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Review

Sustainable Rainwater Management and Life Cycle Assessment: Challenges and Perspectives

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Abstract: Rainwater harvesting is a promising technique for more rational water use. However, its sustainability merits remain a subject of ongoing debate among researchers. Life cycle assessment (LCA), a method employed to measure the environmental impact of varying solutions, is helpful in this regard. Accordingly, this paper delivers an integrative review based on the PRISMA protocol, outlining challenges and potential avenues for the LCA application to rainwater harvesting. The central findings indicate that while residential buildings are most commonly examined, more consensus is needed on a uniform analytical framework. Furthermore, several benefits of rainwater are often not considered in LCA and need further exploration to understand possible synergies for its broader implementation. Finally, LCA integration with a life cycle cost assessment (LCCA) shows exciting results as it may be a more straightforward showcase of the benefits of an integrated assessment. It is concluded that specific details of the LCA of rainwater harvesting may still be simplistic. There is much work to be done in holistic assessments to prove the system's sustainability.

Keywords: rainwater; life cycle assessment; buildings; sustainability; simulation; integrative review

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1. Introduction

The global hydrological system has undergone large-scale, unprecedented and poorly understood changes, contributing to the instability of natural ecosystems and society [1]. It is estimated that almost 80% of the world's population has its future water security strongly threatened by multiple factors, such as climate change, water pollution and population growth [2]. For example, Gosling and Arnell [3] evaluated the impacts of climate change on global water scarcity. They concluded that the number of individuals living in regions susceptible to water scarcity will increase, possibly reaching 4.3 billion people by 2050.

According to Mekonnen and Hoekstra [4], about two-thirds of the world's population is located in regions where there is a possibility of severe water shortages in at least one month of the year, equivalent to 4 billion people. The authors commented that many studies do not consider the intra-annual variation of water demand and availability, obtaining more optimistic results that are inconsistent with reality. The population increase and consequent increase in water demand is a worldwide concern, with a growing incentive to apply sustainability in water use and assess the water footprint of production systems.

Rainwater harvesting has been used for millennia in different regions of the world to mitigate water availability problems [5,6] and, currently, practices are heterogeneously distributed worldwide [7]. Rainwater harvesting involves collecting and storing rainwater from roofs, terraces and other surfaces for on-site use. In general, rainwater is intended for non-potable uses such as toilet flushing, washing clothes, garden irrigation, pavement cleaning and vehicle washing [8]. If adopted on a large scale, such a system can be considered a promising technique for the more rational use of water [9].

Musayev et al. [10] evaluated the ability of rainwater harvesting systems to improve water security in different regions under climate change scenarios. According to the authors, climate change has little influence on the efficiency of residential rainwater harvesting systems, ranking them as an essential technique in addressing water scarcity. The importance of this technique in facing water scarcity was also verified based on other methods used by Ghisi [11].

Considering water scarcity and environmental impacts, several researchers have evaluated the use of decentralised rainwater harvesting methods and alternatives to centralised ones to reduce the environmental impact of water utilities. Analysis through a life cycle assessment (LCA) is fundamental for water management's evolution towards sustainability in cities. LCA is a methodology that assists in evaluating the potential environmental impacts of systems and their alternatives, including defining more sustainable materials, technologies, infrastructures and projects [12].

Tarantini and Ferri [13], for example, used the LCA methodology to evaluate rainwater harvesting systems, rational use of water and greywater reuse in flats located in Italy. The authors concluded that rainwater harvesting and greywater reuse installation costs were not economically feasible. Still, installing the system could decrease the environmental impacts of the flats' water use. They also concluded that energy consumption in the use phase for water pumping was the significant environmental impact assessed for the system with rainwater, greywater and the conventional water supply system.

Ghimire et al. [14] compared a commercial rainwater harvesting system with a centralised (municipal) water supply system employing LCA. The authors evaluated 11 environmental impact indicators, considering the entire production cycle of the materials and their use. In their study, rainwater harvesting systems outperformed the centralised water supply system in 10 of the 11 environmental indicators. Despite presenting a wide range of results, research on the environmental feasibility of rainwater harvesting systems is essential to understand their impacts and benefits thoroughly.

Although this article may not satisfy the demand for state-of-the-art research for LCA specialists, it fills a significant research gap. It serves as an introductory bridge for rainwater harvesting (RWH) researchers to understand life cycle assessment (LCA) as a tool, a novelty in the field.

Considering the importance of the subject, this study aims to disseminate the current state of LCA studies on rainwater harvesting systems by conducting an integrative review of the themes and discussing novel ideas about systems and methods. Furthermore, other complex benefits from the systemic approach were addressed by analysing the effects of adopting rainwater harvesting in urban areas. The integrative review question and objective was to answer the question "How sustainable is rainwater harvesting?".

2. Materials and Methods

The initial part of the study comprised an integrative literature review aiming to explore the existing literature on rainwater harvesting and life cycle assessment (LCA). The PRISMA protocol [15] was used to structure and ensure the future reproducibility of our study. The following sections detail the criteria used in the integrative review and the details sought in the selected documents.

2.1. Integrative Research Details

Adhering to the PRISMA protocol, the first step involves posing a question for the integrative review. The selected question for this paper is "How sustainable is rainwater harvesting?". The primary objective was to establish a broad context within the literature regarding the available LCA frameworks, specific details of the assessment and general conclusions about the system's sustainability.

In this context, the Scopus database was used with the following descriptors: ((("life cycle assessment" OR "life cycle anal*" OR "life-cycle assessment" OR "life-cycle anal*" OR "life cycle analysis" OR "life cycle assessment") AND (("rainwater" OR "rain-water" OR "stormwater" OR "storm-water" OR "rainwater" OR "rainwater") AND ("harvest*" OR "catch" OR "capture")))), generating a total of 109 documents as of 10 May 2023. Fourteen documents were included from other sources, given their relevance and compatibility. The final screening encompassed a total of 123 documents.

Among the screened documents, 18 were excluded due to access limitations and 4 were excluded because they were review papers. A final set of 101 documents underwent eligibility assessment, with 25 excluded for lack of relevance to the subject of this study. Three of the authors double-checked this assessment to ensure comprehensive inclusion. After meticulous evaluations, a final number of 76 documents was selected. Figure 1 presents the identification, selection, screening and inclusion process of the publications listed for the literature review, as outlined in the PRISMA protocol.

