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Integrated systems for rainwater harvesting and greywater reuse: a systematic review of urban water management strategies

A. M. Rodrigues [a,*], K. T. M. Formiga[a] and J. Milograna[b]

[a] Environmental Science Program, Federal University of Goiás, Esperança Avenue, Goiânia 74690-900, Brazil
[b] Sustainable Process Technology Program, Federal Institute of Education, Science and Technology of Goiás, Goiânia 74055-110, Brazil
*Corresponding author. E-mail: andriane.melo@discente.ufg.br

AMR, 0000-0003-4516-7800

ABSTRACT

Combined, decentralized systems for rainwater harvesting and greywater reuse may enhance the water security of urban areas by reducing dependence on the main water supply, in particular during critical periods, such as the dry season. They can also minimize the risk of flooding during the rainy season. The present study assesses the accumulated knowledge of these combined systems based on a systematic review of the literature restricted to academic sources. The review revealed knowledge gaps that must be resolved to better assess the optimum combination of rainwater and greywater recovery, how this affects the need for the treatment of the recovered water, its final quality, potential options for reuse, water economy, and the environmental and economic performance of the system. Further empirical studies are required to determine the most adequate design configuration for these systems, considering their multiple objectives, technological perspectives, and in particular, their potential for improving environmental shortcomings. There is a clear need for widespread use of low-impact technologies to ensure the most effective possible results. Water recovery systems will become increasingly important as a means of tackling the challenges of water supplies in the urban landscape, which are being exacerbated by climate change.

Key words: greywater reuse, minimization of wastewater, stormwater management, sustainable urban water systems, rainwater capture, water conservation

HIGHLIGHTS

- Combined systems of rain and greywater recycling may enhance urban water security.
- In combined systems, greywater reuse compensates for periods of low rainfall.
- The modular expansion of systems is a potential solution for climate change.
- Recycled water may enhance irrigation by providing nutrients, promoting food security.
- Nature-based solutions will be essential for sustainable development.

1. INTRODUCTION

The sixth report of the IPCC (2022) concluded that critical environmental scenarios are expected by the year 2050, with the availability of water resources in watersheds, including urban areas, being impacted globally by anywhere from 42 to 79% This will further exacerbate the vulnerability of urban water services during extreme weather conditions, in particular, in underdeveloped countries.

The diversification of water sources in urban areas may be one alternative solution for these problems. Rainwater harvesting (RWH) and greywater reuse (GWR) systems are currently the two types of decentralized system that are being investigated most widely throughout the world (Stang *et al.* 2021). These systems can either operate independently or be connected to a central water supply service system, helping to minimize water stress, improve sustainability, and contribute to the resilience of the central system (Maskwa *et al.* 2021).

Decentralized RWH and GWR systems can provide a fundamentally important contribution to urban water networks, including the potable, pluvial, and sewage systems. In particular, the implementation of both RWH and GWR systems can reduce the demand for potable water. In addition, RWH systems can contribute to a reduction in the volume and intensity

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of rainwater runoff (Zhang *et al.* 2009, 2010; Zanni *et al.* 2019), while GWR systems reduce the amount of sewage channeled to treatment plants by collecting greywater (domestic wastewater that does not contain significant amounts of feces or other contaminants) for processing and use in specific applications (Penn *et al.* 2013; López Zavala *et al.* 2016; Marinoski & Ghisi 2019; Zhang *et al.* 2021).

An RWH system captures rainwater from impermeable roofs and other surfaces, and stores this water for specific uses. While harvested rainwater can reduce the demand for water supplies, rainfall is irregular and the size of the roofs and storage reservoirs will limit the potential for savings of potable water (Ghisi & Oliveira 2007; GhaffarianHoseini *et al.* 2016; Leong *et al.* 2017). By contrast, a GWR system collects and processes the wastewater produced by a household or building, which tends to be produced at a relatively constant rate throughout the year (Ghisi & Ferreira 2007; Leong *et al.* 2018b). Greywater is wastewater produced by bathing and washing, rather than toilets, and thus has a reduced load of organic matter, including nutrients and pathogens (Pidou *et al.* 2007).

The combination of RWH and GWR systems is considered to be a highly efficient and cost-effective strategy for reducing the consumption of potable water (Leong *et al.* 2018a; Oviedo-Ocaña *et al.* 2018; Wanjiru & Xia 2018; Zhang *et al.* 2021; Gómez-Monsalve *et al.* 2022). The combination of systems permits the continuous generation of non-potable water, by alternating between the increased capture of rainwater during rainy periods and the reuse of greywater during drier periods (Leong *et al.* 2018b).

While research on the combination of RWH and GWR systems has progressed considerably in recent years, the available data have yet to be reviewed systematically for the identification of recent trends and the consolidation of the information on the integration of these systems. This limits the understanding of the benefits of this innovative approach, and up to a point, restricts the more widespread implementation of this technology.

In this context, the present study reviewed the available literature to identify current trends in the combination of RWH and GWR systems, methods used and the criteria adopted for the design of projects, as well as the existence of potential knowledge gaps in this field of research. Overall, the study aims to compile the principal practical applications of the approach and the perspectives for research on the combination of these systems.

2. METHODS

The first step in the present study was a systematic review of the published literature on combined RWH and GWR systems. A systematic review provides a reliable approach for the collection and processing of data, given that it is a rigorous method that minimizes the risk of bias, while also identifying research or knowledge gaps that should be addressed in future studies (Rubak *et al.* 2005; Petticrew & Roberts 2008). Up to now, there has never been a systematic review of the published data on the design, characteristics or analysis of the performance of combined RWH and GWR systems. This means that the present study can provide important insights for the understanding of the potential of this approach, and in particular, the identification of opportunities for future research and development.

