alter the governance pillar, making it less comparable with European S-LCA frameworks;
- Affordability constraints and different social acceptance dynamics make European-derived social indicators inapplicable without significant adaptation;
- Climate variability in arid and semi-arid regions creates environmental trade-off profiles that differ substantially from temperate European baselines;
- Informal reuse practices—widespread in LMIC urban contexts—are not captured by formal LCSA boundaries.

Future studies must address these specifics explicitly rather than applying Northern-context LCSA frameworks uncritically. Emerging African-context LCA work (e.g., Ogbu et al. [26]) represents an important step in this direction.

4.5. Nature-Based Solutions (NBSs): Evidence vs. Extrapolation

The integration of Nature-Based Solutions (NBSs)—such as constructed wetlands, green roofs, and soil-aquifer treatment—into water reuse systems shows promise, particularly for lower energy use and biodiversity co-benefits. However, a critical distinction must be maintained between three categories of evidence:

- Category 1 (Direct evidence): NBS-based water reuse LCSA studies reporting full three-pillar results—currently the smallest category, limited to a handful of pilot-scale studies;
- Category 2 (Adjacent evidence): The broader NBS LCA/LCSA literature (e.g., Larrey-Lassalle et al. [27]) and NBS performance in related water management contexts—relevant but not directly water-reuse-specific;
- Category 3 (Extrapolation): Conceptual claims about NBS performance in water reuse without direct empirical grounding—common in the literature but often overstated.

It is also important to note that ‘grey infrastructure’ in this context refers primarily to conventional centralized wastewater treatment plants, distribution networks, and collection systems. Traditional retention and detention solutions (constructed wetlands, retention basins) occupy a hybrid position, as they can function both as NBS components and as hydraulic infrastructure for local flood management. Their role in flow hydraulics and flood risk reduction—particularly in dense urban settings—is not negligible and should be assessed under the environmental LCA pillar (Step 3) and as a governance dimension (Step 1) of the RENEW-LCSA Framework. In the RENEW-LCSA Framework (Step 3), NBSs are included as assessable options with an explicit requirement to document the evidence category for any NBS performance claim. Where evidence falls primarily into Category 3, NBS integration should be framed as a future research priority rather than a demonstrated performance advantage.

5. Performance in Context: Key Contextual Drivers

One of the most consistent findings is the strong context dependency of LCSA results. Benefits observed in one setting can diminish substantially—or even reverse—when key conditions change. This section synthesizes the evidence from the coded study database, organized by reuse type.

5.1. Non-Potable Urban Reuse

Non-potable applications (toilet flushing, urban irrigation, industrial cooling) generally show the most robust performance. Cluster-scale and hybrid decentralized systems perform best when transport distances are short and low-carbon energy is available. Benefits decrease sharply under fossil-heavy energy grids or long distribution networks [11,12,17].

5.2. Agricultural Reuse

Agricultural irrigation performs well when reclaimed water displaces desalination or over-exploited groundwater, particularly in Mediterranean and arid regions. Economic advantages become clearer when environmental externalities are internalized [18,19]. Key limiting factors include crop type, soil salinity tolerance, and the need for rigorous treatment to minimize health risks for field workers and consumers.

5.3. Potable Reuse (Indirect and Direct)

Direct potable reuse exhibits the highest variability and risk. While it can deliver water security benefits in extreme scarcity contexts, it is highly sensitive to energy intensity and public acceptance. GWP can increase by up to 34% compared to conventional alternatives under fossil-energy scenarios [17]. Indirect potable reuse (e.g., groundwater recharge followed by extraction) tends to perform better due to the additional environmental buffer and higher public acceptance.

Tables 4 and 5 confirm that urban municipal wastewater reuse is not inherently sustainable but conditionally sustainable.

Table 4. Heuristic synthesis of contextual factors influencing LCSA performance of urban municipal wastewater reuse.

Contextual Factor	Non-Potable Urban Reuse	Potable Reuse	Agricultural Reuse	Overall Impact	Primary Evidence Source(s)
Energy Source & Grid Carbon Intensity	Positive → Conditional	Conditional → Negative	Positive	Decisive	Negi & Chandel [17]; Souza et al. [12]
System Scale (Cluster vs. Centralized)	Strongly Positive	Conditional	Positive	Highly Favourable	Opher et al. [11]; Souza et al. [12]
Transport/Distribution Distance	Positive (short)	Negative (long)	Conditional	Very Sensitive	Opher et al. [11]
Local Water Scarcity Level	Strongly Positive	Positive	Positive	Major Determinant	Kalboussi et al. [18]
Treatment Intensity	Conditional	Negative	Positive	Important Trade-off	Negi & Chandel [17]
Public Acceptance & Trust	Positive	Conditional/Negative	Positive	Critical	Opher et al. [21]
Regulatory & Governance Strength	Positive	Strongly Positive	Conditional	Major	Multiple studies
Integration with NBS	Conditional	Limited Evidence	Positive	Promising but Uncertain	Larrey-Lassalle et al. [27]

Note: This table presents a heuristic synthesis based on structured qualitative coding of the 25 retained studies (Section 1.2). Directional assessments (Positive/Conditional/Negative) reflect the dominant patterns in the evidence base rather than universal findings. They should be interpreted as indicative summaries to support decision-making. Specific quantitative results and local applicability must always be verified against primary studies and site-specific conditions.

Table 5. Quantitative synthesis of selected impacts (relative to conventional water supply systems).

Study/Region	Scale	Reuse Type	GWP/Energy Impact	Eutrophication/ Water Depletion	Economic Performance	Key Observations
Opher et al. [11]—Israel	Cluster	Non-potable	−15% to −40%	Strong reduction	Competitive at short distances	Best overall balance; scale matters strongly
Souza et al. [12]—Brazil/ Germany	Hybrid Decent.	Non-potable	−20% to −60% (with renewables)	−30% to −70%	Positive in long term	Up to 4.8× sustainability score under optimal conditions
Negi & Chandel [17]—India	Urban	Non-potable/ Direct potable	+5% to +34% (direct potable)	−50% to −100%	Variable	High energy dependence for direct potable
Kalboussi et al. [18]—Tunisia	Field	Agricultural	Moderate reduction	Significant reduction	Better with externalities	Context-specific to Mediterranean crops
Ogbu et al. [26]—South Africa	Decent.	Non-potable	−10% to +25%	Local reduction	High initial costs	Strong local context sensitivity; governance fragility
Hybrid NBS–grey systems	Cluster/ Peri-urban	Non-potable	Generally lower	Reduction + co-benefits	Potentially favourable	Lower energy; biodiversity co-benefits; scaling uncertainty

Note: GWP = global warming potential. Ranges reflect variation across scenarios, energy mixes, and system configurations in each primary study. All figures are relative to conventional water supply alternatives as defined in each study. Cross-study comparisons should be interpreted with caution given differences in system boundaries, functional units, and geographical contexts.

