water

MDPI

Review

Stormwater Harvesting from Roof Catchments: A Review of Design, Efficiency, and Sustainability

Karen Bañas [1,2], Miguel Enrico Robles [1,3] and Marla Maniquiz-Redillas [1,*]

[1] Department of Civil Engineering, De La Salle University, 2401 Taft Avenue, Malate, Manila 1004, Philippines
[2] College of Engineering and Architecture, Catanduanes State University, Calatagan, Virac 4800, Philippines
[3] Civil and Environmental Engineering Department, Kongju National University, Cheonan 31080, Republic of Korea
* Correspondence: marla.redillas@dlsu.edu.ph

Abstract: Roof runoff is collected rainwater from a roof using a rainwater harvesting system (RWHS). The construction of an efficient RWHS requires a thorough analysis of the rainwater quality and the appropriate treatment process for its intended use. In line with this, a bibliometric and comprehensive review of studies related to roof rainwater harvesting was conducted. A corpus of 1123 articles was downloaded from the Scopus database and parsed through the CorText Manager to determine the relationships between keywords, journals, and topics related to rainwater harvesting. A comprehensive analysis was also conducted to determine the different designs of RWHS, the quality of harvested rainwater from roof catchments, the efficiency of the system for specific purposes, and its sustainability in terms of economic, environmental, and social aspects. Results show that the effectiveness of a RWHS heavily depends on its installation site, the physicochemical characteristics of the harvested rainwater, and the acceptability of the end users. An effective water treatment process is essential for achieving better water quality for harvested rainwater. Moreover, assessing the financial viability and return on investment of an RWHS is necessary.

Keywords: comprehensive review; rainwater harvesting; rainwater harvesting system design; roof runoff; water quality; water supply; sustainability; reuse

check for updates

Citation: Bañas, K.; Robles, M.E.; Maniquiz-Redillas, M. Stormwater Harvesting from Roof Catchments: A Review of Design, Efficiency, and Sustainability. *Water* **2023**, *15*, 1774. https://doi.org/10.3390/ w15091774

Academic Editor: Luís Filipe Sanches Fernandes

Received: 15 February 2023
Revised: 26 April 2023
Accepted: 30 April 2023
Published: 5 May 2023

1. Introduction

Water scarcity remains a pressing issue worldwide. It has been previously found that about 4 billion people, or two-thirds of the world's population, experience severe water scarcity at least one month per year [1]. This number was projected to reach 6 billion by 2050, with 73% residing in Asia [2]. Furthermore, socioeconomic factors that include population growth, increasing living standard requirements, and rising global temperature contributes to domestic water scarcity [3]. Conventional domestic water sources, including groundwater and surface water, are also vulnerable to contamination. The study of Sui et al. (2015) explained that in certain environmental conditions, groundwater could be susceptible to emerging contaminants, particularly pharmaceutical and personal care products (PPCP) [4]. Every activity that could result in the purposeful or unintentional release of chemicals or wastes into the environment has the potential to contaminate these sources.

Rapid urbanization can also contribute to water scarcity and pollution issues, and future population growth will put more pressure on water infrastructure. Urbanization helps the economy and improves living circumstances, but unplanned expansion carries many hydrological concerns, such as pollution, water supply, and drainage [5]. Increasing impermeable surfaces and poor resiliency of urban drainage system design from constant development increases peak storm runoff, which could harm urban communities and their water security in general [6]. Increased frequency of downpours due to climate change also imposes greater and intensified effects. Precipitation is anticipated to increase at higher latitudes and decrease nearer the equator. Increased rainfall is expected to come in the form of more frequent heavy downpours. Particularly when combined with changes in land use, this change in precipitation patterns will probably result in a higher occurrence of flooding. Moreover, clean freshwater is projected to become more scarce, and illness caused by unclean water is projected to increase. With the overlapping effects of increasing water demand, widespread urban development, and degradation of water quality in conventional sources, exploring alternative domestic and drinking water sources has garnered significant interest among researchers.

Capturing stormwater for reuse has been suggested to counteract the rising peak flow rates and increasing demand for clean and drinkable water [7]. Low-impact development (LID) is an approach to managing stormwater runoff. It is a design approach that employs artificial and natural infiltration and storage methods to manage stormwater where it is generated. Rainwater harvesting systems (RWHS), sometimes called rainwater harvesting (RWH), are LID techniques that could collect roof runoff for storage and supply and can provide effective runoff management and flood reduction benefits while simultaneously serving as a water supply. RWHS are deemed a climate change adaptation tool that could benefit water-scarce areas [8]. RWHS can also be a crucial reserve in emergencies or when the public water supply systems fail during natural catastrophes. Numerous studies also claim that stormwater collection through RWHS has great potential for addressing climate change and preventing domestic water pollution [9–11].

RWHS implementation challenges require various considerations to optimize its usage over an area. The RWHS design depends on several key factors, such as geographical location, building structural design, quality of rainwater harvested, and relevant economic assessments. Likewise, other design parameters such as return period, design rainfall, concentration time, and peak time should be considered in adapting RWH [12]. Additional measures must also be applied in these systems as pollution in rainwater harvesting remains a concern [13]. Filtration is one of the most known methods to decrease debris and solids in rainwater, as stated in previous studies [14–16]. Disinfection may also be applied to improve the physicochemical and microbiological quality of water [9,17]. Furthermore, trapping stormwater and storing it in temporary impoundments for evaporation or ground infiltration can also be an effective option that could successfully complement technologically intensive approaches [6]. Addressing these issues is significant in building a long-term recharge method and controlling stormwater runoff, later contributing to the restoration of preurban hydrology in catchments [18–20].

This review study investigated the innovative study of RWHS focusing on water quality, usefulness, financial viability, and climate change solutions and directs future research initiatives on the topic. Thus, a bibliometric analysis was conducted to identify the research trends regarding roof rainwater harvesting. In addition, a comprehensive review was also conducted to evaluate the quality of harvested rainwater from roof catchments, the different components of RWHS with treatment processes that utilized roof runoff, and its efficiency for reuse, e.g., irrigation, domestic, commercial, and livestock use. The rainfall quantity and the corresponding storage tank capacity were also examined in this review. The evaluation of the current studies regarding the economic, social, and environmental sustainability of RWHS is also highlighted.

2. Materials and Methods

2.1. Bibliometric Review

The research articles used for the bibliometric review were downloaded from the Scopus database [21]. As shown in the methodology framework in Figure 1, the initial search string inputted was TITLE-ABS-KEY (“rainwater harvesting”), resulting in 3117 documents. To filter the documents further and determine the articles relevant to roof rainwater harvesting, the keywords “roof” and “runoff” were added to the search string, resulting in 1123 documents. No filtration of articles from specific years was performed. The resulting documents were downloaded as a Research Information System (RIS) file on

23 August 2022 and parsed into a corpus using the CorText manager, an online software used to quantitatively assess scientific articles based on bibliometric information collected from a set of downloaded research articles [22]. Various scripts that include a network map of keywords, years, and countries, contingency matrices (keyword and journal; keyword and country), and a Sankey diagram of keywords were generated from the CorText Manager for the analysis of terms, references, and trends of topics related to roofing rainwater harvesting.

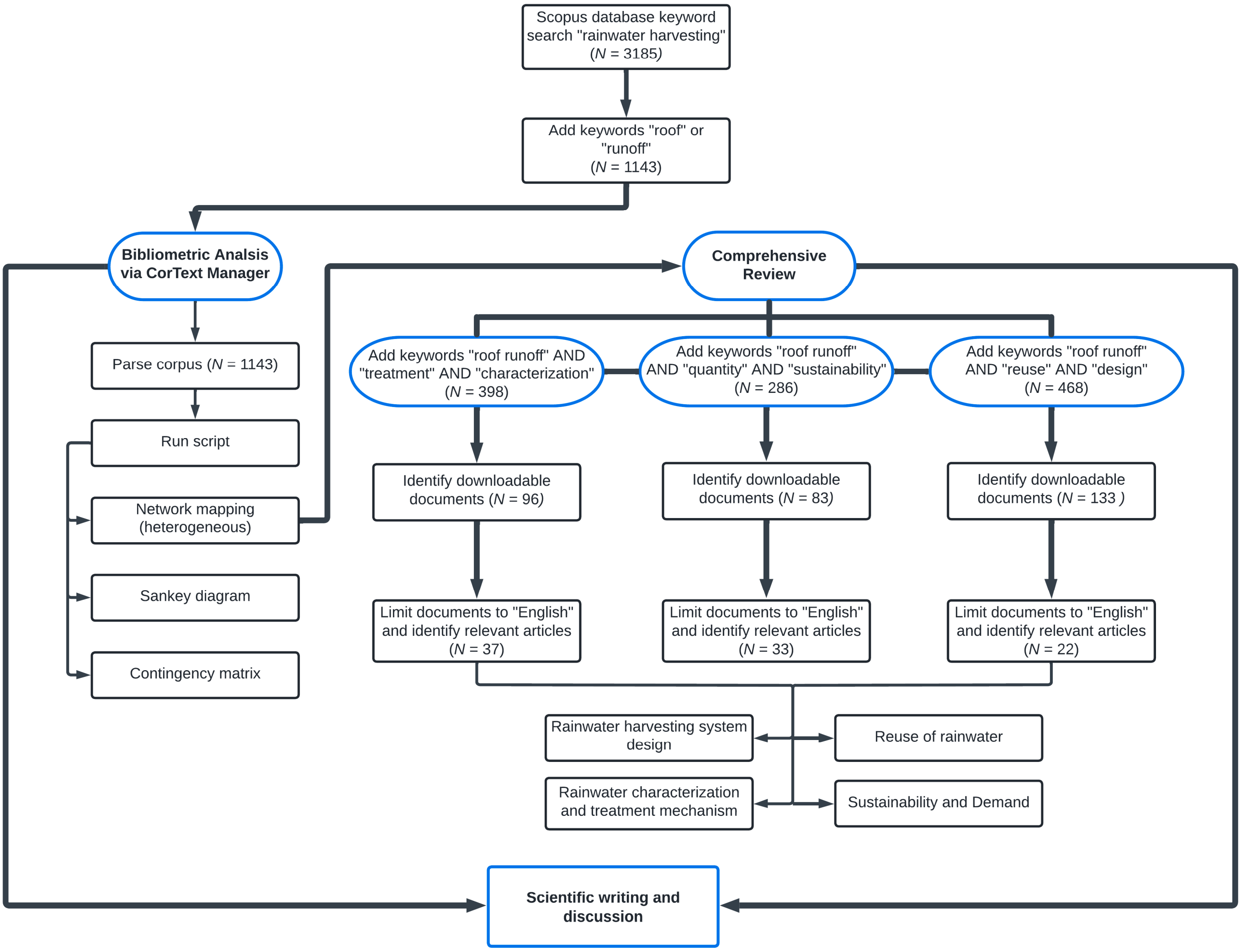

Figure 1. Framework of the review methodology.