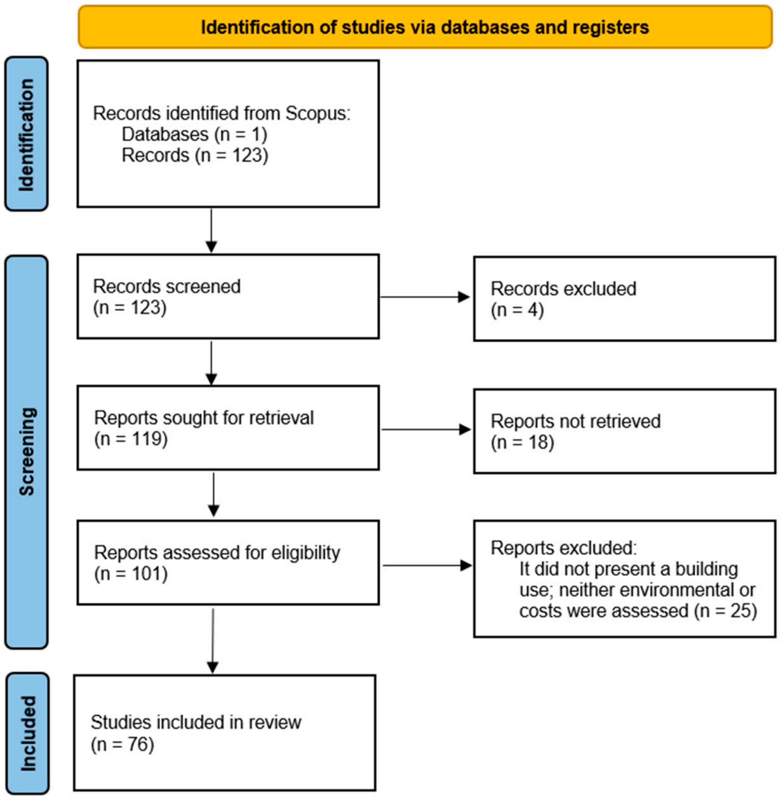

Figure 1. Flowchart of the integrative review protocol (PRISMA).

The eligibility criteria used in this study were designed to maintain a broad approach. The primary exclusion criterion applied to papers not focusing on using harvested rainwater, such as toilet flushing in buildings. A second exclusion criterion centred on the LCA and LCCA focus. Studies not highlighting environmental or cost factors as primary objectives were excluded. However, articles offering partial LCA or LCCA scopes were included; thus, papers providing more superficial assessments, such as CO_2 emission estimates and cost-benefit analyses, were also considered.

Upon reviewing the selected articles, we conducted a bibliometric analysis, assessing contributions from leading countries, authors with the most publications, keyword evolution and other details. This analysis was carried out using pyBibx [16], Bibliometrix [17] and ScientoPy [18], all of which assist in analysing the bibliometric context's metadata and generating visual aids.

2.2. Technical and Environmental Details

Based on the articles selected, the authors found it beneficial to evaluate the technical and environmental parameters most frequently considered in academic studies. For instance, understanding trends in modelled systems and analytical frameworks can help identify potential trends or conceptual gaps that academia needs to address. While rainwater harvesting is widely recognised as a critical alternative for the future city's potable and non-potable water supply, optimising these systems for environmental impact through material selection and using less impactful alternatives is also of interest. Equally important is optimising technical parameters for rainwater harvesting and its use for greater efficiency.

Consequently, the bibliometric analysis divided the results into two major groups. The first group encompassed the LCA analysis of rainwater harvesting systems, highlighting existing frameworks, methodologies and considerations. The second group compiled information on the advantages of rainwater harvesting that are often overlooked in LCA and pinpointed potential challenges and benefits yet to be explored. During the review of the second group, three authors sought specifics on the rainwater harvesting systems. Details such as building typology and type of harvesting surfaces were collected by thoroughly reviewing the papers. Observations on LCCA and other types of assessments were also included.

2.3. Principles and General Considerations

Life cycle assessment (LCA) is a widely used methodology for the environmental assessment of systems and products, focusing on comparison and improvement. The technique aims to comprehend the potential environmental impacts of a system or product throughout its life cycle. This understanding identifies possible improvements and provides crucial environmental performance indicators to better communicate information. As such, the methodology assists decision-makers in exhibiting a company's social and environmental interest, ensuring alignment with values for a sustainable world, a requirement increasingly demanded by society.

Many studies in the literature have deployed LCA concerning rainwater harvesting and its implementation in buildings. Research into the life cycle context of these systems began to be explored in the early 21st century, with a study by Tarantini and Ferri [13] being one of the earliest works available. At the time, the authors evaluated an innovative system of rainwater harvesting, rational water use and greywater reuse in flats located in Italy. Their study concluded that the installation costs of rainwater harvesting and greywater reuse systems did not present a financially viable return over their useful life. However, they found that the system's installation could decrease the environmental impacts of the flats' water usage. Tarantini and Ferri [13] also determined that energy consumption in the water pumping for use phase was the most significant environmental impact for both the innovative system with rainwater and greywater and the traditional system, indicating a prime area for optimisation.

Thus, research employing LCA to evaluate rainwater harvesting is integral to understanding the environmental viability of these systems, that is, to explore the sustainability of the proposed systems and compare them to the conventional water supply system. Teston et al. [19] conducted a comprehensive literature review on rainwater harvesting systems, identifying LCA as a growing guiding element in the context of rainwater harvesting. However, their work did not discuss the bibliometric context of the utilised methodologies. This paper, therefore, aims to augment the existing literature by highlighting and discussing potential methodological gaps in LCA and incorporating new articles and discussions on the applicability of rainwater harvesting systems for enhancing urban sustainability.

3. Results

3.1. Integrative Review Results—Bibliometric Analysis

Initially, the 76 selected documents were formatted into CSV and Bib formats to facilitate use with the chosen tools. Metadata of the documents, such as country of origin, document language, authors, citations, affiliations, keywords and year of publication, were systematically organised for trend visualisation. Figure 2 illustrates the number of publications by country and the evolution over the last five years of available data (2018–2022). The United States had the highest production, followed by the United Kingdom, Brazil and Spain. In the last five years, Brazil showed the most substantial growth in the percentage of publications, while the United States led in the sheer quantity of publications, with nine documents. The selected articles are listed in Table S1 in the Supplementary Data.

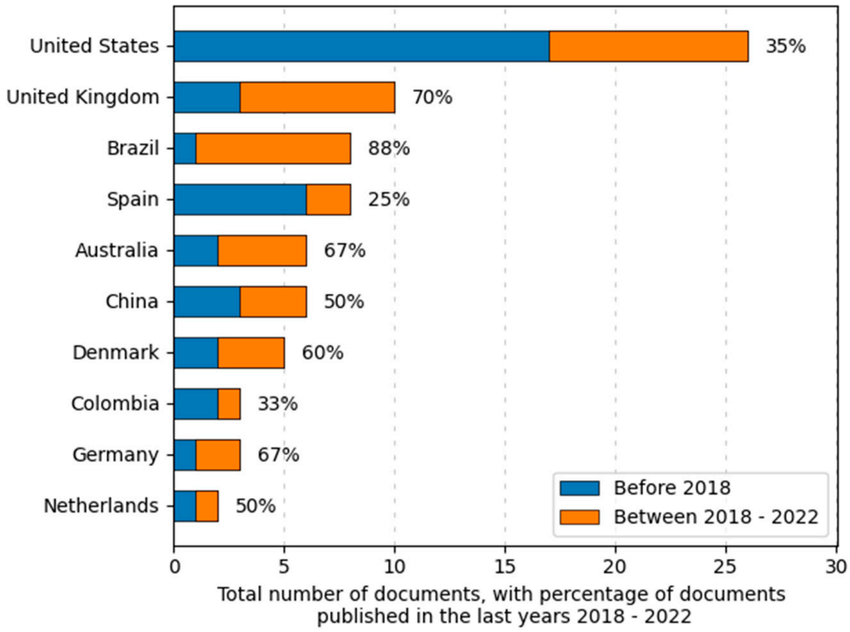

Figure 2. Number of documents and temporal evolution per country.