This review was based on the Cochrane approach, supported by a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist (Moher *et al.* 2015). The StArt (State of the Art through Systematic Review) software, produced by the Software Research Laboratory at the Federal University of São Carlos (LaPES-UFSCar), was also used as an auxiliary search tool.

The first step in the application of this approach is the definition of the questions to be examined. The present study evaluated the following questions:

(i) What are the principal design characteristics of the RWH and GWR systems?
(ii) What are the principal research topics on RWH and GWR systems covered in the published literature?
(iii) What are the current limitations of RWH and GWR systems, as shown in the literature, and how can they be overcome in future research?

The literature searches focused on three databases – SCOPUS, the Web of Science, and Engineering Village (Compendex), and the first step in the process was to define the keywords most relevant to the objectives of the present study. A preliminary analysis of the literature revealed that 'rainwater harvesting' was the term used most commonly to describe RWH systems, while 'greywater reuse' or 'greywater recycling' were used most frequently to designate GWR systems. Given this, the first search string included keywords 'rainwater harvesting', 'rainwater', and 'rain water', while the second string was based on the 'greywater reuse', 'greywater recycling', 'greywater', and 'gray water'. The terms 'water conservation', 'water reuse', 'water recycling', 'water savings', and 'water supply' were included as a third search string, given that they are frequently used in the literature on the topics targeted in the present study.

No restrictions were applied to the search, in terms of the study year, region or type of document, although only publications written in English were considered. Duplicate publications found in different databases were not included in the analyses (i.e., one entry per publication). Initial screening was based on the content of the title and abstract, with subsequent screening focusing on the full text. If the reading of the full text found that the paper did not align with the objectives of the study or did not satisfy the inclusion criteria, the paper was excluded from the analyses.

There were two inclusion criteria, which were applied at each stage of the process: (i) studies that refer to the design, implementation or evaluation of RWH and GWR systems and (ii) studies that refer to combined RWH-GWR systems. There were five exclusion criteria, which were applied to remove inappropriate papers from the analyses: (i) studies that are not related directly to the research topic; (ii) papers that do not present pertinent information on the implementation or evaluation of combined RWH-GWR systems; (iii) papers lacking the full text; (iv) summaries, brief reports or posters, and (v) studies that refer only to one of the systems (RWH or GWR). The data extracted from each paper were fed into an Excel spreadsheet for processing and analysis of biometric parameters and content.

3. RESULTS AND DISCUSSION

3.1. Bibliometric analysis

A total of 613 papers were identified in the literature search based on the initial search criteria. Almost half of these publications were eliminated in the first screening, however, due to their duplication in the different databases (Figure 1). At the end of the screening, based on the PRISMA analysis of their content, 41 papers were considered to be directly relevant to the objectives of the present study.

The SCOPUS database provided the largest number of candidate publications, with 256 (41.8% of the total, including duplicates), and also contributed most to the final total, with 37 (90.2%) of the 41 papers in the final list (Figure 1). The Web of Science database returned the next largest number of candidate publications (185, 30.1% of the total) and 30 (73.2%) of the papers included in the analyses, while Engineering Village provided 172 (28.0%) candidate publications, and 15 (36.6%) on the final list.

Most of the selected papers ($n = 29$; 70.7%) were duplicated in at least two of the databases (Figure 2), while the others were listed in only one. The SCOPUS database had eight exclusive papers, while Web of Science had three, and Engineering Village, only one exclusive publication.

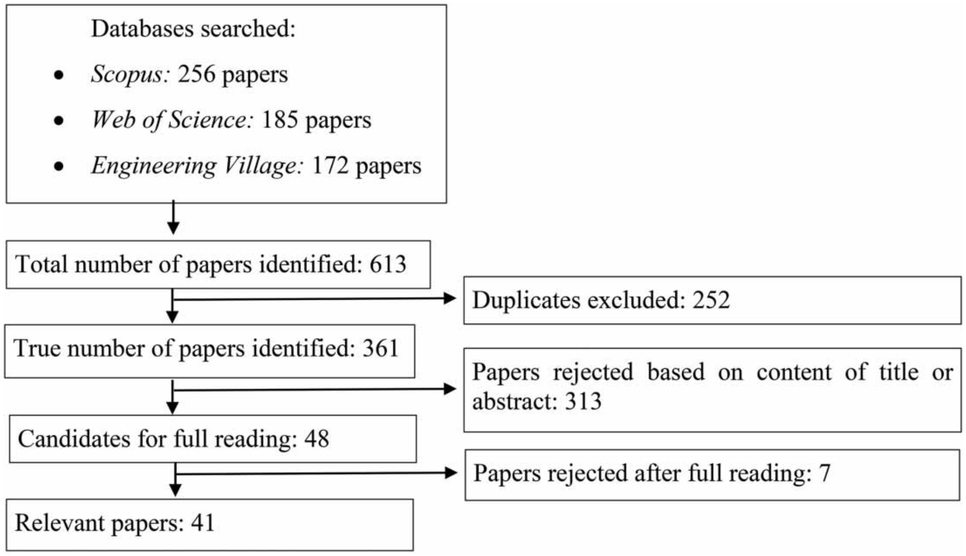

Figure 1 | Flowchart of the literature review process using the PRISMA checklist approach (Moher *et al.* 2015).

