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A Bibliometric Analysis on Hybrid Rainwater Reuse-Greywater Recycling Systems in Buildings

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Abstract

As urbanisation, population growth, and climate change continue to increase, the availability of water resources is declining. Buildings are places where people spend most of their daily lives and are responsible for a significant portion of the consumption of resources. Water is the leading source of these resources. Therefore, efficient and economical water consumption is substantial. Utilising alternative water sources, such as rainwater and greywater, for applications that do not necessitate potable water quality is a key strategy to help minimise the excessive reliance on main water supplies. Integrated systems where rainwater and greywater are used together in buildings or to complement each other are called "hybrid rainwater-greywater systems". This research aims to conduct a bibliometric analysis of existing literature on hybrid rainwater harvesting-greywater recycling systems within buildings. Scopus and Web of Science databases were used for this purpose. The outcomes were visualised using mapping techniques through VOSviewer software. The results indicate that hybrid rainwater harvesting-greywater recycling systems have not yet garnered adequate attention in research. Therefore, it is evident that hybrid water systems will be the subject of more research in the future. In particular, studies on the development of storage tank design and treatment methods that affect these systems' environmental, social, and economic aspects are expected to contribute significantly to developing the sustainability components of hybrid water systems.

1. INTRODUCTION

Approximately three-quarters of the Earth's surface is covered with water. However, only 2.5% of this water can be used by humans [1]. Increasing water demand, water scarcity, water stress, water conflicts, and water management problems due to reasons such as urbanisation, climate change, and population growth are among the most significant issues of our day. For this reason, many studies are being conducted on these issues in our century. While the need for water increases with population growth, rapid urbanisation, and industrialisation, water resources are gradually decreasing and becoming polluted due to environmental pollution, unconscious water consumption, and climate change [2]. In addition, unsustainable water use during the usage phase causes the decrease and pollution of water resources [3]. In light of this, there is a need for more strategic and sustainable methods in water management to relieve the strain caused by the growing demand for water [4].

Although one of the UN 2030 Sustainable Development Goals is “Clean Water and Sanitation”, water scarcity is rapidly growing globally. This situation negatively affects the increasing number of domestic, commercial, industrial, and agricultural water consumers worldwide [5]. Sustainable Development Goals aim to prevent the loss of natural resources by implementing sustainable development policies. Water is at the forefront of these resources. Although water is considered an infinite resource by many people, it has been the subject of many studies that it is gradually decreasing and that water wars will emerge shortly. For this reason, water must be delivered safely to future generations in terms of quantity and quality. Sustainable water management plays a significant role in achieving this requirement. Urban, agricultural, and industrial water use can be completed efficiently with sustainable water management.

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According to a report published by UNICEF and WHO in 2019, approximately 2.2 billion people worldwide do not have access to safe drinking water [5]. This situation, defined as urban water scarcity, is expected to become much more significant in the future. The realisation of this prediction will be a substantial obstacle to achieving the eleventh Sustainable Development Goal, “Sustainable Cities and Communities”, and the sixth, “Clean Water and Sanitation”. Urbanisation, population growth, and socioeconomic development are expected to increase urban, industrial, and domestic water demand by 50-80% in the next thirty years. It is estimated that population growth from 2016 to 2050 will increase water demand, and approximately one billion people will face urban water scarcity [6]. Global water consumption is predicted to increase by 17% in agriculture, 20% in industry, and 70% in domestic consumption in 2025 [7].

Unsustainable water consumption during the usage phase of buildings causes a daily decline and deterioration in water resources [3]. To achieve sustainable water management at the building level, sustainable solutions that reduce water consumption and use alternative water sources must be developed [8]. The most important alternative water sources for saving drinking water include rainwater and greywater [9]. Rainwater and greywater are used at the building scale through rainwater harvesting systems and greywater recycling systems.

Systems where rainwater collected from roofs in buildings is used for purposes that do not require drinking water quality, such as toilet cisterns, garden irrigation, washing clothes, and vehicle washing, are defined as “rainwater harvesting systems.” In this system, rainwater is first flushed away before being transferred to the storage tank via gutters and downpipes on the roofs and then pre-treated to make it ready for use. Systems that purify slightly polluted water from hand wash basins, washing machines, and showers to be used where no manual contact is required, such as toilet flushing and garden irrigation, are called “greywater recycling systems.” These alternative water sources, which are used instead of tap water and provide drinking water savings, also reduce the load on rainwater networks and wastewater discharge systems. Thus, besides their environmental benefits, they contribute economically by lowering water bills.

Hybrid rainwater-greywater systems are systems that allow the use of rainwater and greywater, which are alternative water sources, in an integrated manner within the same building. Greywater coming from sinks, washing machines, and shower/bath/bathroom areas can be treated and used for end-uses such as toilet cisterns and garden irrigation. Rainwater harvested from roofs or impermeable surfaces can be stored and used for end-uses such as toilet reservoir, washing machines, garden irrigation, vehicle washing etc. These two alternative water sources can be evaluated at the same end-use or in different end-uses. This end-use may vary depending on stakeholders such as the consumer or the designer. This study aims o examine the studies conducted on hybrid systems using the bibliometric analysis method.