A heterogeneous network map and a Sankey diagram were generated to visualize the relationship and the magnitude of co-occurrence among keywords related to roof rainwater harvesting. In generating the network map, "keywords", "time steps", and "country" were selected as the first, second, and third variables, respectively. The chi^2 test was selected as the specificity measure, in which the independence and relevance of the variables from each other were measured. Under the same script type, the Sankey diagram was generated by setting the number of slices to 5 on the Dynamics table. Contingency matrices were also generated to visualize the magnitude of the co-occurrence of roof rainwater harvesting-related keywords in both journals and countries. In generating the contingency matrix, "keywords" was selected as the first field, while "journal" and "country" were selected as the second fields of the two scripts. The number of nodes was set at 10, while chi^2 was selected as the contingency analysis measure.

2.2. Comprehensive Review

The research articles used for the bibliometric review were filtered further for the comprehensive review. Specific keywords were added to the initial Scopus search string to identify research articles relevant to roof runoff collection, treatment, and sustainability. Three Scopus searches were conducted for the comprehensive review. In the first search, the keywords “treatment” and “characterization” were added, which resulted in 398 documents. The collected documents were then limited to research articles that were in English and relevant to rainwater characterization and treatment. The filtration resulted in 37 documents for the first Scopus search. The next Scopus search, in which the keywords “quantity” and “sustainability” were added, underwent the same filtration process. The second search turned up 33 documents. In the third Scopus search, the keywords “reuse” and “design” were added, which resulted in 468 documents. It was also limited to articles in English and relevant studies, which resulted in only 11 documents. A total of 92 documents were used for the comprehensive review. The available information in the research articles was synthesized using Microsoft Excel for analysis.

3. Results

3.1. Bibliometric Review

3.1.1. Network Mapping and Evolution of Keywords and Terms

A heterogeneous network map (Figure 2) was created using the CorText Manager to determine the association of keywords, countries, and years relevant to research on roof rainwater harvesting. Keywords within or near a solid circle have high co-occurrences, while keywords surrounding a year have high co-occurrences with that particular year. Moreover, countries that are near each other have high co-occurrences. It can be seen from the figure that the keywords “water harvesting” and “water quality” have high co-occurrences for several years between 2000 and 2013, indicating that water harvesting, regardless of the source and the surface on which it was collected, has been a topic of interest for the mentioned time frame. Furthermore, the high co-occurrence of the two keywords denotes that water quality assessment was the focus of most water harvesting-related research published from 2000 to 2013. It can also be observed that the keywords “tank sizing”, “rainwater tank”, and “water demand” have high co-occurrences with the year 2015, indicating that research initiatives on the efficiency of rainwater harvesting were mainly published in that particular year.

The network map shows that keywords with “rainwater harvesting”, such as “roof-top rainwater harvesting”, “rainwater harvesting (RWH)”, and “domestic rainwater harvesting”, all have high co-occurrences with more recent years. The co-occurrences indicate that rainwater harvesting is an emerging research topic and is becoming more globally relevant as time progresses. It can also be observed that sustainability has been a focus in research on roof rainwater harvesting. The presence of the keywords “sustainability”, “cost-benefit analysis”, and “economic analysis” shows that the sustainability and economic advantages of roof RWHS are widely investigated, mainly in Western countries such as the United States, Canada, and France.

The Sankey diagram in Figure 3 shows the evolution of keywords relevant to roof rainwater harvesting. A darker-colored tube connecting two keywords denotes a strong relationship between the two keywords. In contrast, the thickness of the tube denotes the level of co-occurrence between the keyword and the particular year it belongs to. It can be seen that the years 1989 and 1993 are present in the network map but not in the Sankey diagram. The keywords generated from articles published in the mentioned years are represented in the 1996 column. Since the number of slices generated for the Sankey diagram was limited to five, keywords from articles published before 1996 were displayed in the next year, in which relatively more articles were published. It can be observed that stormwater management and sustainability have been relevant to roof rainwater harvesting since the 1990s. Furthermore, specific purposes of rainwater harvesting were found to be relevant to sustainability in the 2010s, such as “urban commercial infill” and "greywater reuse". The most robust keyword relationship in the diagram was between "supplemental irrigation and economic analysis" and "residential buildings and rainwater harvesting". This strong relationship indicates a significant evolution in the usage of harvested rainwater, from irrigation to domestic use. It can also be seen in the figure that most rainwater harvesting-related research prioritizes water savings, water demand, and drinking water. The keywords "GIS" and "remote sensing" in recent years indicate that advanced has been significantly involved in investigating the effectiveness and efficiency of rainwater harvesting.

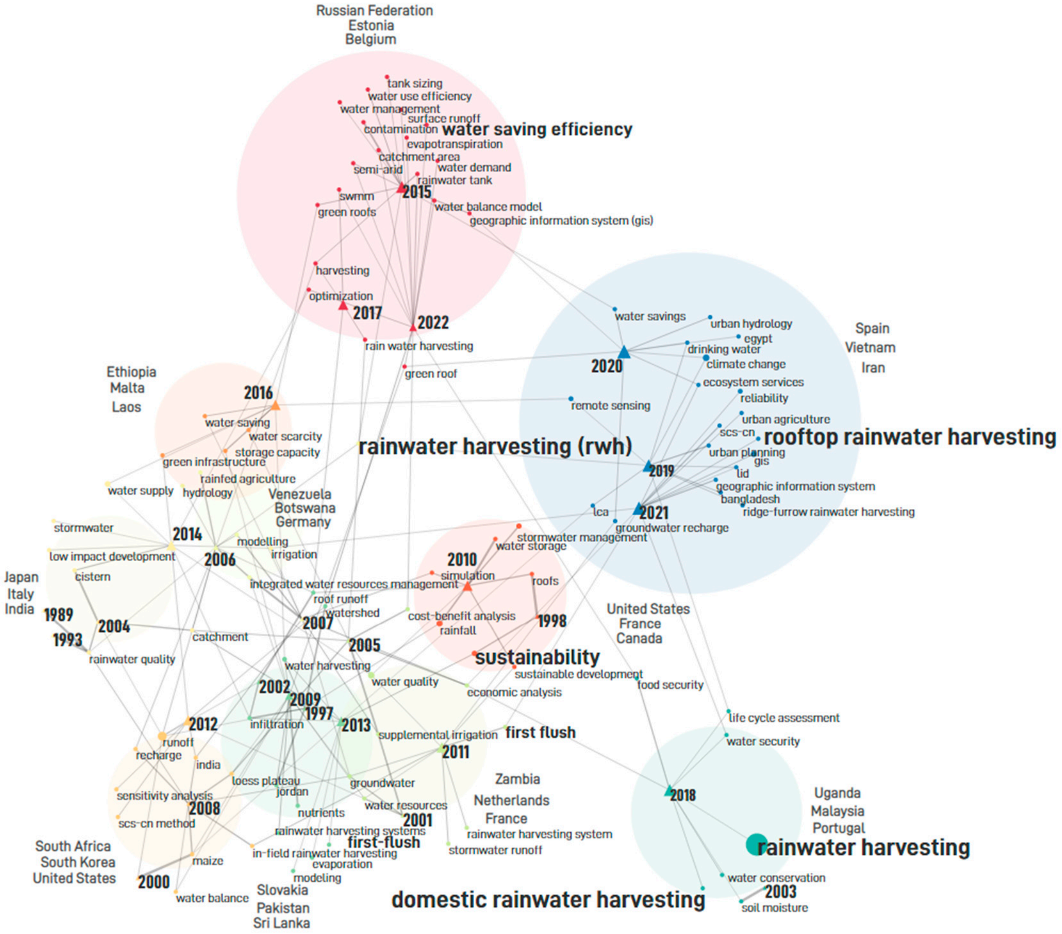

Figure 2. Heterogeneous network map of keywords, countries, and years of research articles collected from the Scopus search using the keywords "rainwater harvesting" and "roof" or "runoff".

3.1.2. Contingency Matrix

Two contingency matrices highlighting the co-occurrence between keywords, journals, and countries are shown in Figure 4. The darkness of a cell in the matrix indicates the magnitude of co-occurrence between two fields. A red cell indicates a strong relationship between two fields, while a blue cell denotes a weak relationship. Moreover, a white cell indicates neutrality between the two fields. The number on the horizontal axis indicates the number of articles in which its corresponding keyword was used. Moreover, the number on the vertical axis denotes the number of articles collected from its corresponding journal or country. On the contingency matrix for keywords and journals in Figure 4a, it can be observed that the keyword "rainwater harvesting" had the highest co-occurrence with the Journal of Hydrology. The mentioned journal had the highest co-occurrence, with the keyword "runoff". The two darkest red cells intersect agricultural water and management and the keywords "climate change" and "runoff". Water (Switzerland) was found to have a co-occurrence with the keywords "GIS", "water supply", and "water quality".

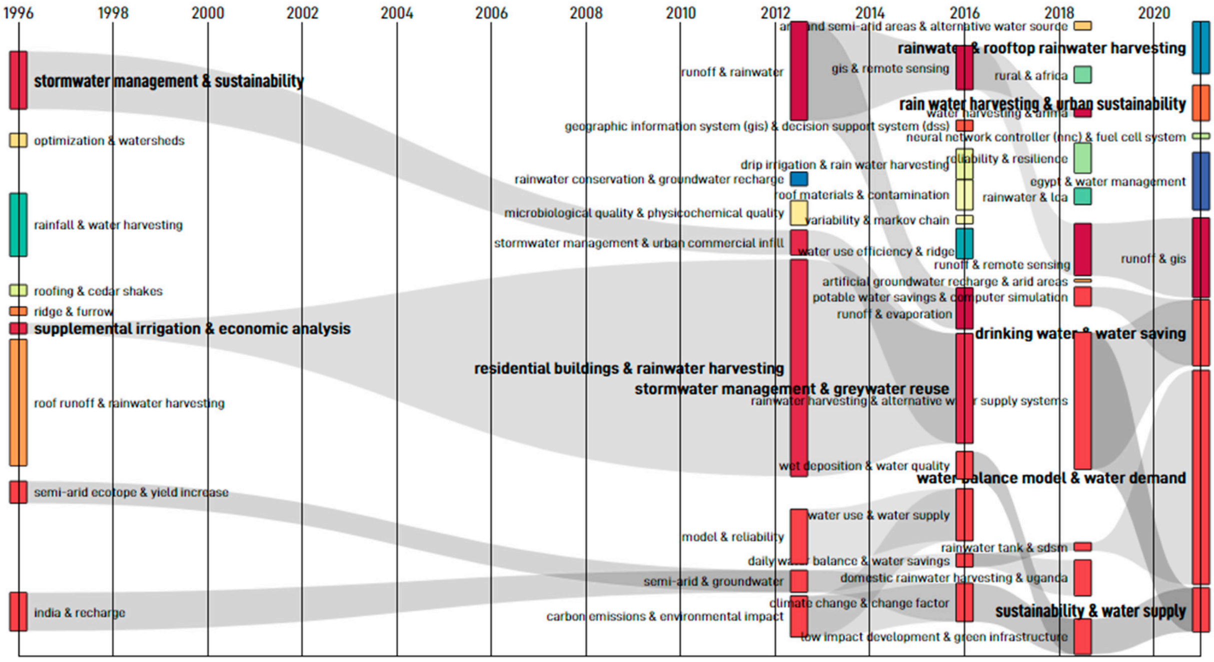

Figure 3. The Sankey Diagram for the keyword search “rainwater harvesting” and “roof” or “runoff” is based on the Scopus database.