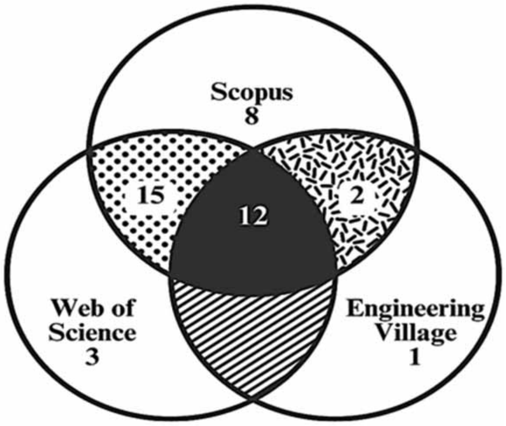

Figure 2 | Venn diagram showing the distribution of the 41 selected papers among the different databases surveyed in the present study.

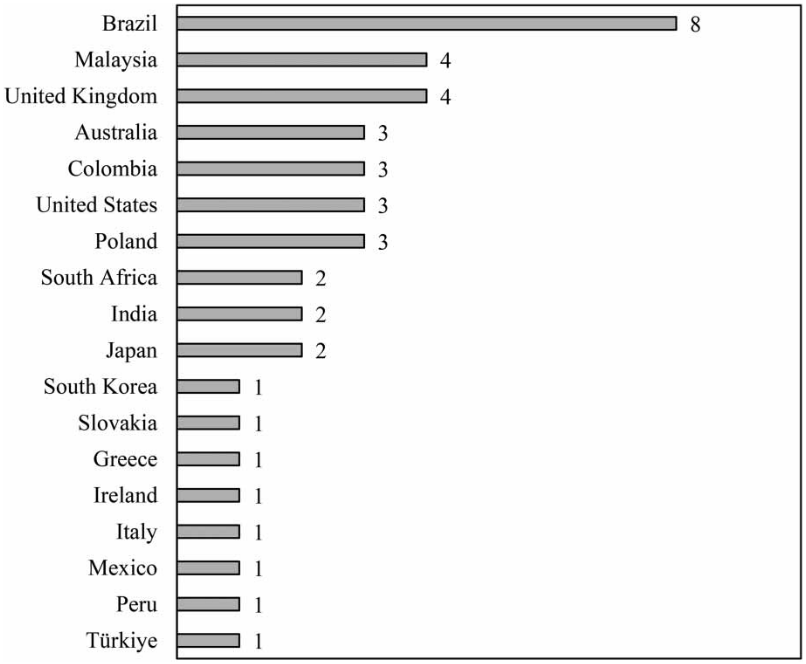

Figure 3 | The number of studies per country, considering the 41 papers analyzed in the present study.

Brazil was the location of the most studies of any country, with eight papers (Figure 3), followed by Malaysia and the United Kingdom, each with four papers, while Australia, Colombia, Poland, and the United States were each the location of three studies. No more than two papers were identified in any of the 11 other countries included here.

Almost half (48.8%) of the papers analyzed in the present study were published in just four journals – the Journal of Cleaner Production, Water Science and Technology, Water, and Resources, Conservation and Recycling (Figure 4), while 13 journals each provided only one paper. None of the papers included in the analyses were published prior to 1999, with the number of studies published per year peaking at six, in 2018 and 2021 (Figure 5). There is a clear tendency for the number of papers published annually to increase over time, except for a marked decline in 2019–2020, which was likely related to the COVID-19 pandemic. The apparent reduction in the number of publications in 2022 is likely related to the fact that the literature search only covered the first half of this year.

The keywords provided in the metadata of the databases were analyzed using StArt, with their relative frequencies being plotted in a word cloud (Figure 6), in which the font size is proportional to the frequency of the word in the 41 papers selected

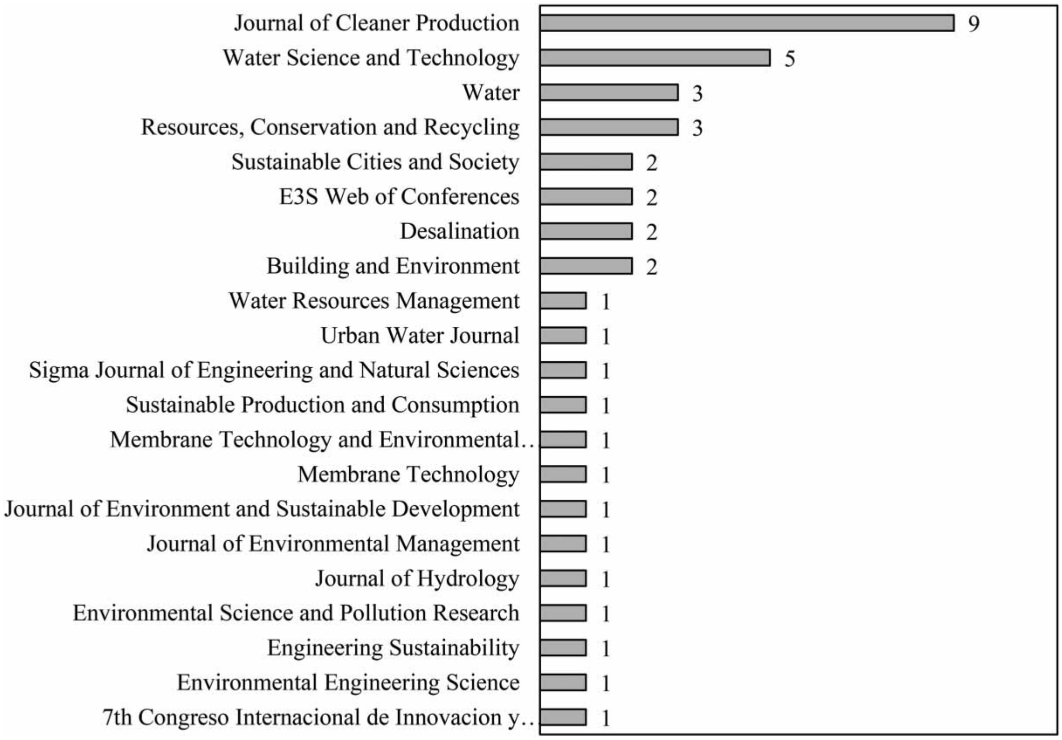

Figure 4 | The number of studies published per journal, considering the 41 papers analyzed in the present study.