Non-potable urban reuse offers the most consistent benefits, while agricultural and potable applications require more careful context matching. This strong context dependency underpins the need for the operational framework proposed in the next section.

6. The RENEW-LCSA Framework: A Six-Step Operational Approach

To address the successes, persistent pitfalls, and strong context dependency identified in Sections 3–5, this paper proposes the RENEW-LCSA Framework (Renewable Water-Oriented Life Cycle Sustainability Assessment Framework)—a practical six-step operational approach specifically tailored for urban municipal wastewater reuse. The framework builds on foundational LCSA principles [1,2] while incorporating: stronger pillar integration; reuse-type-specific social indicators (Table 3); explicit operationalization of absolute sustainability with concrete thresholds; circularity metrics; evidence-based NBS integration; and enhanced applicability to diverse geographical contexts.

The RENEW-LCSA Framework advances beyond three closely related precedents: the generic LCSA approach of Kloepffer and Valdivia et al. [1,2], which it extends through reuse-type specificity and absolute sustainability integration; C-LCSA [9], which incorporates circularity metrics but does not address water-sector-specific S-LCA indicators or absolute sustainability thresholds; and Bhambhani et al.’s [24] LCSA framework for water-sector resource recovery, which is the closest precedent but does not include the absolute sustainability dimension, reuse-type-specific S-LCA indicators, or the evidence-category requirement for NBS claims. The RENEW-LCSA Framework integrates all of these elements into a single, modular operational structure.

It is important to note that the RENEW-LCSA Framework is currently conceptual and has not yet been validated through prospective real-world applications. Future empirical studies are needed to test and refine its practical utility across different reuse types and socio-economic contexts.

Figure 1 illustrates the six interconnected steps and the iterative feedback loop. The framework is organized into three functional clusters: Steps 1–2 (blue) establish the analytical foundation; Steps 3–4 (green) conduct the core assessment including absolute sustainability; Steps 5–6 (red) synthesize results and translate them into policy insights.



Figure 1. The RENEW-LCSA Framework: a six-step operational approach for urban municipal wastewater reuse. Steps are color-coded by functional cluster: blue (Steps 1–2) = scoping and boundaries; green (Steps 3–4) = assessment and absolute sustainability; red (Steps 5–6) = synthesis and policy translation. The iterative feedback arrow (left) indicates that later steps may require revisiting earlier ones. The framework is modular: Steps 1–3 may be applied first for preliminary scoping, with Steps 4–6 elaborated as data become available.

6.1. The Six Steps of the RENEW-LCSA Framework

We propose the RENEW-LCSA framework, a structured six-step approach specifically designed for life cycle sustainability assessment of water reuse systems. Table 6 presents the six-step RENEW-LCSA Framework, detailing the key actions, outputs, and how each step resolves persistent pitfalls in conventional LCSA.

Table 6. The six-step RENEW-LCSA Framework: actions, outputs, and pitfall resolution.

Step	Name	Key Actions	Outputs	How It Resolves Persistent Pitfalls
1	SDG-Aligned Goal & Stakeholder Engagement	Define goal/scope; align with SDG 6; classify reuse type (non-potable/agricultural/potable); engage utilities, regulators, communities, farmers; identify NBS options and classify evidence category	Goal and scope document; stakeholder map; reuse-type classification; NBS evidence inventory	Front-loads participatory design, directly addressing weak social integration; forces early identification of reuse type for indicator selection
2	Harmonized Functional Unit & System Boundaries	Adopt 1 m ³ fit-for-purpose reclaimed water delivered; define cradle-to-cradle boundaries consistently across all three pillars; scope: collection, treatment, distribution, use, and resource recovery	Agreed functional unit; system boundary diagram; boundary justification memo	Resolves inconsistent system boundaries; prevents burden-shifting to omitted life cycle stages; enables cross-pillar comparability
3	Parallel Three-Pillar Assessment with Reuse-Type-Specific S-LCA	Conduct LCA, LCC, S-LCA in parallel with consistent assumptions; apply reuse-type-specific S-LCA indicators from Table 3; assess NBS scenarios; MANDATORY: document evidence category (1/2/3) for all NBS claims	Environmental, economic, and social profiles; NBS comparison scenarios with evidence-source traceability; pillar integration narrative	Directly addresses weak social pillar through reuse-type-specific indicators; requires honest evidence categorization for NBSs; forces genuine three-pillar integration
4	Circularity & Absolute Sustainability Assessment	Assess water and nutrient recovery rates (circularity scorecard); compare GWP against local carbon budget (NDC-derived); compare water depletion against local WSI (Pfister et al.) [28] or WEI+; document threshold sources; flag whether system operates within or beyond local carrying capacity	Circularity scorecard; absolute sustainability comparison table with explicit WSI/carbon budget thresholds and data sources	Operationalizes absolute sustainability with measurable thresholds—resolving the recurring ‘aspirational but vague’ criticism; worked example in Section 6.2

Table 6. *Cont.*

Step	Name	Key Actions	Outputs	How It Resolves Persistent Pitfalls
5	Aggregation, Trade-offs & Sensitivity Analysis	Apply transparent MCDA (TOPSIS or VIKOR) with stakeholder-derived weights; present results via radar charts and trade-off matrices; conduct Monte Carlo uncertainty analysis; test robustness across energy scenarios; document weighting justification	Ranked alternatives with confidence intervals; sensitivity tornado diagrams; radar chart; scenario comparison table	Resolves arbitrary weighting and absence of uncertainty analysis; stakeholder-derived weights counter legitimacy concerns
6	Policy & Implementation Insights	Translate findings into context-specific governance, financing, and monitoring recommendations; define KPIs for adaptive management; align with EU Water Reuse Regulation (2020/741) [3] for EU contexts or equivalent national/international frameworks (WHO, national regulations) for non-EU contexts; specify monitoring KPIs	Policy brief; implementation roadmap with KPIs; regulatory alignment memo	Bridges science–policy gap; ensures LCSA informs actual decisions; addresses jurisdictional specificity concerns

Note: The framework is modular: Steps 1–3 may be applied first for preliminary scoping, Steps 4–6 elaborated as data become available. Applicable from building-level to centralized systems. Step 6 explicitly accommodates non-EU regulatory contexts: the EU Water Reuse Regulation (2020/741) applies only within the EU; for non-EU contexts, WHO Guidelines and national frameworks are the relevant reference points.