The co-occurrence between keywords and journals is shown in Figure 4b. The countries with the highest co-occurrence of the keyword “rainwater harvesting” were Australia, the Netherlands, and Malaysia. South Africa and Spain also had positive co-occurrence values with “rainwater harvesting”. A strong relationship was found between the keywords “runoff” in South Africa and “rainwater” in Spain and Australia. Furthermore, a strong co-occurrence was found between the keyword “stormwater management” and the United States. Other noticeable relationships include the high co-occurrence of India with the keyword “GIS” and China with the keyword “runoff”.

3.2. Comprehensive Review

3.2.1. Roof Runoff Quality

Roof rainwater quality can be influenced by a variety of factors, including roof characteristics (e.g., material, age, slope), environmental factors (air pollution, geographic location, season), and rainfall characteristics (rainfall intensity, antecedent dry period, rainfall duration). Studies have stated that pollutants accumulate both in the air and on the roof from the onset of rainfall until the emergence of roof runoff [23]. Rainwater harvesting components and external factors, such as climatological conditions, including rainfall intensity and dry days, also influence the quality of rainwater runoff [24]. Similarly, rainwater can become corrosive and murky due to air pollution [25]. The demographic and social behavior of the population also influences the quality of harvested rainwater [9]. The identification of contaminants and the conditions in which they arise can help to develop rules, regulations, and maintenance recommendations for small-scale rainwater harvesting [26]. Common contaminants from roof runoff include zinc, copper, and iron [27], although their concentration can depend on the roofing materials, environmental factors, and rainfall characteristics [23].

Figure 5 summarizes influent roof runoff concentration values obtained in the reviewed studies. The highest and lowest values for electrical conductivity are 410 µs/cm and 14.7 µs/cm, respectively. One of the high values of electrical conductivity is 105.59 mg/L which is found in asphalt-felt roof runoff in the study of Boguniewicz-Zabłocka and Capodaglio (2020) [6]. Nitrogen and chlorine content ranges from 9.36 mg/L to 0.02 mg/L and 44.22 mg/L to 1.72 mg/L, respectively. Sulfate comes from emissions of sulfurcontaining compounds that occur primarily from the combustion of petroleum-derived fuels. These could easily combine with rainwater in the atmosphere.

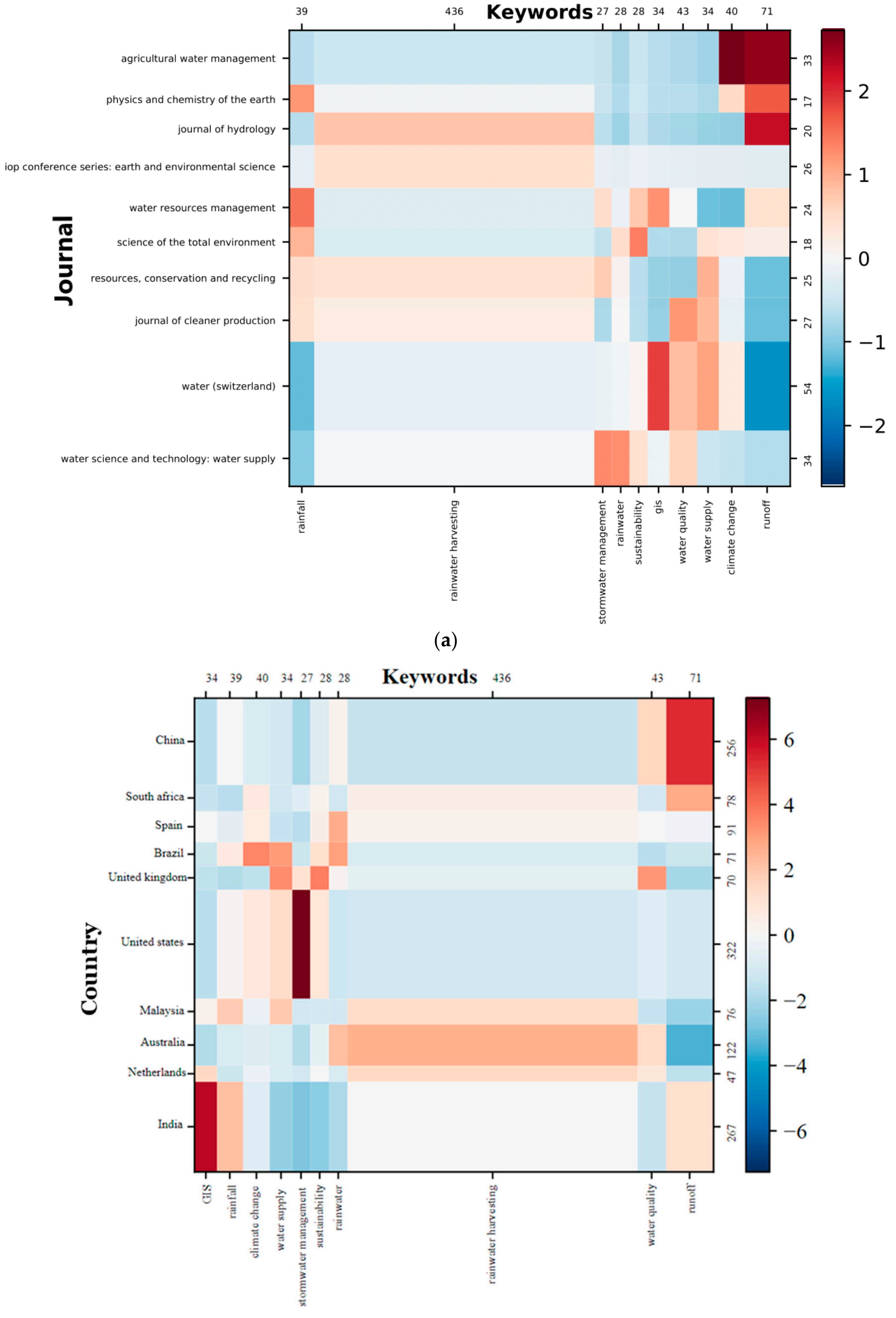

Figure 4. Contingency matrix showing the relationship of (**a**) keywords and journal and (**b**) keywords and country.

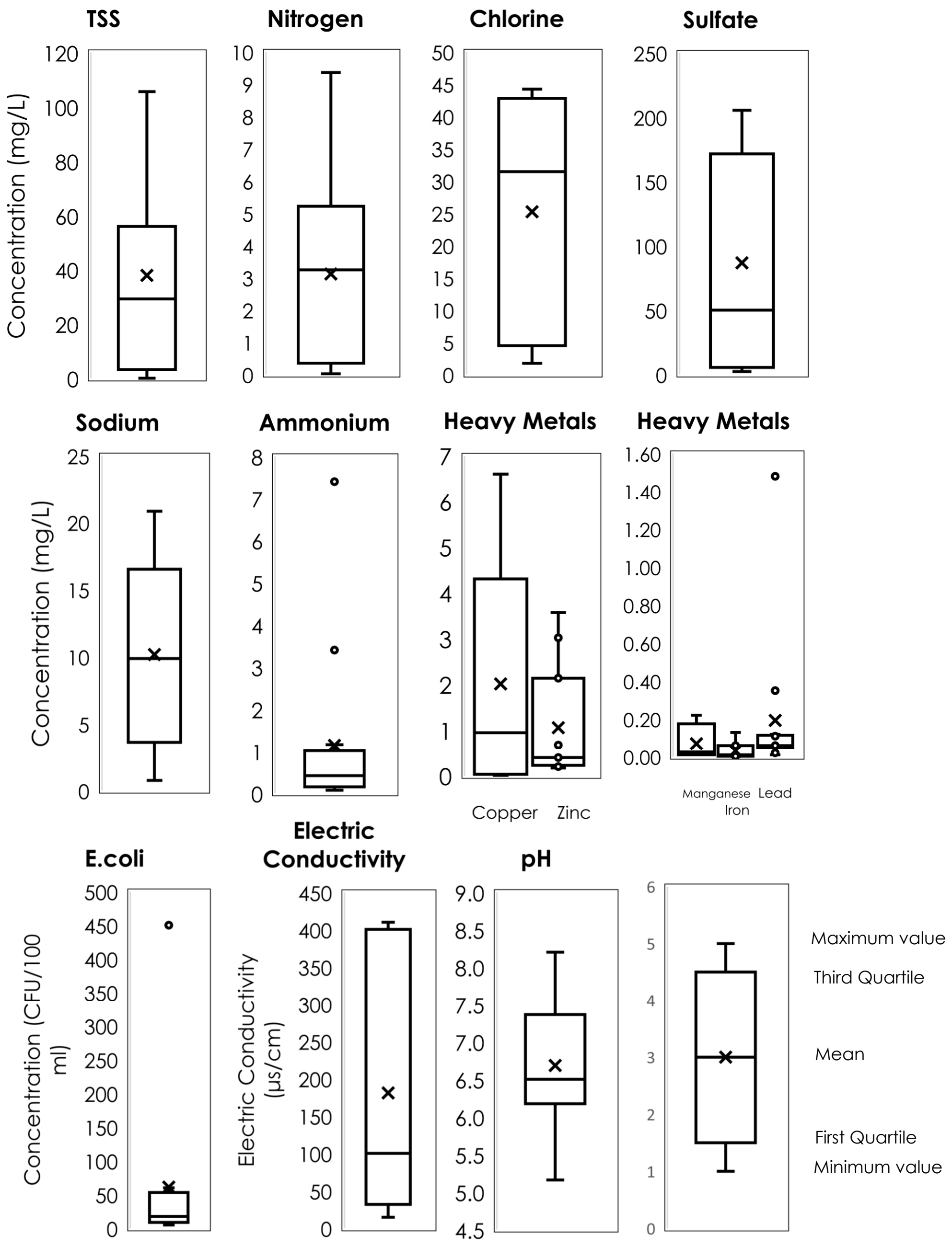

Figure 5. Summary of the influent roof runoff concentration values obtained in the reviewed studies (n = 24).

The highest sulfate concentration is 205.43 mg/L, while the lowest is 2.23 mg/L. Physicochemical characteristics such as *E. coli* came from the feces of animals that accumulated on roofs. Additionally, it was found that coliform bacteria may also develop and increase the contamination of rainwater due to prolonged storage in barrels. The values of *E. coli* obtained from the data of the reviewed studies ranged from 450 CFU/100 mL to 4.90 CFU/100 mL. High concentrations of copper and zinc were observed, implying that some roofing materials affect the water quality, specifically during the onset of rain after a long dry period [15,28].