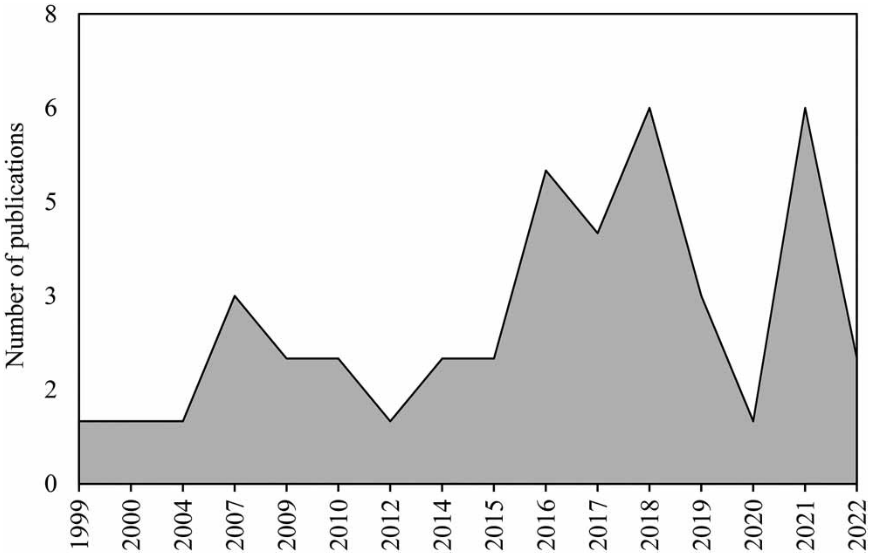

Figure 5 | The number of studies published per year, considering the 41 papers analyzed in the present study.

for analysis. The most frequent keyword was 'water supply', which appeared in 32 (78.0%) papers, followed by 'rain', in 30 (73.2%) papers, and 'wastewater reclamation', which appeared in 24 (58.5%) of the selected papers. Other prominent keywords included 'rainwater', found in 21 (51.2%) papers, 'rainwater harvesting' and 'recycling', both recorded in 13 (31.7%) papers, 'greywater', in 12 (29.3%), 'Brazil', in 11 (26.8%), 'housing', in nine (22.0%), and 'greywater recycling' and 'cost benefit analysis', both recorded in eight (19.5%) of the selected papers.

Figure 6 | Word cloud of the keywords provided by the authors of the 41 papers analyzed in the present study.

3.2. Configurations and limitations of the combined RWH–GWR systems observed in the studies

This section is arranged into two parts. The first part presents and discusses the characteristics and configurations of the combined RWH-GWR systems presented in the studies, and the principal trends found in the literature. The second part addresses the limitations found in the studies that need to be resolved in future research.

3.2.1. Primary configurations and research topics addressed in the studies

The primary configurations of the combined RWH-GWR systems were compiled from the 41 papers selected for analysis in the present study (Supplementary Material, Table S1). Based on the Köppen-Geiger climate classification categories of the study locations (Supplementary Material, Table S1), precipitation levels do not vary significantly over the course of the year at most sites, except Cranbrook, Australia (semi-arid), Athens, Greece (dry summers), Nagpur, India (drier summers), Ankara, Turkey (dry summers), and Cusco, Peru (dry winters).

An extensive dry season can impact the performance of a RWH system by reducing water savings and leaving the storage tanks empty for long periods, which can greatly increase the lag on the payback for the initial investment. In this scenario, it is essential to combine RWH with GWR to avoid stagnation during the dry season or other periods of water scarcity.

A shortage of water supplies affects not only the city itself, but also economic activities such as agriculture and industry, resulting in increased production costs of many goods (Hertel & Liu 2019; IPCC 2022). Low levels in reservoirs also affect the production and costs of hydroelectric power (Hertel & Liu 2019).

In all cases, the RWH and GWR systems were deployed in either households or commercial buildings, including offices and educational facilities (Supplementary Material, Table S1), while none of the studies focused on industrial installations or agricultural infrastructure. Some activities may demand large amounts of water, which exceed the production capacity of the RWH and GWR systems. In this context, the improvement of water management in urban areas will depend on the large-scale development of decentralized systems to relieve the demand for water from mains supplies and avoid the risk of overloading the central system (Sapkota *et al.* 2015).

The characteristics of the RWH and GWR systems described in the papers analyzed in the present study, including the collection, treatment, storage, and final use of the recycled water, are discussed in more detail in the following.

3.2.1.1. Water collection. In the case of commercial buildings (schools, offices, and universities), greywater is collected primarily from sinks, and at some sites, in showers, but never from washing machines or laundries (Supplementary Material, Table S1). At residential sites, regardless of whether the study focused on a single home or a group of houses, grey water was collected most frequently from showers/bathtubs, sinks, and washing machines. Greywater was collected from kitchen sinks in only three cases (Zhang *et al.* 2010; Aybuğa & Işildar 2017; Chen *et al.* 2021). Greywater from kitchen sinks and dishwashers tends to contain more organic contaminants, and is commonly referred to as 'dark grey water' (Leong *et al.* 2017).