6.2. Operationalizing Absolute Sustainability: A Worked Example

Step 4 requires assessing whether a reuse system operates within local and planetary carrying capacity thresholds—a requirement that previous reviews have identified as aspirational but operationally vague. We present a concrete worked example for a hypothetical cluster-scale non-potable urban reuse system in a Mediterranean city.

Water dimension—Water Scarcity Index (WSI): The system recovers 500,000 m³/year of reclaimed water for urban irrigation and toilet flushing, displacing freshwater extraction from a local aquifer. Using the Pfister et al. [28] WSI = 0.85 for the study region (‘high scarcity’ category), avoided freshwater depletion is 425,000 m³-equivalent/year. Assessment: the system displaces 12% of current local groundwater abstraction, reducing pressure below the Water Exploitation Index Plus (WEI+) threshold of 0.20 (20% of renewable resources). Conclusion: the system operates within absolute sustainability limits in the water dimension.

Carbon dimension—Climate-related carbon budget: The system’s energy demand is 1.2 kWh/m³, producing 0.6 kg CO₂-eq/m³ under the current regional grid (0.5 kg CO₂-eq/kWh). Total annual GHG emissions: 300 t CO₂-eq. The avoided freshwater treatment at the conventional plant saves 180 t CO₂-eq/year. Net emissions: 120 t CO₂-eq/year. Assessment: the municipality’s per capita carbon budget (based on national NDC trajectories for 2030) allocates 0.5 t CO₂-eq/capita/year to the water sector; at 200,000 inhabitants served, the sectoral budget is 100,000 t CO₂-eq/year. The system’s 120 t CO₂-eq represents 0.12% of this budget—well within absolute sustainability limits. Under a renewable energy scenario (0.1 kg CO₂-eq/kWh), net emissions fall to −36 t CO₂-eq/year (net carbon negative).

This example demonstrates that absolute sustainability assessment is operationally tractable using: the Pfister et al. [28] WSI database; national NDC trajectories; and Eurostat/

IEA grid emission factors. Practitioners applying Step 4 should document all threshold references and the conclusions drawn, enabling transparent peer review of absolute sustainability claims.

6.3. Illustrative Systematic Application to Three Paradigmatic Cases

To illustrate how the RENEW-LCSA Framework structures analysis across contrasting contexts, three paradigmatic cases were selected: Windhoek (Namibia) for direct potable reuse under extreme water scarcity; Singapore (NEWater) for advanced large-scale indirect potable reuse; and Los Angeles County (USA) for complex metropolitan-scale potable reuse under prolonged drought. These cases collectively cover a wide spectrum of WSI values, governance maturity levels, income contexts, and technological approaches. Other important cases exist—Cape Town’s ‘Day Zero’ response, Barcelona’s reclaimed water network, Melbourne’s stormwater harvesting integration—but the three selected cases represent contrasting situations with the best documentation for systematic framework application.

For Singapore, the analysis draws additionally on Tan [29] and Tan, Lee & Tan [30], which document the long-term water security planning context, phased technology development, policy innovation under Singapore’s ‘Four National Taps’ strategy, and the sustained political will underpinning the NEWater programme since the 1960s.

The comparison across cases confirms that long-term success depends critically on governance quality, social acceptance, local energy conditions, and economic viability—not only on technical and environmental performance. The absolute sustainability assessment (Step 4) reveals context-specific challenges: Windhoek faces a carbon intensity challenge relative to NDC targets that Singapore does not, highlighting the necessity of context-specific rather than universal conclusions.

Figure 2 provides an at-a-glance visual comparison of the three cases across the five RENEW-LCSA sustainability dimensions, drawn from the Step 5 coding in Table 7.



Figure 2. Visual comparison of the three paradigmatic cases (Windhoek, Singapore NEWater, and Los Angeles County) across the RENEW-LCSA sustainability dimensions.

As Figure 2 illustrates, Singapore achieves the most balanced performance profile, reflecting its mature governance, sustained public engagement, and progressive grid de-

carbonisation. Windhoek’s asymmetric radar—strong on water security but weak on social acceptance and carbon intensity—reflects the ongoing public trust challenges and diesel-dependent energy grid documented in Lahnsteiner et al. [31]. Los Angeles occupies an intermediate position, with high uncertainty in the social dimension reflecting variable public acceptance across reuse types. The figure reinforces that no context delivers uniformly high performance across all five dimensions simultaneously—validating the RENEW-LCSA Framework’s emphasis on transparent trade-off analysis (Step 5) over assumptions of universal sustainability benefits. This radar visualization is a heuristic analytical tool; practitioners should construct their own based on site-specific data. A transparent scoring rubric with explicit criteria and weights for each radar dimension is provided in the Case Scoring Protocol subsection. Both authors independently scored each case using this rubric; discrepancies were resolved by consensus.

Table 7. Systematic application of the six-step RENEW-LCSA Framework to three paradigmatic cases.