The selected articles spanned from 2010 to 2022, featuring contributions from 223 authors. The year 2019 saw the peak annual production, with 12 published documents. The *Journal of Cleaner Production* had the highest number of papers on the topic, with 13 entries. The paper with the most citations was "Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits" by Rahman et al. [20]. Given its publication year and relevance to Australia, this article formed the foundation for numerous subsequent water optimisation studies in various countries.

Regarding authors, Figure 3 presents the publication trend among the leading authors in the field. The size of the circle corresponds to the number of published articles (larger stands for more published articles) and the circle's colour corresponds to the number of citations the author had (darker stands for more citations). Apul and Gabarrell were the most prolific, with eight papers each. Eight other authors followed closely with five or six papers, demonstrating a variety of high-producing contributors on the subject. A marked increase in production between 2018 and 2022 is also noteworthy, as depicted in Figure 2.

A word cloud analysis revealed additional contexts beyond those suggested by keyword sequences. The first analysis highlighted the presence of cost-related terms, likely about the life cycle cost assessment (LCCA) theme. The second analysis included terms related to climate change or global warming. The presence of terms related to wastewater indicates a focus and interest in using lower-quality water reuse systems. Figure 4 shows the keyword cloud derived from the selected articles. Moreover, other decision-making contexts, such as management, resources, treatment and conservation, emerged as facets of a science-based approach to future water asset decisions.

3.2. LCA of Rainwater Harvesting Systems

The subsequent sections detail the findings from our analysis of the selected articles. For ease of comprehension, we divided the information into sections. Initially, we explored the fundamental principles of life cycle assessment and their application to rainwater. Subsequently, we addressed the methodological principles concerning LCA and specific rainwater harvesting projects.

3.2.1. LCA, Database and Programmes

Concerning LCA characteristics, no consensus exists regarding the preferred programme, method for the life cycle impact assessment (LCIA) or database, thus requiring the researcher to determine which best suits the study's objectives. The programme most used among the researchers was Simapro, with 22 studies, followed by Gabi with 13 and OpenLCA with 5. Other studies indicated alternative programmes with specific applications or performed calculations using spreadsheets or simplified methodologies. However, it is worth noting that the programme choice does not alter the results since the calculation methodology for LCA is standardised [21] and stems from a similar conceptual framework.

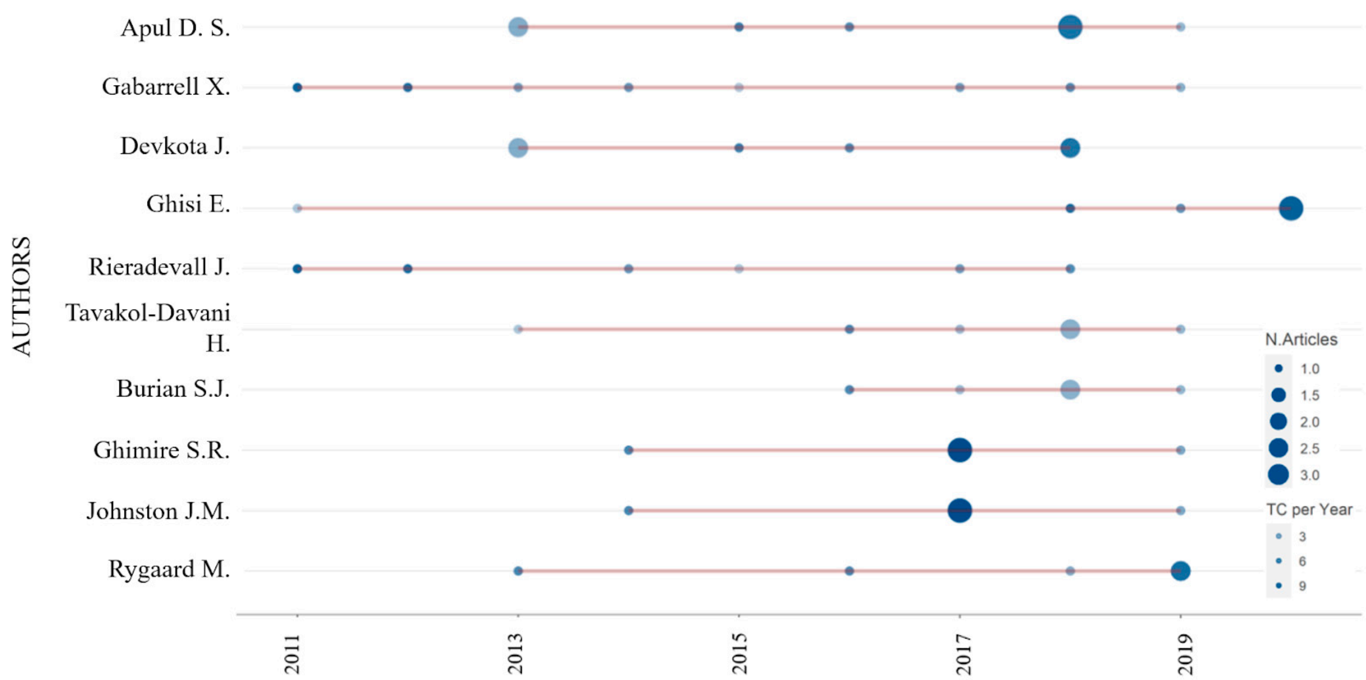

Figure 3. Number of documents and temporal evolution per country (TC—Total citations by colour/Number of articles—the size of the marks).

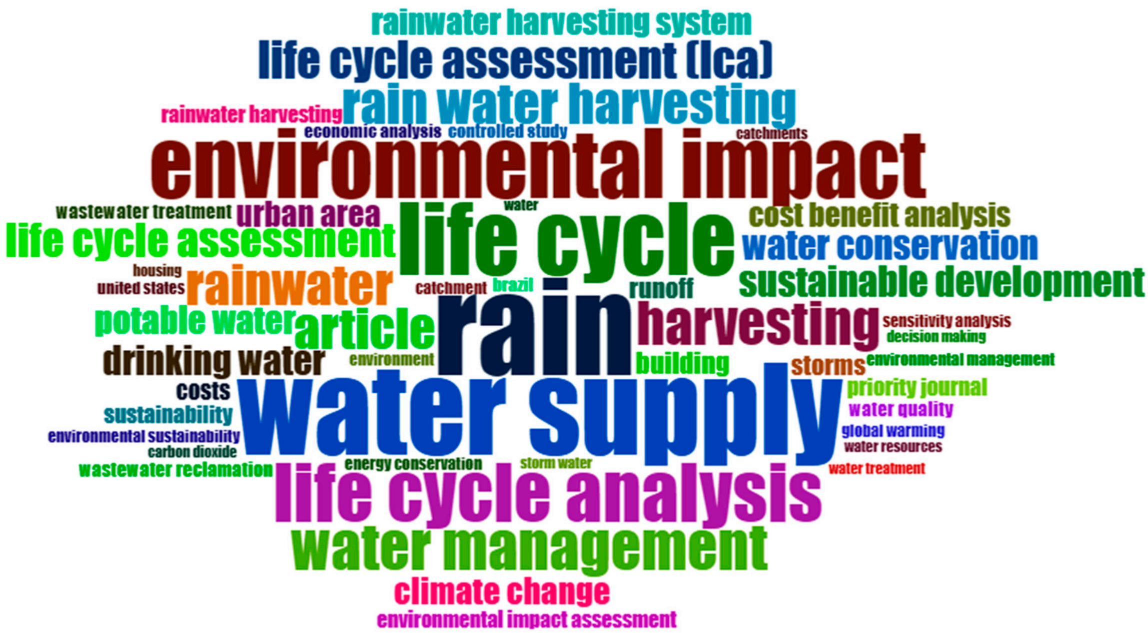

Figure 4. Word cloud of the selected articles' keywords.