Rainwater was harvested exclusively from roofs, with areas ranging from 20 to 100,000 m^2 (Supplementary Material, Table S1), except in the study of López Zavala *et al.* (2016), where water was collected from a catchment area that included roofs, terraces, and parking lots, with a total area of 65,768.75 m^2. It is important to note here that López Zavala *et al.* (2016) used the term 'stormwater', which is distinguished from 'rainwater' (which is collected exclusively from rooftops) due to inclusion of the runoff from all the permeable and impermeable surfaces within the drainage system (Sapkota *et al.* 2015).

3.2.1.2. Water treatment. A number of different treatment methods are available for greywater and rainwater, depending on their intended reuse. The process typically involves the removal of physical, chemical, and biological contaminants to render the water adequate for a specific application. In general physical treatment is a preliminary step prior to chemical or biological processing, or is used as an enhancement phase prior to disinfection. Physical processing helps to eliminate suspended solids, which improves the efficacy of subsequent disinfection treatments (Leong *et al.* 2017).

The physical treatments for rainwater found in the papers analyzed here were first flush, ultrafiltration, reverse osmosis, fiber media and metal membrane filters, self-cleaning leaf filters, sedimentation tanks, grease and oil traps (in stormwater drainage systems), and coarse, multimedia, deep bed, granular activated carbon, and sand filters. In the case of greywater, most of these treatments were used, except first flush and self-cleaning and deep bed filters, with the further addition of slow sand and tile fragment filters, as well as aeration systems (with compressors).

In the case of biological treatments, only artificial wetlands were reported for the treatment of rainwater (Smith *et al.* 2000; Birks *et al.* 2004), whereas a number of different treatments were used for greywater, including wetlands, aerated and crushed tire biofilters, membrane bioreactors, natural soil treatment systems, GW bioMembranes (DeHoust GWM), as well as other, unspecified processes. While more effective for the removal of organic material, procedures that involve aeration or hydraulic pressure can demand large, relatively costly amounts of energy and water for backwashing (Castleton *et al.* 2014). In this case, it is important to assess not only the efficiency of a procedure for the removal of contaminants, but also its environmental and financial feasibility, when selecting treatments.

The most common type of chemical treatment of both rainwater and greywater was chemical disinfection using chlorine (Cl_2), followed by the use of ozone (O_3). Physical disinfection by ultraviolet (UV) radiation was also applied in some studies, although there were no reports of chemical coagulation. It is important to note that neither the O_3 nor the UV techniques leave chemical residues in the water, which can be problematic for storage due to the potential growth of microorganisms. Only two studies referred to the use of residual chlorine following disinfection by UV (Zanni *et al.* 2019) and O_3 (Chen *et al.* 2021).

3.2.1.3. Water storage. The principal model used for the sizing of the storage tanks of the combined RWH-GWR systems was the mass balance model (Supplementary Material, Table S2), which is based on estimates of inflow and outflow rates, together with the stored water levels and the final volume of the tank. In addition, algorithmic models such as the 'yield before spillage' (YBS) and 'yield after spillage' (YAS) approaches (Jenkins *et al.* 1978) and software, such as Netuno, EPA SWMM, RainTANK, and AQUACYCLE, were used to estimate adequate tank size over different time scales, primarily at a daily scale, but also using weekly and historical parameters.

The modeling of RWH systems has considered data such as precipitation, the runoff coefficient (ranging from 0.8 to 0.9), catchment area, and the demand for the recovered water, whereas in GWR modeling, data on the greywater discharge and demand for specific end uses are the most typical parameters. Most of the papers selected for analysis estimated storage tank volumes separately for the RWH and GWR systems, except in some specific cases (Castleton *et al.* 2014; López Zavala *et al.* 2016; Leong *et al.* 2018a, 2018b).

Only two of the papers in the final dataset optimized tank size to meet the demand for water. Stang *et al.* (2021) used the Brent method to maximize energy savings in each household, whereas Zhang *et al.* (2021) modeled hourly data from a 5-year rainfall series with a mixed integer-linear programming model to optimize both tank size and the operation of the system.

Total water demand ranged from 61 to 234 l per capita per day (Supplementary Material, Table S2). Some studies estimated total water consumption from data provided by residents, who measured water consumption by volumetrically at each hydraulic fixture (Ghisi & Ferreira 2007; Ghisi & Mengotti de Oliveira 2007; Vieira & Ghisi 2016; Marinoski *et al.* 2018; Marinoski & Ghisi 2019; Coutinho Rosa & Ghisi 2020). These authors provided an estimate of mean daily water consumption of 147.4 l per person. On average in residential systems, showers account for 29% of total water consumption, while toilet flushes consume 23%, kitchen sinks, 18%, clothes washing, 19%, and washbasins, 6%, with the remaining 5% being dedicated to other uses. The collection of water from showers, washbasins, and washing machines by GWR systems thus represents 54% of the wastewater generated by a household, while the demand for reuse in toilet flushes and clothes washing accounts for approximately 42% of the total consumption.

A number of studies (Dixon *et al.* 1999; Birks *et al.* 2004; Ryan *et al.* 2009; Leong *et al.* 2017; Markovič 2018; Wanjiru & Xia 2018; Chen *et al.* 2022, 2021) indicated that, as shown by Liu *et al.* (2010), the size of a raw greywater storage tank should be adjusted to ensure that storage time does not normally exceed 24 h. This is because malodorous compounds and microorganisms tend to increase over time in greywater stored for periods longer than 24 h, in particular, microorganisms, which will increase exponentially.