Regarding roofing material, some studies showed that the quality of rainwater harvested from roof runoff was greatly affected by the materials used for roofing [13,27]. The concrete roof had a beneficial influence on hardness, EC, pH, and alkalinity compared to the other roof types [29]. Rainwater collected in the spring and autumn with a flat roof covered with epoxy resin had the poorest microbiological quality [30]. When harvesting rainwater for non-drinking purposes, a stabilized soil cistern was considered an alternative [28]. Conversely, on metal roofs, the combined effects of concentrated UV radiation and higher temperatures provided a sterilizing effect, thus improving the water quality of the roof runoff [15]. Green roofs may also be considered when choosing a roofing material; however, one of the studies recommended choosing appropriate components for long-term use [31].

Some findings of water quality tests indicate that particulate matter from the atmosphere was the predominant pollutant in the RWH collection system [32], making rainwater stored in barrels inadequate for human consumption [33]. Studies suggest that pollutants can build up on a roof over an extended dry period, causing pollutant concentrations to be higher. Eliminating ponding on the surface was found to be effective in minimizing the potential of microbiological contamination of the roof runoff [27,34]. Since rainwater is collected from rooftops, studies recommend choosing suitable roofing materials based on the intended application [35].

3.2.2. Components of Rainwater Harvesting System

The reviewed articles found that rainwater harvesting systems are typically composed of rainwater barrels for storage. Other RWHS were accompanied by a treatment process to remove contaminants from the harvested rainwater. In some cases, roof runoff RWHS applications depended on the location, type of infrastructure, characteristics of rainwater, and the system itself. Table 1 shows a summary of the components of RWHS. It includes the roofing materials, storage tank capacity, materials used for the treatment process, and the study results. These components are significant in achieving the efficiency of RWHS.

Treatment Process

The surface used to collect rainwater significantly impacts the quality, and microbiological quality typically necessitates a thorough disinfection to create safe drinking water [36]. Good design, construction, and proper use of the system should be followed to have a stable and efficient operation [37]. Using basic filtration technologies has shown a potential to address the need for alternative clean water sources during the dry season [38]. Many countries utilize filtration as the primary treatment process in RWHS, as shown in Table 1. Some studies have applied techniques corresponding to the site conditions and purpose of treated rainwater. Khayan et al. (2019) employed mollusk sand media and activated carbon to purify lead (Pb)-contaminated water collected from lead-coated roofs [25]. Wu et al. (2017) adopted fine mesh filters to treat rainwater in China [28]. Filtration and chlorination can also be used conjointly to make rainwater safe for drinking [16,17]. First flush treatment is also suggested since more contaminants are present at the onset of rain because organic matter builds up in the atmosphere and on roofs during the dry season. Membrane methods such as nanofiltration can produce better-quality, safer drinking water, and have a minor environmental impact than other treatment options [39]. In Vietnam, filtration with a reverse osmosis filter and boiling was used to treat water for drinking and domestic uses [40]. Disinfection using a pilot-scale solar photocatalytic fixed bed tubular reactor was also an effective treatment process in India for potable use [41]. Nanofiltration, using a system consisting of a filtration cell, a nitrogen gas tank with a regulator, a permeate collection cell, and a computer that records data for the flux calculation, was used in Turkey to achieve the standards for drinking water [19]. Using gravel filters also cleanses water in an RWHS, reducing total coliforms to negligible levels [16].

Sedimentation is another treatment process that can be used for rainwater, wherein the sediments are allowed to settle at the bottom of the tank for a period. This process allows a change in the physical parameters of rainwater, improving the quality at the top of the container with time. Poorer water quality, however, could be observed at the bottom of the tank due to the settling solids [35]. Rainwater retention can also enhance the physicochemical and microbiological quality of rainwater collected from any roofing material, regardless of the season or the roofing material used [19]. Closed tanks with no fresh rainwater intake for at least six weeks are necessary to improve the water quality [30].

Table 1. Summary of the Components of RWHS with Treatment Process and its Efficiency.

Country	Roofing Materials	Roofing Area m^2	Type/Capacity of Storage Tank	Treatment Process	Materials for the Treatment Process	Result	Usage	Reference
Canada	Modified bitumen finish ply, polyvinyl chloride (PVC), and thermoplastic polyolefin (TPO)	2052	Precast concrete cisterns 25,000 L	Filtration and disinfection	Multimedia filters; activated carbon; micro-filters (5 to 1 µm nominal pore size); ultraviolet disinfection system; sodium hypochlorite addition	Rainwater collected would be unfit for human consumption if not treated before being distributed throughout the structure.	Non-potable	[26]
China	Asphalt felt roof	37.5	-	Grid filter, flocculation, and sedimentation	-	Roof runoff may satisfy the miscellaneous domestic wastewater quality standard for toilet flushing, city greening, car washing, and house cleaning.	Non-potable	[13]
Brazil	Masonry and ceramic tiles Gutters: galvanized sheet metal, aluminum alloy, and polyvinyl chloride (PVC)	100 900 1422	1000 L and 1500 L	Filtration of coarse materials, discharge of first water, filtration of fine particulate material, and chlorination	For filter screens, 5000 L of water requires 8 g of calcium hypochlorite (65% active chlorine) diluted in 1.5 L of water.	The system is efficient, as the water sent to the sewage system is reused, contributes to utility bill savings, and helps prevent urban floods.	Non-potable	[42]
Indonesia	Zinc roof	-	Rain barrel	Mollusk sand filtration model and activated carbon sorption (0.2–5 mm.)	Activated carbon from coconut shell (0.2–5 mm); Mollusk sand from the shell of the shellfish (0.2–5 mm)	A decrease in turbidity and lead contamination was attained.	Potable	[25]
Nigeria	Asbestos, aluminum, corrugated galvanized iron, and plastic sheets	-	255 L	Chlorination, boiling, alum, and a combination of alum and chlorine	Asbestos; aluminum; corrugated galvanized iron; plastic sheets	A decrease in turbidity after 3 mm diversion, removal of total soluble solids, and *E. coli* removal after alum + chlorine treatment.	Potable	[17]

Table 1. *Cont.*

Country	Roofing Materials	Roofing Area m^2	Type/Capacity of Storage Tank	Treatment Process	Materials for the Treatment Process	Result	Usage	Reference
India	Concrete Slab	-	-	Gravel filter and chlorination	Concrete tank; PVC gutters; gravel filter	Total coliforms dropped to negligible levels. All water samples had a pH that was close to neutral. Almost all water samples had fluoride and iron levels below acceptable standards.	Potable	[16]
New Zealand	Galvanized steel roof	-	Low-density polyethylene resin 200 L	Filtration Chlorination/boiling	200-L emergency rainwater tanks (linear low-density polyethylene resin) with removable lid; Diverter (contains coarse screen), brass tap, and restraining strap	69% of rain-fed tank samples collected in this study exceeded the health-based guideline value for the lead of 0.01 µg/L, indicating that the source is unsuitable for long-term consumption.	Non-potable	[15]
Vietnam	Corrugated tiles and cement, corrugated; steel sheets, or concrete roofs	-	Brick and concrete	6% of Households added disinfectant 30% used strainers/filtration box 98% use Boiling water or Filtration with a reverse osmosis filter	-	All values meet the national standard of Vietnam for drinking water except coliforms; water can be potable if boiled.	Potable	[40]
India	-	-	-	Disinfection using pilot-scale solar photocatalytic fixed bed tubular reactor	Pyrex glass tubes immobilized with Ag-doped TiO_2	Removal of COD after 120 min; complete disinfection against *E. coli* after 120 min.	Potable	[41]
Turkey	Commercial flat sheet polymeric membranes	2000	273,000 L	Nanofiltration	Filtration cell; nitrogen gas tank with a regulator; permeate collection cell; computer	Sulphate and NOM removal was observed.	Potable	[20]

Table 1. *Cont.*

Country	Roofing Materials	Roofing Area m^2	Type/Capacity of Storage Tank	Treatment Process	Materials for the Treatment Process	Result	Usage	Reference
South Korea	-	-	-	Solar-based disinfection of Pseudomonas aeruginosa (9 h)	8 sterile PET bottles of 2 L capacity	Disinfection during sunny weather.	Non-potable	[43]
China	Stabilized-soil catchments	-	8000 L	Fine mesh filter	Fine mesh filter; 8 m^3 capacity cistern (cement, soil stabilizer)	The stored water did not meet drinking water standards due to high levels of bacterial contamination.	Non-potable	[28]
Brazil	-	80	Fatboy slim reservoir 2460 L	Filtration	1.0 mm mesh; 2460-L fatboy slim reservoir with polyethylene coating	The rainwater was not suitable for drinking purposes.	Non-potable	[14]

Treating rainwater as soon as it reaches the surface has become a practical solution in many cases [44]. In rainfall harvesting, the application of green roofs could have a considerable impact on the treatment of incoming rainwater. Green roofs are green infrastructures that could treat runoff and reduce the peak discharge of water. The performance of green roofs is determined mainly by the type of green roof, the climate, and the amount of irrigation received [45–48]. Runoff partially decreases with the use of the green roof's integrated infiltration, filtration, and evapotranspiration processes, and the concentration of pollutants can also be minimized [49]. Due to their low initial investment and ongoing maintenance expenses, extensive green roofs are used more commonly than intensive ones [50]. An intensive green roof typically has a deeper substrate layer restricted to smaller places. In contrast, an extensive green roof likely has a shallow substrate layer covering a large area. Smart RWHS may be an option in choosing green roof designs. It can store rainwater for use while utilizing a new technology. In the study of Oberascher et al. (2021), smart RWH systems release stormwater automatically before rain events, which can further boost integrated system resilience [51].

Efficiency of Treatment

The summary of the efficiency of the rainwater treatment process from the reviewed articles is shown in Table 2. Limited information has been shown in the downloaded articles that include the removal of contaminants. The pH of typical, pure rain ranges from 5.0 to 5.5, which could become more acidic when it interacts with sulfur dioxide or nitrogen oxides, often produced by power plants and automobiles. Therefore, the increase in pH content has been notably shown in the articles to determine the efficiency of the treatment process. Other contaminants such as total suspended solids (TSS), turbidity, chemical oxygen demand (COD), and *E. coli* removal have also been highlighted in these studies. In the studies reviewed, the TSS, turbidity, and COD removal reached up to 72.75 ± 4.27%, 52.71 ± 33.26%, and 63.61 ± 19.26% (mean ± SD), respectively. One reviewed study proclaimed that a 100% removal of *E. coli* removal was observed after six weeks of storage at 12 °C [30]. Most of the treated water experiences an increase in pH, with one achieving a 52.63% increase. A wide variability of change can be distinguished in the pollutant removal, between 0.63 and 0.06. The skewness or measured symmetry of the pollutants can be seen clearly. The results in the percent removal of TSS and percent increase in pH are positively skewed, which implies that the removal and increase are not uniform in the different treatment processes. However, it was observed that the results of the percent removal of *E. coli*, COD, and turbidity are almost the same, which means that the studies reviewed have similar results. Moreover, to have an efficient rainwater treatment system, one should consider the materials and methods to be used and the contaminants to be removed.