On the other hand, the database and LCA method can significantly impact the results and, therefore, require careful consideration. In terms of databases, the Ecoinvent database is widely used, justified by its comprehensive range of materials available for modelling.

However, it is known that Ecoinvent is more specific for European processes, necessitating data quality evaluations to prevent potential inaccuracies from skewing the analysis. Other data sources referenced in the assessed research include previous works, the Gabi program database and Chinese databases.

The LCIA method is responsible for providing the coefficients for classification and characterisation and the impact indicators. Dong et al. [22] studied correlation matrices for building materials across several widely used LCA methods in research. The authors highlighted the variances between the methods, pointing out that there are both comparable indicators and those lacking in comparability. In a case study comparison of LCIA methods by Koch et al. [23], they proposed using multiple assessment methods whenever feasible, given the specific programmes' ability to facilitate this approach.

Our review showed that the ReCiPe method was the most widely used in its 2008 and 2016 versions, followed by the CML2001, TRACI 2.1 and IMPACT 2002+ methods. ReCiPe offers a global approach, contrasting with the primarily European usage of CML and IMPACT and TRACI's North American region application [22]. This broader approach justifies ReCiPe's more prevalent use as it caters to countries outside the European or North American regions and appeals to researchers interested in global impact indicator analyses. Indeed, each method has unique considerations and objectives, thus requiring researchers to select the one that best aligns with their goals judiciously.

The disparate methodological characteristics challenge researchers in clearly comparing results when attempting to compose the state-of-the-art. For instance, as detailed in Section 3.2.4, the life cycle stages considered can entirely alter the LCA results. Furthermore, specific methodological parameters evaluated in this section (such as LCIA and database) can directly influence the results. Therefore, multiple LCIA methods should be used to ensure a reliable analysis. Also, a quality matrix of the flows should be employed, thereby reducing uncertainties and expanding the potential comparability of the study with other analyses.

3.2.2. Building Typology and Catchment Surface

In residential rainwater harvesting systems, rooftops are typically utilised to collect rainwater for on-site use [7]. However, other surface types, such as permeable and non-permeable pavements, could also serve this purpose [24]. The type of material used and the effective catchment surface area significantly impact the harvested rainwater's quality and quantity.

The role of LCA in rainwater harvesting systems is pivotal for progressing towards sustainable water management in cities. A survey of relevant articles reveals that a significant majority (81%) use rooftops as a rainwater catchment surface, as seen in the studies by Rashid et al. [25], Angrill et al. [26], Devkota et al. [27], Gómez-Monsalve et al. [28] and Marinoski et al. [29]. Studies using the permeable pavement as a catchment surface add up to 6.3%, such as the studies by Martins Vaz et al. [30], Antunes et al. [31], Antunes et al. [32] and Wang et al. [33]. The remaining articles (12.7%) used other locations, such as ditches and detention basins, or did not report the location of the rainwater catchment.

Another issue verified in the articles listed for the study was the building typology. More than half of the articles focused on the residential typology (53.8%), such as the studies by Abas and Mahlia [34], Zanni et al. [35], Vialle et al. [36], Rashid et al. [37] and Jeong et al. [38]. Some articles encompassed different typologies in the same study (18.5%), and others considered the urban scale (10.8%), involving different typologies. Some authors have conducted studies in other typologies, such as commercial [14,39,40], which added up to 9.2% of the articles, and public, with 3.1% [30,31]. Studies were also observed in universities [27,41,42], representing 4.6%. Figure 5 summarises the types of buildings found in the selected studies.

From this exploration, it is apparent that rainwater harvesting is becoming increasingly prevalent in residential settings. In contrast, its exploration in other typologies, such as public, commercial and industrial, is less common, revealing research gaps. This observation becomes even more relevant, considering numerous studies suggest that the most significant potential for potable water savings lies within public and university buildings [43] as these settings usually have a higher proportion of non-potable water uses. Nevertheless, it is crucial to note that this point heavily depends on the scope of treatment and end use, a discussion addressed in Section 3.2.5.

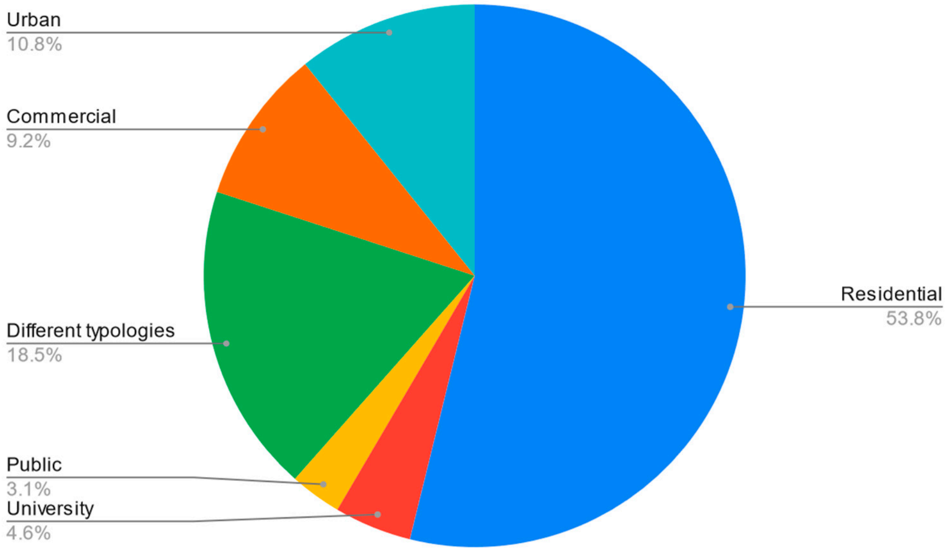

Figure 5. Building typology assessed in the studies.

3.2.3. Life Cycle Stages Considered

Following ISO 14040 [21], four main steps are performed during LCA: definition of research objective and scope, inventory analysis, environmental impact assessment, and interpretation of results. Still, iterativity is fundamental in LCA, and it is necessary to revisit the previous steps at each advancement to confirm the data, definitions and project objective.

In this context, the following terms arise: "cradle", related to the stage of extraction of materials for manufacturing the system; "grave", the final disposal of the waste generated; and "gate", after manufacturing and ready to be transported to the customer [44]. The definition of the boundary can then contemplate from cradle to grave, with all phases of a system, or from cradle to gate, neglecting the use and disposal phase, or variations thereof, given the purpose of the analysis. However, it is noted that ISO 14040 [21] indicates the need to address processes from all phases of the life cycle of the system or product, and the use or disposal phase should not be neglected since it can generate relevant potential environmental impacts.