Chen *et al.* (2021) reported that both raw and treated greywater were discharged into the sewage system after 24 h in a study in Japan, following the recommendation of Liu *et al.* (2010). However, this disposal was deemed unnecessary due to the use of an advanced treatment system, which included a membrane bioreactor, aeration system, and ozone disinfection, with extra levels of residual chlorine. It is interesting to note here that discharge fees are charged for effluent disposal in Japan. This indicates the need to review the 24-h storage limit, given that it may generate unnecessary waste and increase the operating costs of a GWR system, which may compromise critically both its economic and environmental benefits.

3.2.1.4. The end use of the recovered water. The end use of the recovered water, whether rainwater, greywater or a mixture of the two, was identified in all the 41 papers analyzed in the present study (Supplementary Material, Table S1). Toilet flushing was the principal destination for recovered water, especially greywater. Reuse in urinal flushes was limited to commercial buildings. Clothes washing was the most widely accepted application for rainwater, while the irrigation of gardens was the second most frequent use for all three types of recovered water. External uses, including car and pet washing, and floor cleaning, were the third most common reuse option for rainwater. While all three types of water were appropriate for floor cleaning, only rainwater was used for fire control, cooling towers, and dishwashing.

It is interesting to note that none of the studies cited end uses that require potable water, which is likely due to the more straightforward monitoring and lower initial investment costs of RWH and GWR systems, which recover water for non-potable purposes. This reflects the need for frequent analyses to ensure safe consumption and, in particular, the application of public health protocols and water potability standards.

3.2.1.5. Research topics. The final dataset includes papers that focused on a number of different aspects of water management (Figure 7). More than half (25) of the papers analyzed the potential of the systems for saving water, while 13 analyzed the costs, nine evaluated means to reduce water wastage, eight discussed water quality, six discussed life cycle costs (LCC), four were based on life cycle assessment (LCA), while three studies each examined water treatment for reuse and the social acceptance of water management practices.

Over the past 23 years, saving water and cost analyses have been the topics investigated most extensively, while LCC and LCA are relatively new topics, with the first studies appearing in 2015 (LCC) and 2019 (LCA). By contrast, the least popular topics were water treatment, stormwater runoff, and the social acceptance of water management practices.

Studies of the savings of drinking water provided by RWH and GWR systems have been conducted for both the individual and combined systems, although the data show that the hybrid systems provide the greatest water savings (Dixon *et al.* 1999; Ghisi & Ferreira 2007; Ghisi & Oliveira 2007; Li *et al.* 2010; Ghisi *et al.* 2014; López Zavala *et al.* 2016). However, Castleton *et al.* (2014) obtained atypical results in terms of water savings because the cleaning of the rapid filter used to treat the water from both RWH and GWR systems consumed more recovered water than the systems were able to produce. This meant that the process had to be supplemented with potable water from the mains.

When considering the reduction of wastewater by GWR, the concentration of contaminants in brown wastewater is a cause for concern, given that it can have negative impacts on the system, including blockages, odors, and corrosion (Marleni *et al.* 2012; Sapkota *et al.* 2015). However, Guven & Tanik (2020) have suggested that the concentrated content of this water favors anaerobic treatment, with the potential for the generation of electricity through the recovery of methane gas. These findings further emphasize the need for a more systematic evaluation of the impacts of GWR on the collection and treatment of conventional wastewater.