Table 2. Summary of the efficiency of the rainwater treatment process (n = 7).

	TSS (% Removed)	**pH (% Increased)**	**Turbidity (% Removed)**	**COD (% Removed)**	***E. coli* (% Removed)**
Mean	72.75	31.54	52.71	63.61	79.23
Median	71	26	50	64	87.69
Minimum	70	16	11	32.68	50
Maximum	79	52.63	99	90	100
Standard Deviation	4.27	18.93	33.26	19.26	24.57
Coefficient of Variation	0.06	0.6	0.63	0.3	0.31
Skewness	1.73	1.2	−0.07	−0.43	−0.47

3.2.3. Quantity and Reuse

The rainfall amount, duration, intensity, and distribution contribute to the design and implementation of RWHS in any given location [52]. The quantity of rainwater that can be harvested should be considered, along with the purpose it will serve. Figure 6 shows the summary of the roofed area and its corresponding rainfall amount recorded in every study reviewed. Only 29% of the paper reviewed has a value greater than 500 m^2, regardless of the rainfall amount. For example, a rainfall amount of only 640 mm/yr has a roofing area of 2450 m^2 in the paper of Custodio and Ghisi (2019), whereas in the study of Sámano-Romero et al. (2016), a rainfall amount of 4239 mm/yr has a roofing area of only 50 m^2 which shows that the recorded rainfall amount is usually not the basis for computing the area of the roof. However, most buildings' roof spaces are not large enough to collect enough rainwater to meet demand [53]. Nevertheless, catchment area and catchment surface type can be changed to enhance system performance [54]. Due to the dynamic characteristics of rainfall, some studies consider the size of the storage tank rather than the roof area, which makes the storage tank the most significant expense in RWHS and domestic rainwater harvesting (DRWH) systems [55]. Areas with less rainfall would require small storage tanks for economic reasons. The study of rainfall and the area's physical and social factors can help design the RWHS to make it reliable [56]. Figure 7, on the other hand, shows the relationship between the ratio of the runoff volume and tank size versus rainfall amount. The results indicate that as the rainfall amount recorded increases, the ratio of the runoff volume collected to the storage tank volume increases. The volume of roof runoff collected and tank size were critical in the preliminary design of an RWHS in one of the studies reviewed [11]. However, one study can be seen as an outlier. The R^2 value is 0.2795, which implies that the data points are not closer to the mean value.

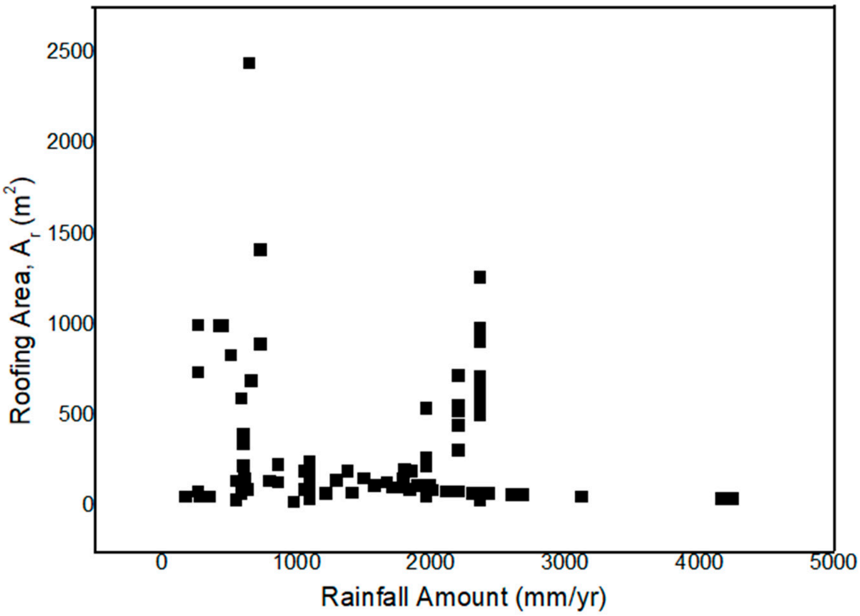

Figure 6. Scatter plot of rainfall amount (mm/yr) and roofing area (m^2) (n = 24).

RWH can act as the primary water source in rural areas where the availability of water resources is a serious problem or as a complement to the main water supply in urbanized areas when integrated with the current conventional water delivery systems [54]. Rainwater collected using RWH systems can then be reused for other purposes. Figure 8 shows the percentage of studies reviewed with data on the reuse of rainwater harvested from roof runoff. Studies show that rainwater is typically used for domestic, commercial, irrigation, and livestock purposes. Among the 54 reviewed studies, 30 papers reviewed the use of rainwater for domestic purposes, of which 13 percent is potable, and 43 percent is non-potable. The rainwater collected from the roof is not potable and should not be used for drinking, but it can be used for flushing, cleaning, and gardening [57]. Nevertheless, treating it appropriately can serve its purpose as a potable water supply. Utilizing rainwater collected from rooftops can promote water sustainability and lessen the vulnerability of the water supply for homes and other uses [58]. In rural communities, especially in developing nations without access to safe drinking water supplies, rainwater harvesting

(RWH) systems can produce drinking water [59]. Since the capacity of rainwater tanks to supply livestock holdings with water is greatly influenced by the research area's regional characteristics, i.e., longer dry periods, tank design cannot be completely standardized [60]. Covered and uncovered rainwater tanks can also be employed to meet irrigation needs. According to Londra et al. (2021), the required tank sizes could lessen local pressure on water resources [61]. Additionally, RWH models are frequently used to assess various system designs, notably the sizing of rainwater tanks [62]. Using RWH can bridge the water deficit for agriculture and the amount of rainfall, lessening potential water system demands and subsidizing irrigation while promoting sustainable development [63].

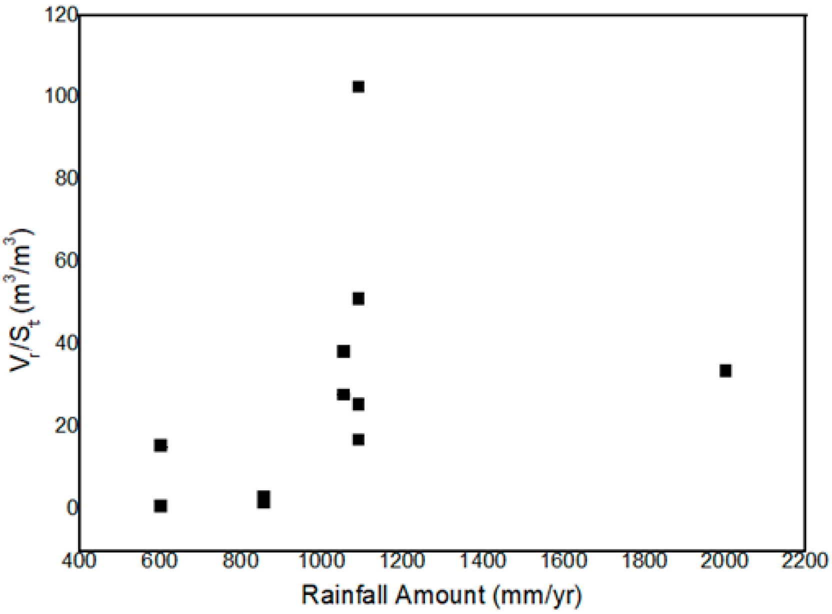

Figure 7. Scatter plot of the ratio of the runoff volume and tank size versus rainfall amount (n = 13).

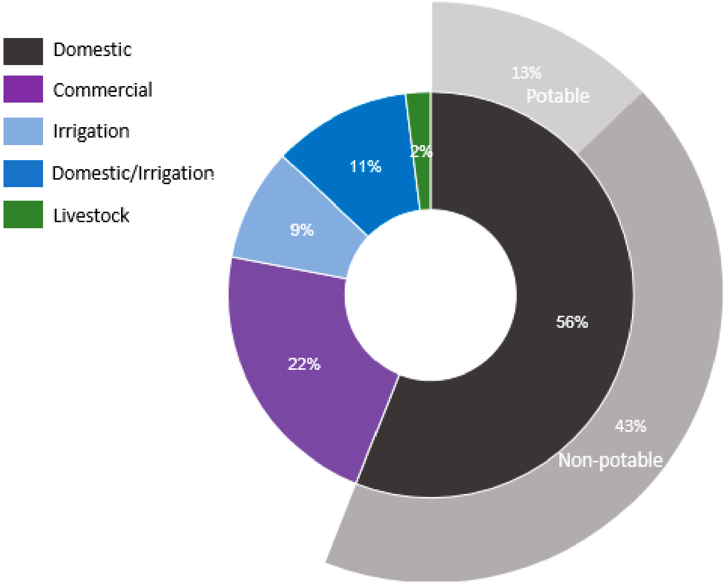

Figure 8. Summary of reuse of rainwater harvested from roof catchments (n = 54).

3.2.4. Rainwater Harvesting Potential and Sustainability

In addition to rainwater harvesting, source separation, and on-site wastewater treatment are important aspects of the water sector's circular economy. Important implications for the wastewater discharge infrastructure include sufficient collection facilities, buffer reservoirs during dry periods, and a different pipe system to collect and distribute the water [64]. Cultural reforms and awareness are required to raise public understanding about the necessity of water conservation and protection [42]. Understanding end-user prioritizing preferences was critical for responding to increasing water constraints and scaling up alternate water delivery systems [65]. Oviedo-Ocaña et al. (2018) state that the end user's desire to use alternative sources (rainwater), the purpose for using alternative sources, the readiness of the end-users to pay for investment, operation, and maintenance, and the willingness to carry out the operational activities are heavily considered in installing RWHS [66]. In the reviewed studies, the amount of water that an RWH method can save was predicated on the situation of the installation sites and the end users. Water end-uses, total water consumption, and catchment area were among the found building attributes [67,68]. The study of Kwon et al. (2018) also implied that collecting rainwater on a neighborhood scale rather than per individual building can be more economically viable [69]. Table 3 compares RWH approaches regarding occupancy category, catchment area, daily consumption, payback period, and Internal Rate of Return (IRR) corresponding to the number of years. The traditional method of determining the payback period of any investment is to use it individually and case by case, taking into account the cost of the investment and its subsequent benefits over time while converting future predicted gains into a lower net present value, taking into account the return rate [70]. A study by Park and Um (2018) explains that the lesser the occupancy and roofing area, the shorter the payback period. Sustainability improves as storage capacity increases and water demand decreases [71].

Table 3. Summary of rainwater harvesting system potential.