Step	Windhoek, Namibia	Singapore (NEWater)	Los Angeles County, USA
1. SDG-Aligned Goal & Stakeholder Engagement	Goal: water security under extreme scarcity (WSI critical, Pfister > 1.0; precipitation ~360 mm/year). Stakeholder mapping identified strong public resistance and institutional trust gaps requiring dedicated, sustained communication campaigns. NBS assessed as climatically unsuitable for volumes required; evidence Category 3 only.	Goal: eliminate dependence on water imports under high water scarcity (WSI high). Long-term planning under Singapore’s ‘Four National Taps’ strategy since 1960s [29,30]. Strong public communication—NEWater Visitor Centre model—embedded from project inception. NBS evaluated but limited by urban density; under evaluation for coastal buffer zones.	Goal: drought resilience and diversification of supply (WSI high, southern California). Public acceptance varies by reuse type: groundwater replenishment (indirect) more acceptable than direct potable reuse. NBS (constructed wetlands, green roofs, soil-aquifer treatment) increasingly integrated as pre-treatment; evidence primarily Category 1–2.
2. Functional Unit & System Boundaries	1 m ³ of reclaimed water for direct potable use; cradle-to-cradle boundaries including Goreangab WWTP, advanced treatment (ozonation, GAC, ultrafiltration, UV), distribution, and end-use [31].	1 m ³ of NEWater delivered for indirect potable use (industrial/cooling and reservoir blending); full cradle-to-cradle including advanced membrane treatment (microfiltration, reverse osmosis, UV) and environmental buffer via reservoir.	1 m ³ of reclaimed water for groundwater recharge via GWRS; boundaries include advanced tertiary treatment (MF, RO, UV/AOP), injection wells, and aquifer residence time.
3. Three-Pillar Assessment (LCA LCC S-LCA with indicators from Table 3)	LCA: strong freshwater depletion savings (WSI critical context); high energy intensity (+40 to +60% cumulative energy demand vs. conventional due to advanced treatment). LCC: high CAPEX partially offset by avoided supply costs; diesel-dependent grid increases OPEX. S-LCA: public acceptance historically weak (critical S-LCA gap; distributional equity concerns around affordability in middle-income context); trust indicators low.	LCA: excellent environmental performance—NEWater GWP comparable to or lower than conventional with Singapore’s increasingly low-carbon grid. LCC: strong economic performance due to avoided import costs. S-LCA: robust governance and high institutional trust; public acceptance high (sustained communication; NEWater Visitor Centre model [29,30]); gender-inclusive governance.	LCA: good environmental gains from reduced imported water dependency (high-impact Colorado River imports, WSI > 0.7); benefits vary with California grid (increasingly renewable toward 100% by 2035). LCC: high CAPEX and OPEX; long payback periods. S-LCA: acceptance varies by end-use; concerns around affordability and governance accountability; NBS pilots improve biodiversity co-benefits.

Table 7. Cont.

Step	Windhoek, Namibia	Singapore (NEWater)	Los Angeles County, USA
4. Circularity & Absolute Sustainability	Circularity: moderate (water recovery >90%; nutrient recovery limited by technology configuration). Absolute: performs well against local WSI threshold—reuse directly offsets critical water depletion. GWP constrained by diesel-heavy energy grid; carbon intensity above Namibia’s NDC trajectories → below absolute water limit but above carbon budget. Action: Step 6 recommends solar/renewables transition.	Circularity: high—water recovery ~95%; energy recovered from biogas in pre-treatment (biogas cogeneration). Absolute: strong performance against Singapore’s WSI (high scarcity); GWP declining as grid decarbonizes. Projected to meet absolute sustainability thresholds across all pillars by 2030 under current energy transition plans [30].	Circularity: improving—GWRS recovers ~30% of local water supply; nutrient recovery limited. Absolute: benefits strongly dependent on displacement of Colorado River imports; GWP increasingly favourable as California grid decarbonizes. Currently within absolute carbon budget in Scope 2 terms.
5. Aggregation, Trade-offs & Sensitivity Analysis	Radar chart (Figure 2): strong on water security (score 3/5) and resource recovery; weak on social acceptance (2/5) and carbon intensity (2/5). MCDA sensitivity: highly sensitive to energy source ($\pm 35\%$ ranking variation) and public acceptance weighting ($\pm 20\%$ ranking change). Critical trade-off: water security urgency vs. social trust deficit.	Radar chart (Figure 2): consistently strong across all five dimensions (scores 4–5/5). Most sensitive to future energy prices ($\pm 15\%$) and long-term membrane replacement costs. Robustly competitive across all scenarios tested; political will reduces governance uncertainty [29].	Radar chart (Figure 2): strong environmental; improving circularity; economic dimension constrained by high capital costs; social dimension intermediate (3/5) with high uncertainty bands. Sensitive to California grid decarbonization timeline; Monte Carlo shows broad social pillar confidence intervals.
6. Policy & Implementation Insights (aligned with non-EU frameworks)	(1) Transition to solar/renewables to close carbon intensity gap vs. NDC targets; (2) sustained multi-level risk communication and public engagement; (3) adaptive governance with independent performance monitoring; (4) regional LCSA data cooperation with SADC partners. Align with SDG 6 and African Water Vision 2025. [WHO Guidelines apply; EU Regulation not applicable]	(1) Maintain institutional coordination and long-term public engagement (NEWater Visitor Centre model [29,30]); (2) integrate NBS pilots for coastal buffer zones; (3) progressive decarbonization roadmap for remaining treatment energy; (4) share methodology via UNEP LCSA networks. Align with Singapore Green Plan 2030. [National framework; EU Regulation not applicable]	(1) Targeted economic incentives (green bonds, federal water grants); (2) regulatory streamlining under California State Water Board; (3) expanded NBS pilots with full LCSA evaluation; (4) enhanced differentiated public engagement by reuse type. Align with CA Water Resilience Portfolio. Bilateral exchange with EU Water Reuse Regulation best practices.

Note: Sources: Lahnsteiner et al. [31] for Windhoek; PUB Singapore Annual Quality Reports, NEWater programme documentation, Tan [29] and Tan et al. [30] for Singapore; LADWP and OCWD reports for Los Angeles. WSI values from Pfister et al. [28] database. Scores in Step 5 are heuristic, derived from qualitative–quantitative coding, and are indicative rather than statistically derived.

7. Barriers, Trade-Offs, and Enabling Conditions

7.1. Key Trade-Offs in LCSA of Urban Municipal Wastewater Reuse

Municipal wastewater reuse systems involve unavoidable trade-offs that must be transparently analysed rather than assumed away. These differ in severity by reuse type:

- **Environmental vs. Economic:** Higher treatment levels improve safety and environmental performance but substantially increase energy consumption, operational costs, and carbon emissions. Tertiary/advanced treatment can raise cumulative energy demand by 30–100% compared to secondary treatment alone.
- **Scale-related:** Cluster-scale and hybrid decentralized systems often deliver better environmental and social performance due to shorter distribution distances, but face higher capital costs per m³ than large centralized plants [11].

- Social vs. Technical: Advanced treatment achieves excellent objective water quality, yet public risk perception and the ‘yuck factor’ can hinder acceptance, especially for direct potable reuse—where technical performance and social acceptability can be inversely related.
- Short-term vs. Long-term: High upfront investments frequently result in negative net present values in the first 5–10 years despite long-term benefits, creating governance challenges for infrastructure planning cycles.
- Nutrient Recovery vs. Contaminant Control: Maximizing nutrient reuse supports circularity and SDG 2 but may increase risks of emerging contaminants and micropollutants if advanced polishing is insufficient.
- NBS Integration vs. Scalability: Hybrid NBS–grey systems may offer lower energy use and biodiversity co-benefits but require more land, may serve dual functions as hydraulic flood management infrastructure, and face greater operational complexity at scale.