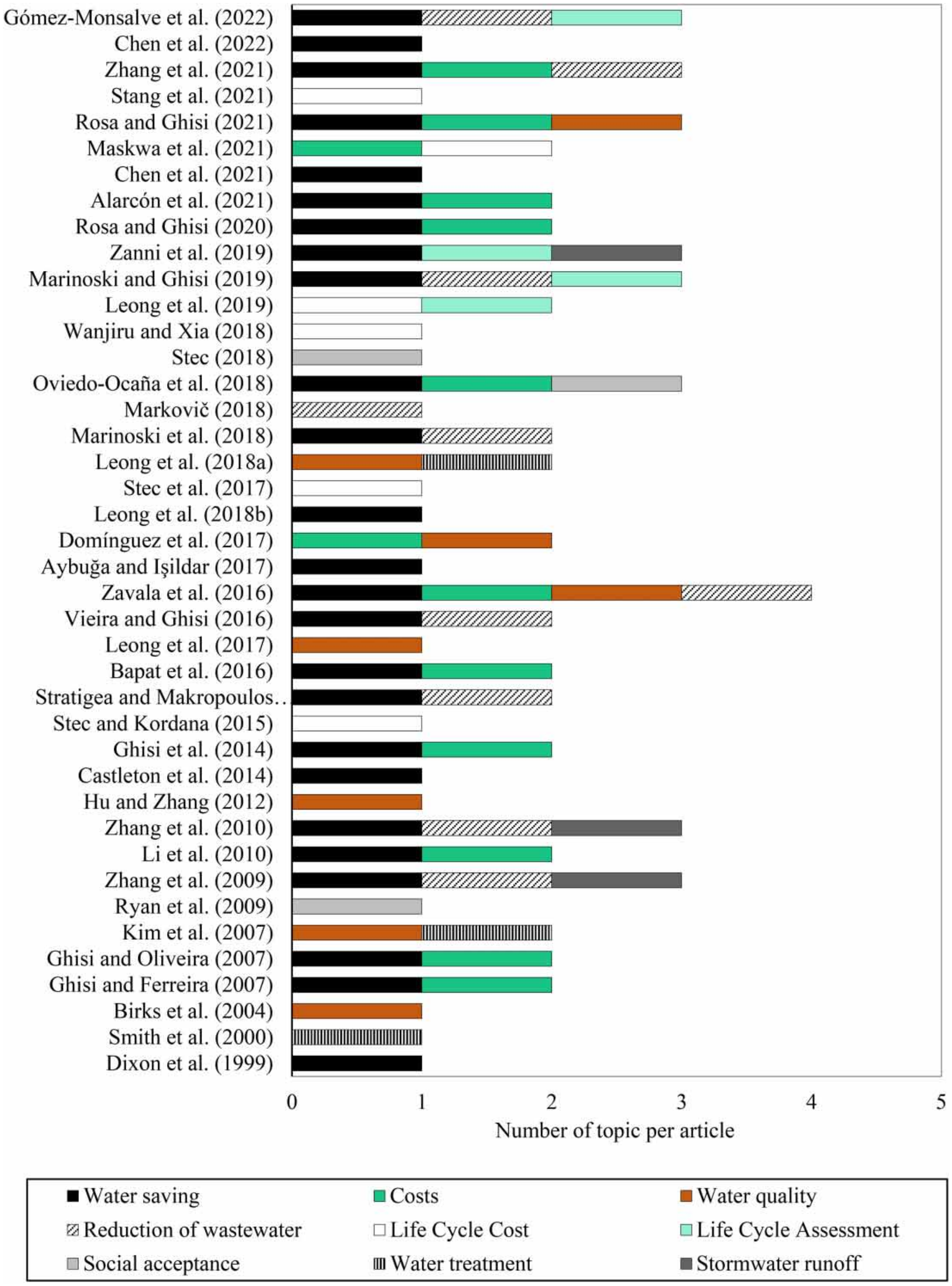

Figure 7 | Principal research topics considered in the evaluation of RWH and GWR systems in the 41 papers analyzed in the present study.

The RWH systems can reduce stormwater runoff, which can relieve pressure on the drainage network and reduce the risk of flooding, depending on the number of systems implanted in the watershed (Xu *et al.* 2022). However, few studies have evaluated the potential of RWH for the mitigation of urban flooding, especially at a large scale.

The cost analysis studies focus mainly on the economic potential of combined rainwater and greywater recovery systems, while neglecting the assessment of environmental feasibility. Meanwhile, the LCA and LCC studies have concentrated primarily on construction and operation phases, comparing RWH and GWR systems with the mains water supply. This comparison is relatively redundant, given that the main purpose of using these decentralized systems is precisely to complement the mains water supply, not to replace it.

Overall, these studies have many deficiencies in both their environmental and economic aspects, primarily because current GWR and RWH systems depend on considerable inputs, including high levels of energy consumption, abundant quantities of chemicals, and continuous maintenance (Razman *et al.* 2022). Given this, one research priority is clearly the need to develop more efficient and sustainable systems that minimize environmental impacts and reduce operational costs. In addition, LCA and LCC studies should focus on the entire life cycle of the system, from the extraction of the raw materials to the final disposal of the residues. This would allow for a more accurate evaluation of the environmental and economic performance of the systems, as well as the identification of potential pathways for improvement.

Studies of water quality adopted strict potability standards, even for non-potable uses, which implies that the current standards were not developed specifically for water reuse. In addition, while the treatment technologies used in the reuse studies are similar to those used in the production of potable water, few studies assessed the effectiveness of these technologies. Overall, there is still strong social resistance to the reuse of rainwater and greywater, even after adequate disinfection, which is probably due to the widespread use of potable water for all domestic needs, regardless of whether potability is actually necessary (Ryan *et al.* 2009; Stec 2018).

In this case, the lack of public awareness of the risks of water scarcity and other environmental issues remains a major obstacle throughout much of the world. This is reflected in the scarcity of studies of the social acceptance of RWH and GWR systems, whereas health risks and financial returns are predominant topics. This implies that ensuring effective changes in beliefs and habits is one of, if not the principal obstacle that needs to be overcome to ensure the expansion of decentralized water reuse technologies in urban areas.

3.3. Principal limitations of combined systems and perspectives for future research

First and foremost, it is important to highlight the limited scope of the sources investigated in the present study, given that the literature search was restricted to academic sources. This may not reflect the full extent of the existing knowledge on RWH and GWR systems, given the more practical nature of much of the research. A more comprehensive understanding of the state of the art of these systems would thus need to reach beyond this conventional literature, to sources such as technical reports, government documents, unpublished research, and personal communications with experts and practitioners in the field. This was beyond the scope of the present study, however, and would require a far more extensive and potentially less systematic approach. It should be recognized, therefore, that the current study represents the state of knowledge based on existing traditional literature.

In the specific case of the costs of RWH and GWR systems, for example, a number of the studies cited here examined this specific aspect of the technology, and consistently identified the storage tank as the most expensive component (Oviedo-Ocaña *et al.* 2018; Zhang *et al.* 2021). One potential solution is to combine the storage of the two types of water in a single tank, which reduces both overall investment and operational costs, and avoids having the rainwater tank lie idle during periods when rainfall is scarce or inexistent, an increasingly common scenario in many regions around the world (Toreti *et al.* 2022).

In most cases, especially in the case of RWH systems, the tank design considered only costs and the potential savings (Ghisi & Ferreira 2007; Ghisi & Mengotti de Oliveira 2007; Ghisi *et al.* 2014; Vieira & Ghisi 2016). Clearly, this perspective should be revised to consider objectives such as the minimization of the volumes of rainfall runoff, which will be important to reduce the risk of floods in urban areas.