Country	Occupancy	Roofing Area (m^2)	Daily Consumption (L/d/Capita)	Payback Period (Years)	IRR * (%/# of Years)	Reference
Brazil	2 houses, 4 inhabitants/house	100–1422	150	3.5	19/25	[42]
Colombia	65 houses/5 inhabitants/house	30.5	130	30	4.7/30	[65]
Colombia	1 house, 4 inhabitants	101	203	23	6.5/50	[66]
Netherlands	4 houses	140–235	119	60	-	[36]
Poland	16 multi-family buildings	13,250	-	100	9/12	[72]
Poland	Dormitory/600 inhabitants	2450	-	30	-	[73]
Slovakia	Dormitory/600 inhabitants	4900	-	20.27	-	
Bangladesh	1 residential building/ 60 inhabitants	16.72	135	3–4	-	[74]
Greece	1 house/2 inhabitants	100	200	28	-	[75]
Italy	984 Multi-story/multi-family building/1–6 inhabitants per apartment	25–100	-	10	50/15	[76]
Poland	Single-family house/ 4 inhabitants	230	243.9	30	-	[77]

Note: * IRR—Internal Rate of Return.

A rainwater harvesting system provides positive effects over its entire life cycle, making it cost-effective and reasonable for both the project and society [5]. Additionally, it was learned that the expense of installing a rainwater harvesting system could quickly be recovered in three to four years [74]. It is vital to emphasize the various upfront expenses associated with the infrastructure that makes it possible to deploy rainwater harvesting in households and the costs associated with maintenance and operation over the year [78]. The ability to save tap water, as well as capital and operational costs incurred throughout the system's operation, were also found to significantly impact the cost of employing the rainwater management system [75]. The option in which rainwater from the roof is dumped directly into the sewage system has a lower life cycle cost [79]. Moreover, it was found that the roof area, which is directly proportional to the amount of rainwater collected on the roof, affects the payback times for each initial investment [70]. In Mexico, a local strategy is required to create a nationwide rainwater harvesting program [80].

A flexible framework for planning, executing, and assessing green infrastructure is necessary since it combines specific economic, social, and environmental goals and advantages [81]. In a study in Greece, RWH implied the potential to improve the quality of urban life concerning environmental values. The study claimed that social services such as education and social safety could be strengthened by supplying safe water in a long-term and sustainable manner using RWH [75]. In addition to economic growth strategies that emphasize the environment and promote industry and public engagement in environmental protection activities, nations should implement incentives and stringent environmental protection rules [82]. Highly permeable surfaces are frequently converted to impermeable ones, resulting in increased stormwater runoff, decreased infiltration of groundwater, and surface water quality [83]. Due to the increased disruption of natural landscapes brought on by urban expansion, urbanization has been continuously harming the quality of surface waters; therefore, to lessen these effects, LID technologies were developed to conserve the natural hydrologic cycle [84]. One of the articles reviewed states that when minor rainfall events occur, the number of flooded areas can be reduced by up to 100%. For a rainfall event with a depth of up to 50 mm, a reduction in the region that floods by about 35% can be achieved when using RWHS [85,86]. However, it was found out in one of the studies reviewed that limited labor, high operational expenses, insufficient cash, price changes, inconsistent rainfall, limited accessibility, a shortage of materials, land tenure, and substandard systems available on the market were among the limiting problems faced by end-users [87]. In the Netherlands, utilizing rainwater as a source for decentralized drinking water production has a more negligible ecological impact than using surface water in a centralized system when only consumables are considered [36].

One of the social aspects to be considered is the community's acceptance of the installation and maintenance of RWHS. State agencies must assist householders' increased involvement with their tanks, enhanced understanding of tank operation, and support for tank maintenance education and training [88–90]. The community's attitude, norms, and forms of knowledge about water perception and day-to-day management influence the implementation of water practices and facilitate interaction among stakeholders and local authorities, according to social analysis [64]. To gain crucial insight into the economic viability of RWHS, a detailed cost-benefit analysis should be undertaken for various climate zones [74,91]. Rainwater harvesting has several characteristics appealing to sustainable water resource use: multi-level governance models, increased public participation, increased full-cost recovery, and reduced environmental and social impacts [92]. Policies and regulations reflect regional, national, or international viewpoints and priorities on agreed-upon objectives to offer a framework for defining the rights and obligations of the affected stakeholders. They are shaped to meet their needs [93]. Rainwater can be acceptable to society as an alternative water source because of information campaigns conducted and laws promoting and, in some cases, requiring such solutions. People may be more aware of the potential for saving water and favor alternative solutions [94].

4. Challenges and Future Directions

A more sustainable strategy for exploiting water resources will be necessary to meet water scarcity problems, considering both the quantity and quality of water required for each user. Health risks linked with RWH may be one topic that needs to be addressed immediately. Nevertheless, the greatest challenge in maintaining rainwater quality for its specific consumption is the treatment of harvested roof runoff. Cost and proper maintenance are the factors to be emphasized when utilizing RWHS.

Although green roofs may be the most efficient RWHS that can be used in residential areas, the challenge here is the system's preparation, cost, and maintenance. Moreover, the materials and labor need to be considered before the implementation to give way to the effectiveness and efficiency of the system. Additionally, an extensive study may be conducted on the existing structure to determine the capacity of a building to accept the weight of the green roof. Changes in the design of the structure may be encountered that will incur a more considerable expense. An automated RWHS may also be one of the challenges that some researchers are considering looking into.

With improving dependability and resilience, as well as decreasing susceptibility, RWHS performance becomes more sustainable. Using economic evidence to convince households to adjust existing infrastructure and invest in rainwater retention systems is worthwhile. High operational costs, price volatility, an inconsistent rainfall pattern, insufficient financing, and limited accessibility were all factors that hindered the adoption of RWHS to capture and preserve water. Granting benefits and incentives that may take the form of tax incentives to encourage the compliance of establishments and structures to practice RWH may also be considered. It is also vital to establish consideration when establishing RWH policy. The governing body may establish regulations for RWH, identify acceptable end uses and treatment standards, and require system components, maintenance practice standards, and reuse rates.

Moreover, to advance in the use of decentralized water management alternatives, some changes must occur at various levels and domains, as well as several conditions to be favored: public acceptability of users and other social factors must be assured, costs must be reasonable, health, technical, and environmental risks must be acceptable, new regulations and incentives must be made available, and social learning processes and adaptation capacity must be enhanced. Further, RWH research should concentrate on financial analysis considering multiple benefits, life cycle analysis that includes energy use and greenhouse gas emissions, productive water use, such as boosting rural and urban agriculture, and institutional and socio-political support to improve RWH acceptability.

5. Conclusions

Upon conducting the bibliometric analysis, it was revealed that the growth of stormwater harvesting, particularly from roof catchments, as a topic of interest in the field of research has been on an upward trend. The high co-occurrence of rainwater harvesting in recent years showed the topic's emergence and growing significance. The results of the bibliometric analysis also revealed that sustainability, water demand, and rainwater reuse are the primary concerns of studies on roof runoff harvesting conducted in the last decade. The evolution of rainwater harvesting as a subject, presented through the network map and Sankey diagram, suggests that RWH possesses great potential in addressing water scarcity globally.

The comprehensive review results revealed the characteristics of an RWHS, the quality of roof runoff, and the system's sustainability. The results indicate that rainwater harvesting is one of the sustainable solutions to water scarcity and, potentially, to global warming and climate change. Roof runoff was found to be one of the significant sources of rainwater that can be collected for domestic water purposes, helping to solve the problem of water scarcity. It was also learned that basic yet effective water treatment equipment is necessary to assure higher quality before use. Contamination prevention or treatment systems for RWH should also be addressed at the design stage to reduce contamination, which is mostly caused by TSS, turbidity, and total or fecal coliforms. Green roofs are one of many tools aimed at encouraging more urban greening to make communities greener, healthier, and more resilient to the effects of climate change.

The roof runoff generated from rainfall, if properly collected and preserved, can help alleviate water scarcity in households, although the government must provide subsidies to improve system accessibility. The suggested system should be financially viable, and a return on investment can be expected. The results of this study could help end-users, researchers, and developers choose the best RWHS for a particular desired purpose harvested rainwater may serve.

Author Contributions: K.B.: Data Curation, Investigation, Formal Analysis, Writing—original draft preparation. M.E.R.: Data Curation, Software, Investigation, Formal Analysis, Methodology, Validation, Writing—original draft preparation. M.M.-R.: Conceptualization, Data Curation, Investigation, Formal Analysis, Methodology, Validation, Writing—original draft preparation, Writing—review and editing, Funding acquisition, Visualization, Project Administration, Resources. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Department of Science and Technology (DOST) under the 'DOST's Grants to Outstanding Achievement in Science and Technology Program.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the support of the De La Salle University Research and Grants Management Office for project grant #20 F 2TAY21-3TAY22. The authors would also like to thank Sergi Garbanzos for proofreading the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mekonnen, M.M.; Hoekstra, A.Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2016**, *2*, e1500323. [CrossRef] [PubMed]
2. Burek, P.; Satoh, Y.; Fischer, G.; Taher Kahil, M.; Scherzer, A.; Tramberend, S.; Fabiola Nava, L.; Wada, Y.; Wiberg, D.; Cosgrove, B.; et al. Water Futures and Solution Fast Track Initiative-Final Report. International Institute for Applied Systems Analysis. Laxenburg, Austria, 2016. Available online: https://www.iiasa.ac.at (accessed on 13 June 2022).
3. Tzanakakis, V.A.; Paranychianakis, N.V.; Angelakis, A.N. Water Supply and Water Scarcity. *Water* **2020**, *12*, 2347. [CrossRef]
4. Sui, Q.; Cao, X.; Lu, S.; Zhao, W.; Qiu, Z.; Yu, G. Occurrence, sources and fate of pharmaceuticals and personal care products in the groundwater: A review. *Emerg. Contam.* **2015**, *1*, 14–24. [CrossRef]
5. Li, H.; Lu, Y. Analysis and Evaluation of the Urban Rainwater Harvesting System in Green Buildings. In *E3S Web of Conferences*; EDP Sciences: Shanghai, China, 2019; Volume 118, p. 03028. [CrossRef]
6. Boguniewicz-Zabłocka, J.; Capodaglio, A.G. Analysis of Alternatives for Sustainable Stormwater Management in Small Developments of Polish Urban Catchments. *Sustainability* **2020**, *12*, 10189. [CrossRef]
7. Gee, K.D.; Schimoler, D.; Charron, B.T.; Woodward, M.D.; Hunt, W.F. A Comparison of Methods to Address Anaerobic Conditions in Rainwater Harvesting Systems. *Water* **2021**, *13*, 3419. [CrossRef]
8. Villar-Navascués, R.; Pérez-Morales, A.; Gil-Guirado, S. Assessment of Rainwater Harvesting Potential from Roof Catchments through Clustering Analysis. *Water* **2020**, *12*, 2623. [CrossRef]
9. Ranaee, E.; Abbasi, A.A.; Yazdi, J.T.; Ziyaee, M. Feasibility of Rainwater Harvesting and Consumption in a Middle Eastern Semiarid Urban Area. *Water* **2021**, *13*, 2130. [CrossRef]
10. Huang, Z.; Nya, E.L.; Rahman, M.A.; Mwamila, T.B.; Cao, V.; Gwenzi, W.; Noubactep, C. Integrated Water Resource Management: Rethinking the Contribution of Rainwater Harvesting. *Sustainability* **2021**, *13*, 8338. [CrossRef]
11. Ward, S.; Butler, D. Rainwater Harvesting and Social Networks: Visualising Interactions for Niche Governance, Resilience and Sustainability. *Water* **2016**, *8*, 526. [CrossRef]
12. Bigurra-Alzati, C.A.; Ortiz-Gómez, R.; Vázquez-Rodríguez, G.A.; López-León, L.D.; Lizárraga-Mendiola, L. Water Conservation and Green Infrastructure Adaptations to Reduce Water Scarcity for Residential Areas with Semi-Arid Climate: Mineral de la Reforma, Mexico. *Water* **2020**, *13*, 45. [CrossRef]
13. Hou, L.; Zhang, X. Comparing urban runoff quality of a felt roof and an asphalt road in Beijing. *Hydrol. Res.* **2014**, *45*, 282–291. [CrossRef]
14. Maroneze, M.M.; Zepka, L.Q.; Vieira, J.G.; Queiroz, M.I.; Jacob-Lopes, E. A Tecnologia de Remoção de Fósforo: Gerenciamento Do Elemento Em Resíduos Industriais. *Rev. Ambient. Agua* **2014**, *9*, 445–458. [CrossRef]
15. Stewart, C.; Kim, N.D.; Johnston, D.M.; Nayyerloo, M. Health Hazards Associated with Consumption of Roof-Collected Rainwater in Urban Areas in Emergency Situations. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1012. [CrossRef]
16. Deshmukh, S. Comparitive study on physico-chemical and bacteriological analysis of harvested rainwater and non harvested groundwater. *Rasayan J. Chem.* **2018**, *11*, 331–338. [CrossRef]
17. John, C.K.; Pu, J.H.; Moruzzi, R.; Pandey, M.; Azamathulla, H.M. Reusable rainwater quality at the Ikorodu area of Lagos, Nigeria: Impact of first-flush and household treatment techniques. *J. Water Sanit. Hyg. Dev.* **2021**, *11*, 732–745. [CrossRef]
18. Hamilton, K.A.; Parrish, K.; Ahmed, W.; Haas, C.N. Assessment of Water Quality in Roof-Harvested Rainwater Barrels in Greater Philadelphia. *Water* **2018**, *10*, 92. [CrossRef]
19. Köse-Mutlu, B. Natural organic matter and sulphate elimination from rainwater with nanofiltration technology and process optimisation using response surface methodology. *Water Sci. Technol.* **2021**, *83*, 580–594. [CrossRef]