In the LCA analyses, most articles used the cradle-to-grave concept when considering the life cycle stages. These considered the production of materials and system components, including raw material extraction and processing; transportation and construction of the system; operation and replacement of components over the system's lifetime; energy consumption for system operation; and final disposal of components at the end of life. Briefly, these articles encompassed materials, construction, transportation, use and deconstruction, such as the studies by Angrill et al. [45], Arden et al. [46], Bhakar et al. [42], Vialle et al. [36] and Borrion et al. [47]. Angrill et al. [26] performed LCAs of different urban planning approaches, diffuse and compact, for different rainwater harvesting systems. All the evaluated systems considered rainwater harvesting via buildings roofs, differing in the type and location of the cistern for storage. The authors considered the phases of materials, transportation, construction, use and deconstruction, without using the disposal or recycling phases. They also considered the structural requirement placed on the building structure for each type of cistern location. Structural reinforcement was added to the system's inventory to understand the impacts of location.

The results show that the tank's location on the roof of the building was the most optimal position, with the consequent uniform structural distribution in the building. This result was independent of concentrated or diffuse urban planning but with different trends for both models. Lower environmental impacts were observed for compact planning, with the water distribution system being the main contributor. For the diffuse planning, it was observed that impacts related to the cistern were the main contributors. They, therefore, concluded that planning for rainwater harvesting systems should be incorporated as early as the urban planning phase to optimise outcomes and decrease greenhouse gas emissions and other environmental impacts. As a disclaimer, one should note that each design has a different optimal tank size, and the possibility of locating it on the roof must be appropriately assessed.

Vialle et al. [36] performed an LCA of a rainwater harvesting system for houses in France. As a main result, they found that the system supplied only by potable water and the system supplied partially by rainwater generated similar environmental impacts when all life cycle phases were considered. However, they mention that the rainwater harvesting system may reduce the stress on water resources by requiring less harvesting, which is interesting in the context of water scarcity. Another interesting point is the possibility of considering a rainwater disinfection system, an element addressed in one of the scenarios analysed by the authors. All considerations were listed as local-dependent and technology-dependent, which made them also comment on the specific approach of the LCA performed, with several considerations specific to the system analysed. Finally, design features could be optimised to decrease environmental impacts and favour decentralised technologies.

Notably, there needs to be a standardised analysis trend, as each author observed and specified the level of detail based on their preference. Hence, it is beneficial to highlight the essential elements at the intersection of the evaluated studies. Figure 6 outlines a continuum of main processes evaluated among the authors and indicated in comprehensive analyses. Additionally, new indications of benefits may be incorporated depending on the scope and purpose of the evaluation. For instance, the following sections discuss the often-overlooked benefits of LCA in rainwater harvesting, which can be incorporated into the foundational framework depicted in Figure 6.

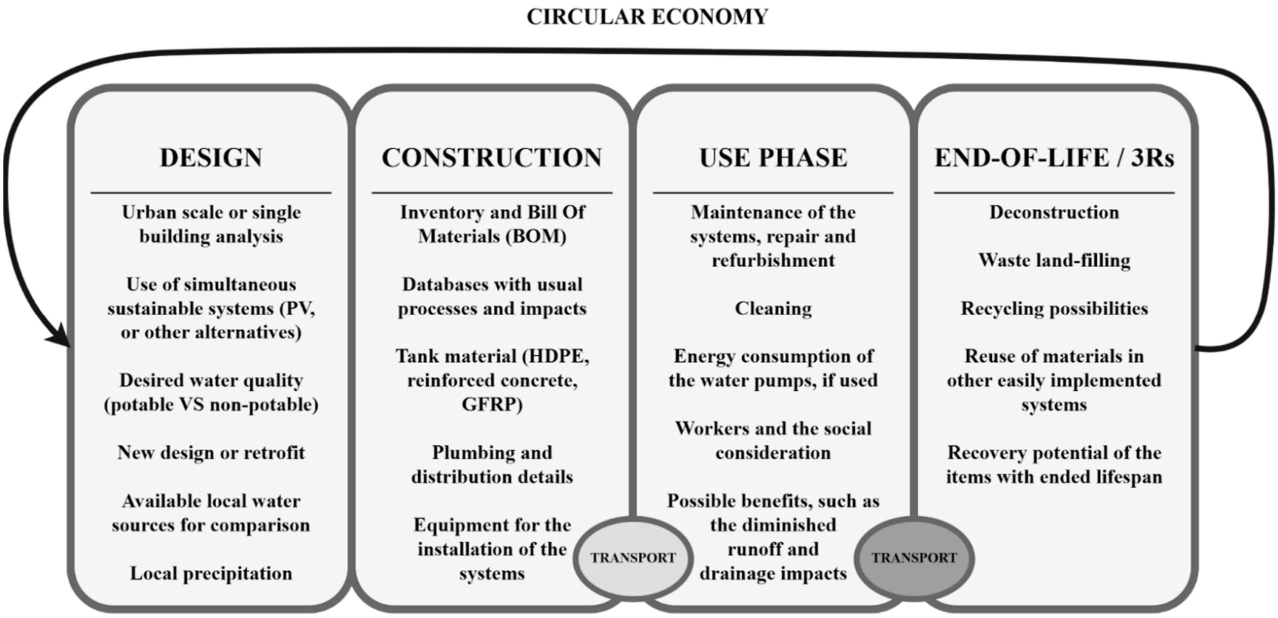

Figure 6. Standard LCA framework, which extends to rainwater harvesting.

3.2.4. Rainwater Harvesting as an Alternative for Decentralisation

Several researchers have evaluated the use of decentralised catchment methods and alternatives to centralised catchment to reduce the environmental impact of water utilities. The alternatives are broader than strategies involving only water. Still, they can be indirectly applied to modernising facilities, using photovoltaic energy in treatment plants and other technological approaches. Lam and Hoek [48], for example, evaluated possible strategies to be used by the Amsterdam water utility in the Netherlands for greenhouse gas emission abatement. As a main conclusion, the authors commented that several alternatives become economically interesting for water utilities, many of them being opportunities for broad strategies that do not directly involve the utility's actions. Thus, as a society, it is interesting to observe the possible synergies and partnerships between the different sectors of society to enhance and amplify the use of more sustainable strategies.

A notable aspect is the interplay between cleaner energy and water. The water–energy nexus poses a significant consideration for comprehensive assessments in various countries as interconnections between water and energy resources may differ considerably. For instance, there are plenty of water sources in Brazil, but decentralised solutions have become attractive because of the country's dimensions and the difficulties and costs of distributing this water. Also, in locations with a higher rate of energy-intense treatments, it is necessary to address the energy source, such as photovoltaics, hydroelectric power or wind energy. If there is a heavy reliance on fossil fuels, an additional layer of scenario planning must be incorporated into the LCA.

Nazer et al. [49] evaluated the environmental, social and economic impacts of adopting different types of strategies for water management in households in Palestine. The authors aimed to evaluate the applicability and economic and environmental variables of installing different types of technologies. Rainwater harvesting, faucet aerators, low-flow showerheads, dual-flush toilets, dry toilets, actions to prevent pipe leaks and greywater reuse were evaluated. As main conclusions, the authors obtained that adopting different methods could reduce water demand by up to 50%. The environmental impacts could be reduced by up to 38% if rainwater harvesting systems were considered. The other alternatives also resulted in reduced environmental impacts, with economic feasibility found for using faucet aerators, low-flow showerheads and dual flushes. The authors also concluded that residents of the evaluated region in Palestine had great social acceptance and willingness for the rational use of water and conservation of water resources. They mentioned that education on the subject is fundamental for advancing water sustainability.

Upon analysis of the articles, it becomes evident that rainwater harvesting can serve as a viable option for decentralising water supply systems and an effective alternative for conserving water resources. This is particularly relevant to other alternatives, such as installing water-saving devices. The findings emphasise the pivotal role of innovative, sustainable strategies in addressing water management challenges and shaping a more sustainable future.