It will also be essential to consider the future impacts of climate change on combined system projects, even though this may result in increased initial costs, due to the need to increase tank volume and the harvesting area. One potential solution for this problem is the modular expansion of projects proposed by Loiola *et al.* (2019), which permits the spreading of construction costs over time, while improving the capacity of the system to adapt to extreme climate scenarios, such as droughts and floods.

In the context of water scarcity, it is important to note that agriculture alone accounts for 72% of the global consumption of freshwater, whereas urban consumption accounts for only 12% of the total, and industrial applications, 16% (FAO 2021). It would thus be essential to design combined RWH-GWR systems considering not only water security, but also food security, including irrigation for small-scale and sustainable food production, especially in urban areas. The use of rainwater and greywater for irrigation can reduce the need for fertilizers (Chojnacka *et al.* 2020), while pathogenic microorganisms can be eliminated by disinfection.

Liu *et al.* (2010) alerted that the quality of greywater may degrade after being stored for more than 24 h. Given this, it will be necessary to investigate more systematically both the environmental conditions that favor the growth of microorganisms and the most effective disinfection processes, in order to avoid wasting recovered greywater and ensure the financial viability of GWR systems.

The advanced treatment technologies commonly used in RWH and GWR projects, such as MBR, BFA, filtering and metallic membranes, despite being highly effective for the removal of contaminants, have a short lifespan and high energy consumption, which can reduce both the environmental and economic performance of the systems. It is thus necessary to design systems that reduce energy consumption, inputs, and the need for module replacement, principally by using technologies that rely on ecosystem services, i.e., nature-based solutions (NbSs), such as artificial wetlands and biofilters. A number of studies have shown that these technologies are capable of removing all types of contaminant, ranging from suspended solids to emerging micro-pollutants, such as pesticides and antibiotics, from artificial wetlands (Datta *et al.* 2013; Vymazal & Březinová 2015).

The parameters evaluated most frequently in the papers analyzed in the present study included potable water savings and costs, as well as LCA and LCC assessments. However, any evaluation of the environmental performance and economic viability of combined systems will be redundant if these systems are not rethought to become more sustainable. In particular, it will be necessary to reconcile water treatment technologies with renewable sources of electricity, such as solar panels and anaerobic biodigesters.

One important aspect that has been widely overlooked is social acceptance, which will be essential to ensure scientific dissemination and the creation of a platform for dialogue among researchers, policy makers, companies, and communities. Despite the importance of the economic and hygiene aspects, it will be essential to approach social acceptance in an innovative and comprehensive manner, considering all the different facets and challenges of this fundamental problem.

It will also be important to evaluate systematically the implications of the large-scale introduction of RWH and GWR systems in urban watersheds. In particular, it will be important to determine how to evaluate the effects of these systems on the hydrological cycle, in particular in the urban context. While some studies have employed smart water meters (Castleton *et al.* 2014; Vieira & Ghisi 2016; Markovič 2018), real-time measurement is still incipient in this field of research. The more accurate measurement of water input and output in these systems will provide more reliable data for realistic hydrological modeling.

These combined systems should also be designed bearing the objectives of the United Nations' Sustainable Development Goals (SDGs) of the 2030 Agenda in mind. These goals include water savings, the reduction of urban runoff and carbon emissions, nutrient cycling, food production, and energy savings. Given this, it is important to have precise data on the different variables to best evaluate the benefits provided by these systems and their implications for urban resilience.

Although there have been important advances in the research on RWH and GWR systems, the general lack of regulations or standards, and the weak integration of systems remain a major challenge. In particular, it will be vital to provide insights that favor the regulation of decentralized systems and the water quality standards for reuse, which will ensure the development of more efficient and sustainable water management practices.

Overall, then, close collaboration between researchers, professionals, and stakeholders will be crucial to strengthen the fundamental principles addressed in the present review. The understanding of RWH and GWR systems would also benefit greatly from the implementation of case studies and the collection of empirical data, which would be recommended for future studies. Practical, real-world evidence can provide important input, and complement ongoing scientific research, providing a more comprehensive overview of the state of the art of the field, while addressing the knowledge gaps identified here in an effective and reliable manner.

4. CONCLUSIONS

The present study was based on a systematic review of the scientific literature on combined RWH and GWR systems. The selection of studies based on the search criteria resulted in the identification of 41 papers that were relevant to the objectives of the present study. In general, these systems have been implemented primarily at residential and commercial scales, as a complement domain water supplies. The recovered water was used for toilet flushing, floor cleaning, and garden irrigation. Rainwater was treated using simple procedures for the removal of suspended solids and pathogenic microorganisms, while the greywater treatment also included the removal of organic matter. Tank sizing was based on mass balance models using historical rainfall data and estimates of water demand. The topics covered most frequently in the papers analyzed here were potable water savings and cost analyses.

Finally, the present study highlights the need to invest in innovative technologies that satisfy demands for sustainability, such as the use of renewable sources of energy, recyclable materials, and the reduction of environmental impacts. In order to ensure the performance of these systems in both environmental and economic terms, it will be necessary to better evaluate the interaction between this technology and contextual factors, including the local climate, the availability of resources, and existing infrastructure. It will also be important take social acceptance into consideration and the potential for the involvement of the local community. These factors will be essential for the successful implementation of the systems and their long-term sustainability, especially in the context of ongoing shifts in climate. Overall, the quest for effective, decentralized water management solutions in urban areas will be essential to guarantee adequate supplies of water in the future.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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