20. Song, Y.; Du, X.; Ye, X. Analysis of Potential Risks Associated with Urban Stormwater Quality for Managed Aquifer Recharge. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3121. [CrossRef]
21. Scopus Preview—Scopus—Welcome to SCOPUS. Available online: https://www.scopus.com/home.uri (accessed on 24 June 2022).
22. Home—Cortext. Available online: https://www.cortext.net/ (accessed on 24 June 2022).
23. Zhang, L.; Liu, W.; Zheng, B.; Xu, A.; Sun, B. Features of Roof Rainwater Runoff Pollution in a Northern Coastal City under the Effects of Multiple Factors. *Int. J. Sustain. Dev. Plan.* **2020**, *15*, 431–438. [CrossRef]
24. Wahyuningsih, N.D.; Suwartha, N.; Hartono, D.M.; Pratama, M.A. Evaluating the effect of roof type variations on the quality of rainwater runoff for rainwater harvesting development. In *AIP Conference Proceedings*; American Institute of Physics Inc.: Melville, NY, USA, 2020; Volume 2230, p. 050004. [CrossRef]
25. Khayan, K.; Husodo, A.H.; Astuti, I.; Sudarmadji, S.; Djohan, T.S. Rainwater as a Source of Drinking Water: Health Impacts and Rainwater Treatment. *J. Environ. Public Health* **2019**, *2019*, 1760950. [CrossRef]
26. Cupido, A.; Baetz, B.; Guo, Y.; Robertson, A. An evaluation of rainwater runoff quality from selected white roof membranes. *Water Qual. Res. J.* **2012**, *47*, 66–79. [CrossRef]
27. Hossen, A.; Hoque, A.; Salauddin, M.; Pal, S.K.; Muktadir, M.G.; Jahan, H. Evaluation of physicochemical and trace metal qualities of rainwater in the south-eastern region of Bangladesh. *Ann. Laparosc. Endosc. Surg.* **2021**, *70*, 757–772. [CrossRef]
28. Wu, L.; Gao, J.; Zhao, W.; Xu, X.; Yin, Y.; Wu, L. Quality assessment of rainwater and harvested rainwater stored in different types of cisterns. *Water Sci. Technol. Water Supply* **2016**, *17*, 652–664. [CrossRef]
29. Bradford, A.; Denich, C. Rainwater management to mitigate the effects of development on the urban hydrologic cycle. *J. Green Build.* **2007**, *2*, 37–52. [CrossRef]
30. Zdeb, M.; Zamorska, J.; Papciak, D.; Skwarczyńska-Wojsa, A. Investigation of Microbiological Quality Changes of Roof-Harvested Rainwater Stored in the Tanks. *Resources* **2021**, *10*, 103. [CrossRef]
31. Karczmarczyk, A.; Baryła, A.; Kożuchowski, P. Design and Development of Low P-Emission Substrate for the Protection of Urban Water Bodies Collecting Green Roof Runoff. *Sustainability* **2017**, *9*, 1795. [CrossRef]
32. Strzebońska, M.; Gruszecka-Kosowska, A.; Kostka, A. Chemistry and Microbiology of Urban Roof Runoff in Kraków, Poland with Ecological and Health Risk Implications. *Appl. Sci.* **2020**, *10*, 8554. [CrossRef]
33. Hazmi, A.; Rosadi, M.Y.; Desmiarti, R.; Li, F. Effect of Radio-Frequency Treatment on the Changes of Dissolved Organic Matter in Rainwater. *Water* **2022**, *14*, 111. [CrossRef]
34. Lundström, T.S.; Åkerstedt, H.O.; Larsson, I.A.S.; Marsalek, J.; Viklander, M. Dynamic Distributed Storage of Stormwater in Sponge-Like Porous Bodies: Modelling Water Uptake. *Water* **2020**, *12*, 2080. [CrossRef]
35. John, C.K.; Pu, J.H.; Pandey, M.; Moruzzi, R. Impacts of sedimentation on rainwater quality: Case study at Ikorodu of Lagos, Nigeria. *Water Supply* **2021**, *21*, 3356–3369. [CrossRef]
36. Hofman-Caris, R.; Bertelkamp, C.; de Waal, L.; Brand, T.v.D.; Hofman, J.; van der Aa, R.; van der Hoek, J.P. Rainwater Harvesting for Drinking Water Production: A Sustainable and Cost-Effective Solution in The Netherlands? *Water* **2019**, *11*, 511. [CrossRef]
37. Rahman, A. Recent Advances in Modelling and Implementation of Rainwater Harvesting Systems towards Sustainable Development. *Water* **2017**, *9*, 959. [CrossRef]
38. Muktiningsih, S.D.; Putri, D.M.A.R.M.S. Study of the potential use of rainwater as clean water with simple media gravity filters: A review. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing Ltd.: Bristol, UK, 2021; Volume 733, p. 012147. [CrossRef]
39. Fitobór, K.; Quant, B. Is the Microfiltration Process Suitable as a Method of Removing Suspended Solids from Rainwater? *Resources* **2021**, *10*, 21. [CrossRef]
40. Dao, D.A.; Tran, S.H.; Dang, H.T.T.; Nguyen, V.-A.; Do, C.V.; Han, M. Assessment of rainwater harvesting and maintenance practice for better drinking water quality in rural areas. *Aqua Water Infrastruct. Ecosyst. Soc.* **2021**, *70*, 202–216. [CrossRef]
41. Saran, S.; Arunkumar, P.; Devipriya, S.P. Disinfection of roof harvested rainwater for potable purpose using pilot-scale solar photocatalytic fixed bed tubular reactor. *Water Sci. Technol. Water Supply* **2017**, *18*, 49–59. [CrossRef]
42. Lima, C.A.S.; de Souza, R.S.; Almeida, A.K.; de Almeida, I.K. Economic feasibility of a rainwater harvesting system in a residential condominium in the Brazilian Midwest. *Int. J. Sustain. Eng.* **2021**, *14*, 1950–1961. [CrossRef]
43. Amin, M.N.; Nawaz, M.; Han, M. Solar Disinfection of Pseudomonas aeruginosa in Harvested Rainwater: A Step towards Potability of Rainwater. *PLoS ONE* **2014**, *9*, e90743. [CrossRef]
44. Ahmed, S.M.; Zhou, B.; Zhao, H.; Zheng, Y.P.; Wang, Y.; Xia, S. Developing a Composite Vertical Flow Constructed Wetlands for Rainwater Treatment. *Membr. Water Treat.* **2020**, *11*, 87–95. [CrossRef]
45. Bus, A.; Szelągowska, A. Green Water from Green Roofs—The Ecological and Economic Effects. *Sustainability* **2021**, *13*, 2403. [CrossRef]
46. Hardin, M.; Wanielista, M.; Chopra, M. A Mass Balance Model for Designing Green Roof Systems that Incorporate a Cistern for Re-Use. *Water* **2012**, *4*, 914–931. [CrossRef]
47. Da Silva, M.; Najjar, M.K.; Hammad, A.W.A.; Haddad, A.; Vazquez, E. Assessing the Retention Capacity of an Experimental Green Roof Prototype. *Water* **2019**, *12*, 90. [CrossRef]
48. Pirouz, B.; Palermo, S.A.; Turco, M. Improving the Efficiency of Green Roofs Using Atmospheric Water Harvesting Systems (An Innovative Design). *Water* **2021**, *13*, 546. [CrossRef]