3.2.5. Water Quality and Use

The quality of rainwater harvested from rooftops can be affected by the type of roof used and the quality of the raw rainwater [50]. In urban areas, rainwater pollution usually originates from air pollutants from industrial activities or the burning of fossil fuels [51]. In rural areas, this type of pollution can be related to the use of pesticides [52]. The accumulation of dust and faecal deposits from birds and rodents on roofs can also affect the quality of rainwater [53].

Regarding the quality of treated water, most works considered non-potable uses with simple treatments for basic improvement, with a few works performing tertiary treatments to obtain potable water. For example, Yan et al. [54] evaluated a point-of-use rainwater treatment as an alternative drinking water supply measure. The authors indicated that the system could not provide lower environmental impacts, with higher impact results than those obtained using a conventional supply. However, they indicated that the system may benefit in locations with smaller environmental footprints in energy supply as energy consumption was highly impacted in the alternative system.

Most of the papers evaluated used a system for non-potable purposes as, in these systems, there are fewer treatment processes, higher financial returns in the short term and more accessible applications. Therefore, two different approaches can be taken that completely change the scope of the LCA. In non-potable systems, the aim is to save drinking water, while in potable systems, the aim is to obtain new water supply sources.

An additional point of interest is the relatively straightforward process of water quality improvement. For instance, in systems with permeable pavements, filtration through the pavement enhances the quality of water available for non-potable use or disposal to local drainage systems. Some recent LCA studies on permeable pavements [55,56] aimed to assess the impact of quality improvement within the analysis boundaries. Such an interpretation can also be integrated into rainwater harvesting systems when a quality improvement process, like filtration, is included. Thus, this underlines the importance of assessing and understanding the varied facets of rainwater harvesting, including treatment options and their corresponding impact, as we strive towards more sustainable water management solutions.

3.3. Benefits Overlooked in LCA and Challenges of Rainwater Harvesting

This section discusses the benefits of rainwater use that can be more thoroughly evaluated in future LCA research. The aim is to include epistemological contexts that support a complex and complete analysis similar to LCA. Consequently, forthcoming LCA frameworks for rainwater harvesting might incorporate some, if not all, of the mentioned benefits and items. It is acknowledged that applying LCA is intricate, necessitating methodological boundaries. Yet, it offers a sweeping perspective that serves as a macro overview of potential trends and conceptual inconsistencies in the comparison of rainwater harvesting systems.

3.3.1. Impacts at the Urban Scale

In general, rainwater harvesting systems share the common goal of reducing the potable water demand from centralised distribution facilities. Ghisi et al. [57] compared water demand and availability in 195 cities in the southeastern region of Brazil and investigated the potential savings of potable water when rainwater is used for non-potable purposes in the residential sector. They found an average potential of 41% of savings of potable water per year, emphasising the importance of this type of solution to mitigate problems of water availability.

Ghisi et al. [58] described the scenario of rainfall availability and water consumption in 62 municipalities in Santa Catarina, southern Brazil. They found that the average potential for drinking water savings for these cities is 69%, which would allow, if necessary, the consumption of rainwater even for a portion of potable uses. According to the authors, this significant savings potential could only be achieved in practice if there were some kind of government incentive to implement rainwater harvesting systems.

From an LCA perspective, few studies incorporate the municipal scale, notable exceptions being the works of Tavakol-Davani et al. [59] and Valdez et al. [60]. Tavakol-Davani et al. [59] compared the implementation of rainwater harvesting and greywater reuse systems for long-term sewer overflow control at the municipal scale in Toledo, Ohio. They considered using harvested rainwater for toilet flushing in buildings and concluded that rainwater harvesting could make overflow control more sustainable in the long run, improving life-cycle cost benefits by 48%. Valdez et al. [60] compared the greenhouse gas emissions and energy consumption of buildings supplied by utility and rainwater harvesting in Mexico City. Life cycle analysis methodology was used to evaluate the operation and construction of the system. The results showed that rainwater harvesting could reduce greenhouse gas emissions and mitigate flood risk. Both Tavakol-Davani and Valdez et al. [59,60] present municipal-scale results. It is worth noting that Valdez et al. [60] also analysed the potential for flood reduction, which researchers often overlook.

Despite their multiple benefits, it is notable that rainwater harvesting systems still need to gain the recognition necessary for their more comprehensive application. The public administration plays an essential role in the widespread application of rainwater harvesting systems by implementing regulatory and incentive policies.

Brown et al. [61] pointed out, from the perspective of the Australian experience, that practical structural changes, such as the extensive implementation of rainwater harvesting systems, only occur if they are supported at the institutional and socio-political levels. In this direction, several cities around the world are gradually adopting incentives and regulations for the application of rainwater harvesting systems on a larger scale, such as Barcelona, Spain [62]; Berlin, Germany [63]; Melbourne, Australia [64] and Tucson, USA [65].

Gonela et al. [66] evaluated different scenarios of fiscal incentives for decentralising the water supply in a rural city in Texas, USA. Three incentive schemes were proposed and investigated: no subsidy, constant rate and progressive subsidy rate, depending on the system's storage capacity. In this case, it was suggested that the source of resources for these incentives be the savings generated for the government from the decentralisation of water distribution. The authors pointed out that the incentive scheme with a progressive rate proved to be more efficient in improving the performance of water use systems at the municipal scale, besides promoting greater adherence to this type of solution. The incentive scheme with a fixed rate was the one that most promoted savings for the public administration.

Given the above, for the impacts of rainwater harvesting to be felt on a large scale, a widespread installation of the system should be conducted. It is also essential to have the support and incentive of local public policies, either through legislation, tax subsidies or financial support for installing the system. LCA can benefit from this large-scale method by providing other benefits such as city-scale water pumping energy, maintenance of water supply systems and acceptability, among others. There is still a necessity to assess such changes within LCA boundaries.

As for specific cost assessments, several studies have analysed the incentives for rainwater worldwide [67–70]. However, the countries have many differences and specific details for each incentive. Thus, they must be separate from worldwide conclusions since each location has specific details to assess. This represents a difficulty in obtaining a global LCCA framework since some specific considerations must be performed. Nevertheless, the studies presented in this section provide an overview which can identify potential elements for consideration in some regions of the globe.

3.3.2. Impacts on Reducing the Utility's Demand

During much of world history, centralised water management was present in urban centres to meet hygienic standards and ensure the water safety of cities. However, with the advance of climate change and the need to save water and ensure water resilience, rainwater harvesting has returned to assist water supply.

One of the benefits that can be attributed to rainwater harvesting in urban areas is the reduction of operational costs associated with centralised water supply operations. Cureau and Ghisi [71] evaluated the potential for electricity savings from different water-saving scenarios for Joinville, Santa Catarina. When considering using rainwater in the city's buildings for non-potable uses, the utility could stop consumption between 1000 and 7500 MWh annually. Additional savings could also be achieved by reducing the need to expand supply systems.