These trade-offs are generally more manageable in non-potable urban applications and more pronounced in direct potable and agricultural reuse.

7.2. Major Barriers and Enabling Conditions

Several interconnected barriers continue to limit the widespread adoption of water reuse and the application of robust LCSA. Table 8 summarizes the main barrier categories, specific barriers, enabling conditions and strategies, as well as the key responsible actors for overcoming them.

Table 8. Barriers, enabling conditions, and responsible actors for water reuse and robust LCSA.

Barrier Category	Specific Barrier	Enabling Conditions and Strategies	Responsible Actors	Expected Impact
Institutional & Governance	Fragmented responsibilities among water, environment, health, and agriculture authorities	Integrated governance frameworks with cross-sectoral mandates; mandatory LCSA requirements embedded in permitting processes; national water reuse strategies	National governments, regulators, basin authorities	Improved policy coherence; reduced regulatory uncertainty
Financial & Economic	High upfront capital costs; uncertain revenues; failure to internalize environmental externalities in tariffs	Blended finance (green bonds, development bank loans); performance-based contracts; shadow pricing of externalities in LCC pillar; life cycle cost guarantees	Utilities, investors, finance ministries, World Bank, EIB	Reduced investment risk; longer evaluation time horizons; greater competitiveness of reuse vs. conventional supply
Knowledge & Data	Scarcity of context-specific LCA/LCC/S-LCA data, especially in Africa, South Asia, and Latin America; over-reliance on European databases	Regional LCSA databases co-developed by research institutions and utilities; South–South capacity building; open-access data repositories	Research institutions, UNEP Life Cycle Initiative, World Bank, national research councils	Higher geographical representativeness; reduced bias; improved LMIC applicability

Table 8. Cont.

Barrier Category	Specific Barrier	Enabling Conditions and Strategies	Responsible Actors	Expected Impact
Social & Cultural	Low public acceptance, particularly for potable reuse; ‘yuck factor’; perceived health risks; distributional equity concerns	Early, transparent, and sustained stakeholder engagement; participatory co-design; differentiated communication by reuse type; S-LCA indicators from Table 3 integrated into assessments	Utilities, local governments, NGOs, communication specialists	Higher social license to operate; reduced project delays; stronger social pillar in LCSA
Methodological	Weak pillar integration; arbitrary weighting; static modelling; insufficient absolute sustainability; underdeveloped social indicators	Adoption of RENEW-LCSA Framework; dynamic modelling with scenario analysis; standardized S-LCA indicators by reuse type (Table 3); explicit absolute sustainability assessment (Section 6.2); submission of S-LCA indicators to UNEP Life Cycle Initiative and ISO TC/207 for standardization consideration	Researchers, journals, funding agencies, UNEP, ISO TC/207	More robust, transparent, and policy-relevant LCSA; reduced overly optimistic conclusions
NBS Integration	Limited empirical evidence at scale (Category 1 evidence scarce); difficulty distinguishing evidence from extrapolation; scaling uncertainty; hydraulic complexity	Dedicated NBS–water reuse LCSA studies; upscaling methodologies; pilot-to-scale assessment frameworks; explicit evidence-category documentation (Step 3)	Interdisciplinary research teams (engineers, ecologists, LCSA practitioners)	Better characterized NBS performance; evidence-based NBS integration; reduced overstatement of NBS benefits

Note: Enabling conditions are mutually reinforcing. The RENEW-LCSA Framework is proposed for submission to the UNEP Life Cycle Initiative and ISO TC/207 as a basis for international standardization of water-sector-specific LCSA methodology.

8. Research and Policy Agenda: Paving the Way Forward

Building on the synthesis above and the RENEW-LCSA Framework, this section outlines a prioritized, time-horizon-structured agenda. Responsibilities are explicitly assigned to avoid the common weakness of generic research agendas without accountable actors.

8.1. Research Priorities

- Strengthening the Social Pillar (Short-term: 1–2 years). Develop, test, and standardize the reuse-type-specific S-LCA indicators (Table 3) across multiple urban contexts. Move beyond generic worker metrics to include community acceptance, distributional equity, and governance dimensions using mixed methods. Responsible: academic researchers in co-creation with communities and NGOs. Expected outcome: more balanced and socially robust LCSA studies. Pathway to standardization: submission to UNEP Life Cycle Initiative and ISO TC/207.

- Multi-Contextual Comparative Studies (Short-to-medium-term: 2–4 years). Shift from single-case studies to systematic multi-scale and multi-region comparisons emphasizing underrepresented contexts in sub-Saharan Africa, South Asia, and Latin America. Responsible: international research consortia. Expected outcome: reduced geographical bias and improved generalizability.
- Evidence-Based NBS Integration (Short-to-medium-term). Fund dedicated full LCSA studies (all three pillars) of hybrid NBS–greywater reuse systems at pilot and cluster scale, including hydraulic performance. Develop standardized upscaling methodologies distinguishing evidence Categories 1, 2, and 3 explicitly. Responsible: interdisciplinary teams. Expected outcome: Category 1 evidence base for NBS integration.
- Dynamic and Prospective Modelling (Medium-term: 3–5 years). Integrate LCSA with system dynamics modelling, scenario analysis (2030/2050 energy transition), and Monte Carlo uncertainty analysis. Responsible: academic researchers in collaboration with utilities and energy modellers.
- Operationalizing Absolute Sustainability (Medium-to-long-term). Develop replicable, open-access tools linking LCSA outputs to WSI, WEI+, planetary boundaries, and NDC targets, building on the worked example in Section 6.2. Responsible: UNEP Life Cycle Initiative, national research councils.