49. Flores, P.E.D.; Maniquiz-Redillas, M.C.; Kim, L.-H. Evaluation on the environmental effects of rain garden treating roof stormwater runoff. *J. Wetl. Res.* **2016**, *18*, 10–15. [CrossRef]
50. Słyś, D.; Stec, A.; Zeleňáková, M. A LCC Analysis of Rainwater Management Variants. *Ecol. Chem. Eng. S* **2012**, *19*, 359–372. [CrossRef]
51. Oberascher, M.; Dastgir, A.; Li, J.; Hesarkazzazi, S.; Hajibabaei, M.; Rauch, W.; Sitzenfrei, R. Revealing the Challenges of Smart Rainwater Harvesting for Integrated and Digital Resilience of Urban Water Infrastructure. *Water* **2021**, *13*, 1902. [CrossRef]
52. Bafdal, N. Rainfall Harvesting as Resources of Self Watering Fertigation System with Various Growing Medias. *Int. J. Adv. Sci. Eng. Inf. Technol.* **2016**, *6*, 787. [CrossRef]
53. Custódio, D.A.; Ghisi, E. Assessing the Potential for Potable Water Savings in the Residential Sector of a City: A Case Study of Joinville City. *Water* **2019**, *11*, 2074. [CrossRef]
54. Liuzzo, L.; Notaro, V.; Freni, G. A Reliability Analysis of a Rainfall Harvesting System in Southern Italy. *Water* **2016**, *8*, 18. [CrossRef]
55. Corvaro, S. Water efficiency and economic assessment of domestic rainwater harvesting systems in buildings with one- to three-floor elevations. *Water Sci. Technol. Water Supply* **2019**, *19*, 2422–2434. [CrossRef]
56. Taffere, G.R.; Beyene, A.; Vuai, S.A.H.; Gasana, J.; Seleshi, Y. Reliability analysis of roof rainwater harvesting systems in a semi-arid region of sub-Saharan Africa: Case study of Mekelle, Ethiopia. *Hydrol. Sci. J.* **2016**, *61*, 1135–1140. [CrossRef]
57. Abuelfutouh, N.A.K.; Jamie, M.; Nour, A.; Fuad, N.I. Rainwater harvesting quality assessment and evaluation: IIUM case study. *IIUM Eng. J.* **2020**, *21*, 12–22. [CrossRef]
58. Singh, O.; Turkiya, S. Assessing Potential for Rooftop Rainwater Harvesting:An Option for Sustainable Rural Domestic Water Supply in Arid Region of Haryana. *J. Rural Dev.* **2017**, *36*, 49. [CrossRef]
59. Ross, T.T.; Alim, M.A.; Rahman, A. Community-Scale Rural Drinking Water Supply Systems Based on Harvested Rainwater: A Case Study of Australia and Vietnam. *Water* **2022**, *14*, 1763. [CrossRef]
60. Londra, P.; Theocharis, A.T.; Baltas, E.; Tsihrintzis, V.A. Assessment of rainwater harvesting tank size for livestock use. *Water Sci. Technol. Water Supply* **2017**, *18*, 555–566. [CrossRef]
61. Londra, P.A.; Kotsatos, I.-E.; Theotokatos, N.; Theocharis, A.T.; Dercas, N. Reliability Analysis of Rainwater Harvesting Tanks for Irrigation Use in Greenhouse Agriculture. *Hydrology* **2021**, *8*, 132. [CrossRef]
62. Snir, O.; Friedler, E. Dual Benefit of Rainwater Harvesting—High Temporal-Resolution Stochastic Modelling. *Water* **2021**, *13*, 2415. [CrossRef]
63. Al-Batsh, N.; Al-Khatib, I.A.; Ghannam, S.; Anayah, F.; Jodeh, S.; Hanbali, G.; Khalaf, B.; van der Valk, M. Assessment of Rainwater Harvesting Systems in Poor Rural Communities: A Case Study from Yatta Area, Palestine. *Water* **2019**, *11*, 585. [CrossRef]
64. Pearlmutter, D.; Pucher, B.; Calheiros, C.S.C.; Hoffmann, K.A.; Aicher, A.; Pinho, P.; Stracqualursi, A.; Korolova, A.; Pobric, A.; Galvão, A.; et al. Closing Water Cycles in the Built Environment through Nature-Based Solutions: The Contribution of Vertical Greening Systems and Green Roofs. *Water* **2021**, *13*, 2165. [CrossRef]
65. Domínguez, I.; Ward, S.; Mendoza, J.G.; Rincón, C.I.; Oviedo-Ocaña, E.R. End-User Cost-Benefit Prioritization for Selecting Rainwater Harvesting and Greywater Reuse in Social Housing. *Water* **2017**, *9*, 516. [CrossRef]
66. Oviedo-Ocaña, E.R.; Dominguez, I.; Ward, S.; Rivera-Sanchez, M.L.; Zaraza-Peña, J.M. Financial feasibility of end-user designed rainwater harvesting and greywater reuse systems for high water use households. *Environ. Sci. Pollut. Res.* **2018**, *25*, 19200–19216. [CrossRef]
67. Cureau, R.J.; Ghisi, E. Reduction of Potable Water Consumption and Sewage Generation on a City Scale: A Case Study in Brazil. *Water* **2019**, *11*, 2351. [CrossRef]
68. Zubala, T. The Working Conditions and Optimisation of a Large Rainwater Harvesting and Treatment System in an Area at a Risk of Erosion. *Water Resour. Manag.* **2022**, *36*, 135–152. [CrossRef]
69. Kwon, Y.; Hwang, J.; Seo, Y. Performance of a RBSN under the RCP Scenarios: A Case Study in South Korea. *Sustainability* **2018**, *10*, 1242. [CrossRef]
70. Imteaz, M.A.; Bayatvarkeshi, M.; Karim, R. Developing Generalised Equation for the Calculation of PayBack Period for Rainwater Harvesting Systems. *Sustainability* **2021**, *13*, 4266. [CrossRef]
71. Park, D.; Um, M.-J. Sustainability Index Evaluation of the Rainwater Harvesting System in Six US Urban Cities. *Sustainability* **2018**, *10*, 280. [CrossRef]
72. Godyń, I.; Grela, A.; Stajno, D.; Tokarska, P. Sustainable Rainwater Management Concept in a Housing Estate with a Financial Feasibility Assessment and Motivational Rainwater Fee System Efficiency Analysis. *Water* **2020**, *12*, 151. [CrossRef]
73. Stec, A.; Zeleňáková, M. An Analysis of the Effectiveness of Two Rainwater Harvesting Systems Located in Central Eastern Europe. *Water* **2019**, *11*, 458. [CrossRef]
74. Rahman, S.; Khan, M.T.R.; Akib, S.; Din, N.B.C.; Biswas, S.K.; Shirazi, S.M. Sustainability of Rainwater Harvesting System in terms of Water Quality. *Sci. World J.* **2014**, *2014*, 721357. [CrossRef]
75. Kakoulas, D.A.; Golfinopoulos, S.K.; Koumparou, D.; Alexakis, D.E. The Effectiveness of Rainwater Harvesting Infrastructure in a Mediterranean Island. *Water* **2022**, *14*, 716. [CrossRef]
76. Campisano, A.; D'amico, G.; Modica, C. Water Saving and Cost Analysis of Large-Scale Implementation of Domestic Rain Water Harvesting in Minor Mediterranean Islands. *Water* **2017**, *9*, 916. [CrossRef]

77. Musz-Pomorska, A.; Widomski, M.K.; Gołębiowska, J. Financial Sustainability of Selected Rain Water Harvesting Systems for Single-Family House under Conditions of Eastern Poland. *Sustainability* **2020**, *12*, 4853. [CrossRef]
78. Tavares, L.C.; Bravo, J.M.; Tassi, R.; Almeida, I.R.; Wartchow, D. Socioeconomic potential for rainwater harvesting systems in southern Brazilian municipalities. *Water Supply* **2021**, *22*, 14–30. [CrossRef]
79. Everett, G.; Lamond, J. Green roof perceptions: Newcastle, UK CBD owners/occupiers. *J. Corp. Real Estate* **2019**, *21*, 130–147. [CrossRef]
80. Sámano-Romero, G.; Mautner, M.; Chávez-Mejía, A.; Jiménez-Cisneros, B. Assessing Marginalized Communities in Mexico for Implementation of Rainwater Catchment Systems. *Water* **2016**, *8*, 140. [CrossRef]
81. Chini, C.M.; Canning, J.F.; Schreiber, K.L.; Peschel, J.M.; Stillwell, A.S. The Green Experiment: Cities, Green Stormwater Infrastructure, and Sustainability. *Sustainability* **2017**, *9*, 105. [CrossRef]
82. Hsueh, S.-L.; Feng, Y.; Sun, Y.; Jia, R.; Yan, M.-R. Using AI-MCDM Model to Boost Sustainable Energy System Development: A Case Study on Solar Energy and Rainwater Collection in Guangdong Province. *Sustainability* **2021**, *13*, 12505. [CrossRef]
83. Freeborn, J.R.; Sample, D.J.; Fox, L.J. Residential stormwater: Methods for decreasing runoff and increasing stormwater infiltration. *J. Green Build.* **2012**, *7*, 15–30. [CrossRef]
84. Flores, P.E.D.; Maniquiz-Redillas, M.C.; Geronimo, F.K.F.; Alihan, J.C.P.; Kim, L.-H. Transport of nonpoint source pollutants and stormwater runoff in a hybrid rain garden system. *J. Wetl. Res.* **2016**, *18*, 481–487. [CrossRef]
85. Huang, C.-L.; Hsu, N.-S.; Wei, C.-C.; Luo, W.-J. Optimal Spatial Design of Capacity and Quantity of Rainwater Harvesting Systems for Urban Flood Mitigation. *Water* **2015**, *7*, 5173–5202. [CrossRef]
86. Freni, G.; Liuzzo, L. Effectiveness of Rainwater Harvesting Systems for Flood Reduction in Residential Urban Areas. *Water* **2019**, *11*, 1389. [CrossRef]
87. Bernard, B.; Joyfred, A. Contribution of Rainfall on Rooftop Rainwater Harvesting and Saving on the Slopes of Mt. Elgon, East Africa. *Sci. World J.* **2020**, *2020*, 7196342. [CrossRef]
88. Sharma, A.K.; Gardner, T. Comprehensive Assessment Methodology for Urban Residential Rainwater Tank Implementation. *Water* **2020**, *12*, 315. [CrossRef]
89. Lupia, F.; Baiocchi, V.; Lelo, K.; Pulighe, G. Exploring Rooftop Rainwater Harvesting Potential for Food Production in Urban Areas. *Agriculture* **2017**, *7*, 46. [CrossRef]
90. Fanteso, B.; Yessoufou, K. Diversity and determinants of traditional water conservation technologies in the Eastern Cape Province, South Africa. *Environ. Monit. Assess.* **2022**, *194*, 161. [CrossRef] [PubMed]
91. Xu, W.D.; Fletcher, T.D.; Duncan, H.P.; Bergmann, D.J.; Breman, J.; Burns, M.J. Improving the Multi-Objective Performance of Rainwater Harvesting Systems Using Real-Time Control Technology. *Water* **2018**, *10*, 147. [CrossRef]
92. Domènech, L. *Rethinking Water Management: From Centralised to Decentralised Water Supply and Sanitation Models*; Documents d'Anàlisi Geogràfica: Barcelona, Spain, 2011; Volume 57.
93. Seo, Y.; Park, S.Y.; Kim, Y.-O. Potential Benefits from Sharing Rainwater Storages Depending on Characteristics in Demand. *Water* **2015**, *7*, 1013–1029. [CrossRef]
94. Stec, A.; Słyś, D. Financial and Social Factors Influencing the Use of Unconventional Water Systems in Single-Family Houses in Eight European Countries. *Resources* **2022**, *11*, 16. [CrossRef]