Melville-Shreeve et al. [72] demonstrated through a multi-criteria analysis that the reduction in potable water consumption provided by rainwater harvesting systems contributes to a decrease in energy consumption associated with the abstraction, pumping and treatment of water in centralised water supply facilities. Vieira et al. [73] compared the water–energy ratio of rainwater harvesting systems with that of conventional water supply systems. According to the authors, rainwater harvesting systems tend to use more energy per unit of produced water than conventional systems. However, the research shows that rainwater utilisation systems have an energy consumption equivalent to that of centralised systems when adequately sized, especially when using systems with indirect rainwater distribution.

Therefore, as observed in the selected articles, rainwater harvesting systems can reduce the demand for drinking water and energy by utilities, reducing the environmental impact caused by the extraction, treatment and pumping of centralised urban water supply systems.

Such considerations, aligned with the urban scale, may be incorporated in LCA studies to provide a broader view of the impacts of a significant utilisation of rainwater harvesting.

3.3.3. Impacts of Reducing the Use of Potable Water

Most articles considered using rainwater for non-potable purposes to save potable water and conserve this resource as the possibility of water scarcity is one of today's most critical environmental issues. Untreated rainwater is unsuitable for human consumption but can be used for various purposes, such as power generation, equipment cooling, vehicle washing, fire breaks and irrigation. Therefore, rainwater harvesting allows more water to remain available for other purposes, ensuring its rational use.

Custódio and Ghisi [74] evaluated the potential for saving drinking water through rainwater harvesting in Joinville, southern Brazil. Physical and demographic characteristics of the houses were obtained from the city hall, allowing the simulation of 33,720 scenarios. The average potential for drinking water savings was 40.8% when used for flushing toilets and washing clothes.

Leong et al. [75] evaluated the potential for saving water from the central supply in Selangor, Malaysia, through rainwater harvesting systems. The rainfall availability of the locality studied could provide up to 91.8% of the water volume required for non-potable water uses in households. Belmeziti et al. [76] also evaluated the potential for drinking water savings through rainwater harvesting for Colombes in the Paris region. The potential obtained was 10% at the urban scale, with residential buildings representing 64% of this figure. This study considered the generalised application of rainwater harvesting systems throughout the city and the existing buildings' particularities.

Li et al. [77] analysed the water demand profile in Irish households, finding that non-potable uses represent between 30% and 90% of total water consumption. Rainwater harvesting systems could supply these uses. However, the authors pointed out that the cost involved in implementing such a technique may discourage users from adopting it.

On the other hand, a wide climatic diversity can be observed in Turkey, ranging from temperate and humid climates to hot and arid situations. In these two climates, Şahin and Manioğlu [78] evaluated the amount of rainwater collected and the potential for drinking water savings from using rainwater. In a more humid climate, an average savings potential of 15.5% was observed; in a drier climate, the average potential was 6.0%.

As an overall conclusion of the studies assessed, non-potable uses range highly as typologies have many differences. Even within one specific sector, there is a wide range of end-uses depending on the characteristics of the building, such as the presence of gardens, number of users, size of the building and economic standards, among other parameters. For each typology, a thorough comprehension must be acquired by, for example, further assessing a specific review. The papers of Marinoski et al. [79] and Mazzoni et al. [80] are examples of assessments on the topic.

Most of the articles aimed to verify the potential for saving drinking water, considering using rainwater for non-potable purposes. This is one of the most appropriate uses of rainwater since water treatment is straightforward. On the other hand, rainwater harvesting may be considered for potable purposes in places with water scarcity, requiring more advanced treatments to make the water suitable for drinking, as reported by Yan et al. [54]. In their study, Yan et al. [54] considered using rainwater harvesting for potable purposes to supplement the centralised supply of potable water and help alleviate water security issues.

The consideration of potable water treatment may be an overlooked item highlighted by the studies assessed. As these studies considered potable water savings as one benefit, they addressed potable water as a flow in LCA. This flow may vary widely per place and potable water supply plant. Thus, there is significant uncertainty about this benefit, and the characterisation of the comparison may be conducted using a broader approach in further studies. Potable water treatment in case of storm events and climatic stress may increase the environmental burdens per cubic meter of potable water. All these discussions arise and may be further studied using LCA.

3.3.4. Synergy with Urban Sustainable Drainage Systems

Rainwater harvesting systems offer various additional benefits. These include reduced energy consumption linked to the treatment and distribution of drinking water, reduced greenhouse gas emissions, decentralisation of water supply and mitigation of flood flows in heavy rainfall events [7]. But, in most cases, these systems are designed in isolation rather than incorporated as part of a broader urban drainage strategy [81].

One of the features of rainwater harvesting that interests urban designers and managers includes the possibility of a synergy of rainwater harvesting with drainage systems and local pollution treatment. Deitch and Feirer [82] examined the hydrological effects of rainwater retention in the Perdido River basin, Florida, USA, which is frequently affected by flooding. Two distinct scenarios were evaluated. In the first scenario, runoff reduction reached 10% in only a few areas of the studied region. In the second scenario, rainwater storage allowed a reduction of over 20% of runoff in most sectors of the study area.

Sustainable urban drainage systems (SuDS) are effective for urban flood mitigation. According to Campisano et al. [7], rainwater harvesting systems can be considered part of this broad classification. If applied extensively, these systems can reduce urbanisation's impacts on drainage systems and mitigate flood risks, especially in small or medium precipitation events [83,84].

In this context, the LCA of rainwater harvesting may use SuDS as a possible consideration for augmenting the benefits. This extends the boundaries by optimising the urban context, as stated in Section 3.3.1. Also, it may augment other areas not considered by LCA studies, such as amenities, safety and other benefits. If possible, synergies should always be targeted, and the context applies to rainwater harvesting and other SuDS.

3.3.5. Reducing Runoff and Drainage

In densely urbanised areas, the extensive implementation of rainwater harvesting systems can significantly reduce the volume and peak flows of urban runoff [85–87]. The attenuation of urban runoff helps to increase the life of drainage systems and contributes to reducing urban flood risks [67].

Campisano et al. [88] evaluated rainwater harvesting systems as a source runoff control measure at the household scale. The study carried out in the Italian region of Sicily showed that a significant reduction in peak flows (30–65% in at least 50% of the events) can be achieved through rainwater harvesting, depending on the volume of the reservoir used and the water demand patterns in the building considered.

Steffen et al. [89] also evaluated the performance of rainwater harvesting systems to reduce peak flows, this time in the North American context. The system's performance in this aspect was related to the size of the reservoir. According to the authors, the reduction in peak flows can reach up to 20% in semi-arid regions, with lower performances in locations with higher precipitation volumes. The research results indicate that the use of rainwater in buildings can be considered an effective measure to control urban runoff, as well as an alternative water source.

Custódio and Ghisi [90] evaluated the influence of rainwater use on residential runoff in the Cachoeira River basin in Joinville, southern Brazil. Two scenarios were analysed. In the first scenario, rainwater use was not considered, and in the second scenario, rainwater use was considered in all houses and buildings. The potential reduction in surface runoff varied from 2.7% to 14.3% in the sub-basins studied, with the most significant reduction occurring in the sub-basin where there were more single-family buildings than multi-storey ones.

Therefore, it can be observed that rainwater harvesting systems when used on an urban scale, i.e., when installed on a large scale, can reduce surface runoff, according to some studies presented. This reduction in runoff reduces the pressure on existing drainage facilities, reducing urban flooding. This is one of the advantages that should be addressed in studies. This benefit was only sometimes pointed out in the studies assessed when studying the feasibility or environmental burdens of implementing a rainwater harvesting system. In addition to the benefits presented above, new methods have recently been applied to identify more subjective gains promoted by rainwater harvesting systems.