8.2. Policy and Implementation Priorities

- Embed LCSA in Regulatory Processes (Short-term). Require or strongly incentivize use of the RENEW-LCSA Framework in permitting processes under the EU Water Reuse Regulation (2020/741) [3] for EU member states; under WHO Guidelines and national frameworks for non-EU contexts. Include absolute sustainability assessment as a mandatory component of environmental impact assessment for new reuse projects. Responsible: European Commission DG Environment; national regulators globally. Note: The EU Regulation applies exclusively within the EU; for other jurisdictions, equivalent national frameworks are the relevant reference.
- Guidelines, Tools, and Capacity Building (Short-to-medium-term). Develop open-access LCSA guidelines and computation tools calibrated for LMIC data constraints. Fund South–South capacity-building programmes. Responsible: UNEP, World Bank, national environmental agencies. Expected outcome: methodological consistency and capacity in underrepresented regions.
- Innovative Financing Mechanisms (Medium-term). Establish green bond frameworks, blended finance instruments, and performance-based contracts specifically designed for water reuse life cycle investments. Responsible: finance ministries, development banks, private investors.
- Regional Data Infrastructure (Medium-to-long-term). Fund regional LCSA databases for Africa, South Asia, and Latin America as open-access public goods. Responsible: UNEP Life Cycle Initiative, national research councils, World Bank.
- ISO Standardization Pathway (Medium-term). Submit the RENEW-LCSA Framework’s reuse-type-specific S-LCA indicators and absolute sustainability methodology to ISO TC/207 for consideration in the next revision of ISO 14040/14044 or as a water-sector-specific technical specification. Responsible: research networks, UNEP Life Cycle Initiative, standardization bodies.

9. Limitations and Conclusions

9.1. Limitations

This review has several inherent limitations. First, the synthesis is selective and interpretive rather than exhaustive: from over 300 initial references, approximately 25 peer-

reviewed studies were retained, prioritizing pattern identification over comprehensive coverage. Second, geographical coverage remains biased toward Europe, Israel, China, and a small number of Global South countries. Third, Tables 4 and 5 present heuristic syntheses from qualitatively coded literature; directional assessments are indicative rather than statistically derived, and cross-study comparisons should be interpreted with caution given differences in system boundaries and functional units. Fourth, the RENEW-LCSA Framework is conceptual and not yet empirically validated; the worked absolute sustainability example (Section 6.2) uses plausible hypothetical parameters that practitioners must calibrate to site-specific data. Fifth, the search was restricted to English and Portuguese, which may have excluded relevant studies in other languages (e.g., Spanish, French, Chinese, Arabic); this language bias is acknowledged as a limitation of the synthesis. Lastly, a degree of advocacy bias cannot be ruled out given the authors' prior work in LCSA and water reuse; we have mitigated this through a consistently critical tone and explicit acknowledgement of trade-offs, context dependency, and remaining uncertainties.

9.2. Conclusions

The conclusions distinguish between (a) evidence-derived findings supported by the 25 retained peer-reviewed studies, and (b) the RENEW-LCSA Framework and its components, which represent the authors' proposed methodological innovation and have not yet been empirically validated in prospective real-world applications.

This review has demonstrated that the sustainability of urban municipal wastewater reuse is conditional rather than inherent, shaped by system scale, energy source, reuse type, and local governance capacity. Revisiting the three guiding research questions:

What works? Cluster-scale and hybrid decentralized systems—particularly those combining greywater treatment with rainwater harvesting—consistently deliver better environmental and economic performance under favourable conditions (low-carbon energy, short transport distances, appropriate reuse-type matching). Non-potable urban reuse provides the most consistent benefits, with hybrid systems achieving up to $4.8\times$ higher overall sustainability scores and cluster-scale systems reducing GWP by 15–40% versus conventional alternatives. Benefits are conditional, not guaranteed, and highly context-dependent.

What are the pitfalls? The field remains constrained by weak pillar integration, an underdeveloped social dimension, inconsistent system boundaries, over-reliance on relative rather than absolute sustainability, strong geographical bias toward high-income countries, predominantly static analyses, and the frequent conflation of evidence categories when NBSs are discussed. Many optimistic conclusions in the literature are highly context-dependent and may not hold under real-world conditions.

How can we strengthen LCSA practice? The proposed RENEW-LCSA Framework addresses these gaps through six operational steps: SDG-aligned scoping, harmonized functional units and cradle-to-cradle boundaries, parallel three-pillar assessment using reuse-type-specific S-LCA indicators (Table 3), explicit absolute sustainability assessment against WSI and local carbon budgets (Section 6.2), transparent MCDA aggregation with stakeholder-derived weights, and context-specific policy translation. Figures 1 and 2 illustrate the framework's structure and its comparative application across three paradigmatic cases. The accompanying agenda in Section 8 sets concrete short- to long-term priorities with explicit responsible actors and an ISO standardization pathway.

The transition to safe, equitable, and genuinely circular urban water management cannot rely on optimistic assumptions. Researchers must adopt more rigorous, reuse-type-specific, and context-sensitive approaches including absolute sustainability assessment. Policymakers and utilities should embed LCSA requirements in planning, permitting,

and financing processes, adapted to their regulatory context (EU Regulation 2020/741 or equivalent national frameworks). International standardization bodies should consider the RENEW-LCSA Framework's S-LCA indicators and absolute sustainability methodology for incorporation into future ISO guidance. Only through such coordinated efforts can LCSA fulfil its potential as a powerful decision-support tool for achieving SDG 6 and advancing sustainable urban water management worldwide.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18147291/s1>, Figure S1: PRISMA Flow Diagram—Identification, Screening, and Inclusion of Studies. This diagram follows the spirit of the PRISMA 2020 flow diagram, adapted for a critical narrative review; Table S1: Borderline Studies Excluded After Full-Text Assessment; Table S2: List of Included Studies (Part A). References [1,2,4–46] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, E.S.; methodology, E.S.; formal analysis, E.S.; writing—original draft preparation, E.S.; writing—review and editing, E.S. and Z.A.; project administration, E.S.; funding acquisition, E.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by national funds through FCT—Fundação para a Ciência e a Tecnologia, I.P., under the project AWARE (Ref. 3599-PPCDTI), as part of the Water4All/0005/2024 initiative; by the ERA Chair BESIDE project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 951389 (<https://doi.org/10.3030/951389>); and through the projects UID/50017/2025 (<https://doi.org/10.54499/UID/50017/2025>), UID/04928/2025 (<https://doi.org/10.54499/UID/04928/2025>) and <https://doi.org/10.54499/Water4All/0005/2024>.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new primary data were generated or collected in this study. The analysis is based entirely on secondary sources identified through the structured literature search described in Section 1.1, and publicly available quantitative indicators from official sources (Eurostat, WHO, national agencies), all of which are fully cited in the manuscript. The coding matrix and analytical framework (Section 1.2) are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
CAPEX	Capital Expenditure
C-LCSA	Circular Life Cycle Sustainability Assessment
EIB	European Investment Bank
GWP	Global Warming Potential
GWRS	Groundwater Replenishment System (Los Angeles)
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LADWP	Los Angeles Department of Water and Power
LMICs	Low- and Middle-Income Countries

MCDA	Multi-Criteria Decision Analysis
MF	Microfiltration
NBSs	Nature-Based Solutions
NDC	Nationally Determined Contribution (under Paris Agreement)
NF	Nanofiltration
OCWD	Orange County Water District
OPEX	Operational Expenditure
PPE	Personal Protective Equipment
PUB	Public Utilities Board (Singapore)
RO	Reverse Osmosis
S-LCA	Social Life Cycle Assessment
SDG	Sustainable Development Goal
SADC	Southern African Development Community
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UNEP	United Nations Environment Programme
UV	Ultraviolet (disinfection)
VIKOR	Visekriterijumska Optimizacija I Kompromisno Resenje
WEI+	Water Exploitation Index Plus
WHO	World Health Organization
WSI	Water Scarcity Index [28]

References

1. Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89–95. [[CrossRef](#)]
2. Valdivia, S.; Backes, J.G.; Traverso, M.; Sonnemann, G.; Cucurachi, S.; Guinée, J.B.; Schaubroeck, T.; Finkbeiner, M.; Leroy-Parmentier, N.; Ugaya, C.; et al. Principles for the application of life cycle sustainability assessment. *Int. J. Life Cycle Assess.* **2021**, *26*, 1900–1905. [[CrossRef](#)]
3. Regulation (EU) 2020/741; Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on Minimum Requirements for Water Reuse (Text with EEA Relevance); Official Journal of the European Union: Brussels, Belgium, 2020.
4. Backes, J.G.; Traverso, M. Application of life cycle sustainability assessment in the construction sector: A systematic literature review. *Processes* **2021**, *9*, 1248. [[CrossRef](#)]
5. Fauzi, R.T.; Lavoie, P.; Sorelli, L.; Heidari, M.D.; Amor, B. Exploring the current challenges and opportunities of life cycle sustainability assessment. *Sustainability* **2019**, *11*, 636. [[CrossRef](#)]
6. ISO 14040; Environmental management—Life cycle assessment—Principles and framework. International Organization for Standardization: Geneva, Switzerland, 2006.
7. Bruno, A.; Menichini, T.; Silvestri, L. Life Cycle Sustainability Assessment (LCSA): A comprehensive overview of existing integrated approaches to LCA, S-LCA, and LCC. *Eur. J. Sustain. Dev.* **2025**, *14*, 13. [[CrossRef](#)]
8. Hackenhaar, I.C.; Moraga, G.; Thomassen, G.; Taelman, S.E.; Dewulf, J.; Bachmann, T.M. A comprehensive framework covering life cycle sustainability assessment, resource circularity and criticality. *Sustain. Prod. Consum.* **2024**, *45*, 509–524. [[CrossRef](#)]
9. Luthin, A.; Traverso, M.; Crawford, R.H. Circular life cycle sustainability assessment: An integrated framework. *J. Ind. Ecol.* **2024**, *28*, 41–58. [[CrossRef](#)]
10. World Health Organization. *WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater: Volume 2—Wastewater Use in Agriculture*; World Health Organization: Geneva, Switzerland, 2006. Available online: <https://www.who.int/publications/i/item/9241546832> (accessed on 9 July 2026).
11. Opher, T.; Friedler, E.; Shapira, A. Comparative life cycle sustainability assessment of urban water reuse at various centralization scales. *Int. J. Life Cycle Assess.* **2019**, *24*, 1319–1332. [[CrossRef](#)]
12. Souza, H.H.d.S.; Morandi, C.G.; Boncz, M.Á.; Paulo, P.L.; Steinmetz, H. Life cycle sustainability assessment of greywater treatment and rainwater harvesting for decentralized water reuse in Brazil and Germany. *Resources* **2025**, *14*, 96. [[CrossRef](#)]
13. Leong, J.Y.C.; Balan, P.; Chong, M.N.; Poh, P.E. Life-cycle assessment and life-cycle cost analysis of decentralized rainwater harvesting, greywater recycling and hybrid systems. *J. Clean. Prod.* **2019**, *229*, 1211–1224. [[CrossRef](#)]
14. Zhang, H.; Duan, L.; Li, S.; Gao, Q.; Li, M.; Xing, F.; Zhao, Y. Simultaneous wastewater treatment and resources recovery by forward osmosis coupled with microbial fuel cell: A review. *Membranes* **2024**, *14*, 29. [[CrossRef](#)] [[PubMed](#)]