3.4. Economic Feasibility of Rainwater Harvesting Systems

The economic viability of rainwater harvesting systems is crucial for the broader dissemination of such systems. The costs of rainwater harvesting systems can be characterised by high initial investment followed by low maintenance costs over their lifetime [91]. The high market value of this type of solution is still a limiting factor for its implementation in many cases, making it advisable to provide incentives from public authorities to encourage the population to adopt it [9].

In rainwater harvesting systems, installation costs may vary widely, mainly depending on the volume of the main reservoir used. The variables that influence this cost are the catchment area, availability of rainfall in the region and water demand.

Liang and Van Dijk [92] verified the economic and financial viability of rainwater harvesting for irrigation in rural areas of Beijing, China. Six hundred rainwater harvesting systems built since 2006 were analysed, employing a cost-benefit analysis. The results show that this type of system is economically feasible and brings tangible social benefits from the point of view of public administration but is highly dependent on the amount charged for water from the centralised supply.

Jing et al. [93] analysed the efficiency and economic feasibility of rainwater harvesting systems for non-potable uses in eight cities of four climate zones in China. Multi-storey buildings with 100 inhabitants and a catchment area corresponding to 1000 m^2 were considered in the research as this is the most common typology in these cities. Three scenarios of rainwater use were considered. The results indicate higher reliability indices and potential drinking water savings for systems with higher storage capacities and lower demand located in more humid regions. The economic viability of rainwater harvesting systems was achieved in humid and semi-humid regions for correctly sized systems. However, the cost-benefit ratio obtained in arid regions did not indicate feasibility.

Li et al. [77] found that, in Ireland, the cost of rainwater harvesting systems is relatively high. In this country, the return on investment times varied between seven and twenty years for tank capacities between 1500 and 10,000 L, considering the tariff policy practised at the time of the study by the local utility. For example, Istchuk and Ghisi [94] studied which variables correlated to the feasibility of domestic rainwater harvesting systems in Brazil. The authors found that tank capacities were the second most crucial design variable, in which the number of inhabitants and rainwater consumption came first. This matches the study of Li et al. [77], where the tank capacity was an important variable in the overall feasibility of the systems. Istchuk and Ghisi [94] also assessed the importance of rainfall distribution in the feasibility indicators; the authors found that places with low seasonality indexes have a higher probability of obtaining feasibility.

These advantages become significant only after the comprehensive application of rainwater harvesting systems on an urban scale [81,85]. To achieve this, their implementation must be economically feasible for the user. Residential rainwater harvesting systems are known to have high installation costs and long payback times [19,91]. This reality discourages potential investors from using rainwater. Therefore, the role of local governments is essential and, considering the full benefits of these systems, they should provide incentives or subsidies for their application [9], as has been occurring in several parts of the world [95]. Economic gains from the decentralisation of water distribution in cities can be significant [71] and could be one of the sources of capital to encourage this practice.

3.5. Integration between LCA and LCCA

Leong et al. [40] conducted an LCA and life cycle cost analysis (LCCA) of different types of water supply for commercial and residential buildings in Malaysia. Different scenarios involving conventional water supply, the use of rainwater harvesting, greywater reuse and a hybrid system with rainwater and greywater were analysed. Other works have also been evaluated with more focus on the LCCA of rainwater harvesting systems to understand the system's applicability.

Within this context, one can see the interest in obtaining comparability for the analyses since trade-offs exist between economic and environmental evaluation. That said, within the articles evaluated, 34 articles compared both analyses (LCA and LCCA), with a large part performed separately. That is, there is the analysis on one spectrum, LCA, determining impact profiles, and on the other, LCCA, determining the cost in the life cycle, but without obtaining a balance of both results in favour of a joint analysis.

Ghimire and Johnson [96] conducted a multicriteria analysis of green infrastructure, which included rainwater harvesting. The authors considered economic parameters such as the investment's cost and return period and environmental parameters as integration factors in the analysis. The mathematical technique used by the authors was data envelopment analysis, which performs weighting averages with parameters for the economic and environmental characteristics.

Another mathematical possibility for weighting the results is using the analytical hierarchic process (AHP). Godskesen et al. [97] conducted a study evaluating techniques for increasing the water supply in Copenhagen. In this work, the authors indicated specific evaluations for LCA and LCCA and the use of AHP to compare the results and evaluate the techniques to be indicated for decision-makers. When the highest weights were indicated for sustainability measures, rainwater harvesting was the system that obtained the best performance and consequent indication. When the weights were preferred to the economic and social parameters, groundwater extraction was the best technique for the city. This is an example of applying the AHP mathematical technique, with the respective discussions of weights and parameters to be considered.

Several other mathematical and statistical models can and should be evaluated as measures to compare the mentioned indexes: economic, environmental and social. However, besides the mathematical model used, it is recommended to use a panel of experts in each area and discuss uncertainties and analysis trends. For any comparison of objects of distinct natures, such as the triple bottom line example, a value judgment is made that must always be scientifically supported through the description and detailed considerations. These examples are of worldwide interest since they help decision-makers with more direct answers by incorporating multi-criteria analyses into single indicators that facilitate better visualisation and communication with society.

4. Conclusions

This research aimed to elucidate the current state of rainwater harvesting systems, specifically through the application of life cycle assessment (LCA). Employing the PRISMA protocol, we conducted an integrative literature review that, after applying specific inclusion and exclusion criteria, yielded 76 documents for comprehensive evaluation. A bibliometric analysis underscored key publication trends, revealing the geographical distribution of research activity, the progress made over the last five years and the principal authors contributing to the field.

While the literature showed a surge in research focused primarily on residential typologies, our study revealed an underrepresentation of other building typologies, indicating a clear opportunity for future investigation. Furthermore, the LCIA methods and assessment types used in LCA studies often introduced bias or oversimplification. This resulted in excluding substantial benefits or overlooking local conditions, suggesting that researchers should strive for a more comprehensive and contextual approach.

Our study revealed the importance of broadening the scope of the assessment to include more life cycle phases and multiple LCIA methods. The quality improvement of harvested rainwater, reduced energy consumption by utilities and diminished need for maintenance of water supply systems emerged as underemphasised benefits of rainwater harvesting systems. Moreover, the potential of rainwater harvesting systems to attenuate urban runoff, thereby extending the lifespan of drainage systems and mitigating urban flooding, needed to be more adequately represented in current LCA studies.

Concerning the economic feasibility of rainwater harvesting systems, it became evident that more comprehensive mathematical and statistical models should be used within life cycle cost assessment (LCCA) for a balanced evaluation of economic, environmental and social aspects. The studies analysed in our review offered detailed insights into the challenges and specifics of conducting LCA studies on rainwater harvesting, providing a robust foundation for directing future research.

In conclusion, this study underscores the necessity for a more holistic approach to the LCA of rainwater harvesting systems. Although existing research has made considerable strides, the analysis reveals a tendency towards narrow perspectives that often overlook the multifaceted benefits of these systems. By addressing these identified gaps and incorporating a broader range of variables, future studies can more accurately validate the sustainability potential of rainwater harvesting systems. This shift towards comprehensive and context-specific analyses is crucial in leveraging the full potential of rainwater harvesting systems for sustainable water management.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su151612133/s1, Table S1: Selected articles (continues).

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