15. Huang, S.; Liu, C.; Wu, H. Life cycle sustainability assessment of end-of-life reverse osmosis membranes management options. *Desalination* **2025**, *613*, 119050. [\[CrossRef\]](#)
16. Mahmoud, I.A.; Umar, H.M.; Sa'id, M.; Abdullahi, M.G.; Usman, J.; Maiwada, A.D.; Magaji, M.M. Water-energy nexus for global sustainability: A comprehensive review, challenges, innovations, and strategic solutions. *TECO J.* **2025**, *1*, 26–40. [\[CrossRef\]](#)
17. Negi, R.; Chandel, M.K. Life cycle assessment of wastewater reuse alternatives in urban water system. *Resour. Conserv. Recycl.* **2024**, *204*, 107469. [\[CrossRef\]](#)
18. Kalboussi, N.; Biard, Y.; Pradeleix, L.; Rapaport, A.; Sinfort, C.; Ait-mouheb, N. Life cycle assessment as decision support tool for water reuse in agriculture irrigation. *Sci. Total Environ.* **2022**, *836*, 155486. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Canaj, K.; Mehmeti, A.; Berbel, J. The economics of fruit and vegetable production irrigated with reclaimed water incorporating the hidden costs of life cycle environmental impacts. *Resources* **2021**, *10*, 90. [\[CrossRef\]](#)
20. Gilboa, Y.; Friedler, E.; Schütze, M. Assessing water use and reuse options—A holistic analysis of a model city, coupling dynamic system modelling with life cycle assessment. *Urban Water J.* **2023**, *20*, 844–858. [\[CrossRef\]](#)
21. Opher, T.; Shapira, A.; Friedler, E. A comparative social life cycle assessment of urban domestic water reuse alternatives. *Int. J. Life Cycle Assess.* **2018**, *23*, 1315–1330. [\[CrossRef\]](#)
22. Tsalidis, G.A.; Xevgenos, D.; Ktori, R.; Krishnan, A.; Posada, J.A. Social life cycle assessment of a desalination and resource recovery plant on a remote island. *Sustain. Prod. Consum.* **2023**, *37*, 412–423. [\[CrossRef\]](#)
23. van Dulmen, N.; Rocha, C.F.B.; Toboso-Chavero, S.; Heijungs, R.; Guinée, J. Evaluating the landscape of social assessment methods. *Int. J. Life Cycle Assess.* **2025**, *30*, 3622–3641. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Bhambhani, A.; van der Hoek, J.P.; Kapelan, Z. Life cycle sustainability assessment framework for water sector resource recovery solutions: Strengths and weaknesses. *Resour. Conserv. Recycl.* **2022**, *180*, 106151. [\[CrossRef\]](#)
25. Gallego-Schmid, A.; Tarpani, R.R.Z. Life cycle assessment of wastewater treatment in developing countries: A review. *Water Res.* **2019**, *153*, 63–79. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Ogbu, C.A.; Alexiou Ivanova, T.; Ewemoje, T.A.; Alabi, H.A.; Roubík, H. Towards environmentally sustainable water management in Africa: A comprehensive review of LCA studies in water and wastewater treatment. *Int. J. Life Cycle Assess.* **2025**, *30*, 956–979. [\[CrossRef\]](#)
27. Larrey-Lassalle, P.; Armand Decker, S.; Perfido, D.; Naneci, S.; Rugani, B. Life cycle assessment applied to nature-based solutions: Learnings, methodological challenges, and perspectives. *Land* **2022**, *11*, 649. [\[CrossRef\]](#)
28. Pfister, S.; Koehler, A.; Hellweg, S. Assessing the environmental impacts of freshwater consumption in LCA. *Environ. Sci. Technol.* **2009**, *43*, 4098–4104. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Tan, G.P. *Singapore Chronicles—Water*; Straits Times Press: Singapore, 2016.
30. Tan, Y.S.; Lee, T.J.; Tan, K. *Clean, Green and Blue: Singapore's Journey Towards Environmental and Water Sustainability*; ISEAS: Singapore, 2008.
31. Lahnsteiner, J.; Honer, T.; Ashipala, L.; Nikodemus, K.; Poussade, Y.; van Rensburg, P. Windhoek/Goreangab direct potable water reuse, case study Namibia. In *Handbook of Water and Used Water Purification*; Springer: Cham, Switzerland, 2024; pp. 1301–1318.
32. Tarpani, R.R.Z.; Azapagic, A. Life cycle sustainability assessment of advanced treatment techniques for urban wastewater reuse and sewage sludge resource recovery. *Sci. Total. Environ.* **2023**, *869*, 161771. [\[CrossRef\]](#)
33. Shanmugam, K.; Gadhamshetty, V.; Tysklind, M.; Bhattacharyya, D.; Upadhyayula, V.K. A sustainable performance assessment framework for circular management of municipal wastewater treatment plants. *J. Clean. Prod.* **2022**, *339*, 130657. [\[CrossRef\]](#)
34. Sei, L.K.; Belle, J.; Mshelia, Z.; Dirwai, T.; Oberholster, P.J. A Nexus Analysis of Municipal Wastewater Treatment and Reuse for Agriculture and Sustainability: A Life Cycle Assessment. *Sustain. Dev.* **2025**, *34*, 4367–4385. [\[CrossRef\]](#)
35. Laouane, H.; El Joumri, L.; Halhaly, A.; Arid, Y.; Labjar, N.; El Hajjaji, S. Life-Cycle Assessment of Wastewater Treatment: Enhancing Sustainability Through Process Optimization. *Sustainability* **2026**, *18*, 605. [\[CrossRef\]](#)
36. Rashid, S.S.; Harun, S.N.; Hanafiah, M.M.; Razman, K.K.; Liu, Y.-Q.; Tholibon, D.A. Life Cycle Assessment and Its Application in Wastewater Treatment: A Brief Overview. *Processes* **2023**, *11*, 208. [\[CrossRef\]](#)
37. Larsen, V.G.; Tollin, N.; Sattrup, P.A.; Birkved, M.; Holmboe, T. What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment. *LCSA. J. Build. Eng.* **2022**, *50*, 104203. [\[CrossRef\]](#)
38. Samsami, Z.; Jafari, A.J.; Delnavaz, M.; Naderi, A.; Rashvanlou, R.B.; Inchehboroun, B.M.; Dehghanifard, E. Environmental impact assessment of southern tehran wastewater treatment plant using life cycle assessment (LCA). *Sci. Rep.* **2025**, *15*, 294. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Wang, Y.-Y.; Yeung, C.H.; Hu, X.-M.; Li, X.-Y. An integrated framework of life-cycle environmental, human health, and economic impact assessment for urban water systems. *Water Res.* **2025**, *278*, 123383. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Yu, J.; Li, G. Evaluating Artificial Intelligence-Based Industrial Wastewater Anaerobic Ammonium Oxidation Treatment Optimization and Its Environmental, Economic, and Social Benefits Using a Life Cycle Assessment–System Dynamics Model. *Processes* **2024**, *13*, 59. [\[CrossRef\]](#)

41. Kamble, S.; Singh, A.; Kazmi, A.; Starkl, M. Environmental and economic performance evaluation of municipal wastewater treatment plants in India: A life cycle approach. *Water Sci. Technol.* **2019**, *79*, 1102–1112. [[CrossRef](#)] [[PubMed](#)]
42. Lam, K.L.; Zlatanović, L.; van der Hoek, J.P. Life cycle assessment of nutrient recycling from wastewater: A critical review. *Water Res.* **2020**, *173*, 115519. [[CrossRef](#)] [[PubMed](#)]
43. Aleisa, E.; Al-Mutiri, A. Life Cycle Assessment for Tertiary Wastewater Treatment and Reuse versus Seawater Desalination. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1026*, 012001. [[CrossRef](#)]
44. Santos, L.; Brás, I.; Barreto, A.; Ferreira, M.; Ferreira, A.; Ferreira, J. Assessing water reuse through life cycle assessment: A systematic review. *Processes* **2026**, *14*, 330. [[CrossRef](#)]
45. Wen, J.; Wang, H.; Yang, P.; Luo, J.; Xiao, M. Life cycle assessment comparison of municipal wastewater treatment processes in China. *Water Pract. Technol.* **2026**, *21*, 1993–2010. [[CrossRef](#)]
46. Nika, C.E.; Vasilaki, V.; Expósito, A.; Katsou, E. Water cycle and circular economy: Developing a circularity assessment framework for complex water systems. *Water Res.* **2020**, *187*, 116423. [[CrossRef](#)] [[PubMed](#)]

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