2.METHOD

Bibliometric analysis is the systematic scanning and statistical examination of research conducted on a subject. The year the study was conducted, the author(s) of the study, the source of publication, and the field of research constitute the subject of bibliometric analysis [10, 11].

Different stages have been specified in other studies for the bibliometric analysis method. These generally consist of 6 basic stages: determining the purpose of the study, data collection, data preprocessing and data cleaning, determining analysis techniques, performing analyses according to the selected techniques, and reporting [12, 13, 14]. The method of this study was created by following these stages.

Step 1: This study aims to examine studies conducted on hybrid water systems in buildings using the bibliometric analysis method.

Step 2: Different databases are used to obtain data using the bibliometric analysis technique, one of the research methods used to examine previous studies on a subject and find research gaps [14]. Scopus and Web of Science databases were used in this study. The databases first show the results by entering the keywords related to the subject to be researched in the search section. Therefore, selecting specific and completely covering words about the subject to be examined is essential. Since this study was conducted as part of research on alternative water resources that can be used in buildings, the keywords “rainwater”, “rainwater harvesting”, “greywater”, and “greywater recycling” were entered into the databases. The “title”, “abstract”, and “keywords” sections were selected in both databases for the places where the search will be made. This study aimed to find publications where the keywords rainwater harvesting and greywater recycling were used simultaneously. For this reason, the “All field” option was not preferred.

After determining the place where the keywords would be searched, a systematic search was performed. This systematic search was performed as ("rainwater" OR "rainwater harvesting" OR "rain water" OR "rainwater reuse" OR "rainwater recycling") AND ("greywater" OR "greywater recycling" OR "greywater reuse" OR "greywater" OR "grey water" OR "grey water recycling" OR "grey water reuse"). Here, the OR command is intended to include any of the words in parentheses in the places where the search will be made, and the AND command is intended to select each word in parentheses. Thus, it is anticipated that studies where both rainwater and greywater are researched together will be reached.

Step 3: After entering the keywords, 41 and 34 studies were reached in Scopus and Web of Science databases, respectively. Then, the English language was filtered, and studies written in different languages were eliminated. After filtering, 40 and 34 studies were reached in Scopus and Web of Science databases, respectively. In addition, pre-processing and data cleaning were performed to correct repetitions and spelling errors. Publications that did not have full text and whose abstracts directly included research outside the building as an alternative water source use location were also separated, and finally, 33 studies were obtained in the Scopus database, and 32 studies were obtained in the Web of Science database. 29 studies in both databases were common, and a total of 36 different studies were found. 2 of these were screening articles, and 3 were congress papers.

Step 4: To perform the bibliometric analysis, citation analysis, co-citation analysis, keyword analysis, bibliographic coupling analysis, and co-authorship analysis techniques were used. In addition, analyses were performed regarding the publication years and research areas of the studies.

Step 5: The free VOSviewer software was developed to visualise the results of bibliometric analyses (Van Eck and Waltman, 2010). The results obtained from the databases were transferred to the VOSviewer software and presented as bibliometric mapping.

Step 6: The results of the bibliometric analysis, network maps, and visualisations are presented in the discussion and results section.

3. FINDINGS AND DISCUSSION

In this section, the findings from the analysis are showcased through the application of bibliometric analysis methods and the VOSviewer software. Furthermore, the outcomes are examined by considering the aspects of publication years, authorship, nations, keywords, sources, research fields, and institutions.

3.1. Publication Years

Figure 1 illustrates the number of studies conducted on the subject in the databases by year. The years in which regular publications appear on a topic are those in which active publications are made [12]. Both databases, 2012 to 2018, are active publication years for this topic. At least 2 studies have been published in both databases from 2015 to the present. Since the number of publications regarding the studies that constitute the subject of this study is limited, year filtering was not performed.

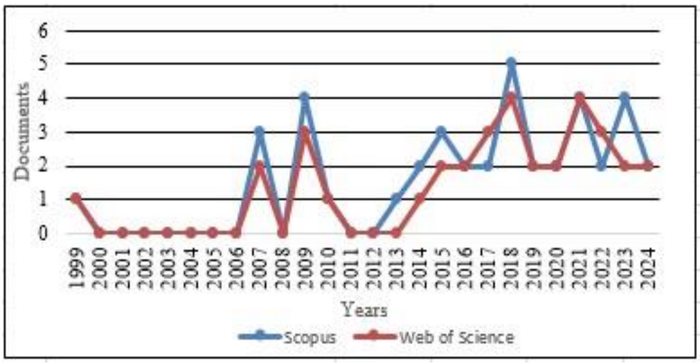

Figure 1. *Publications by years (Scopus and WOS database)*

3.2. Analysis of Authors

Table 1 presents the publication and citation counts of the authors who contributed to the research identified in the databases. Notably, Ghisi, E., Chong, M. M., Leong, J. Y. C., and Poh, P. E. have conducted considerable research in this area and received numerous citations. Although Stec, A. has three publications listed in the Scopus database, he trails behind the other authors regarding the citation totals. Therefore, it can be concluded that the works of the authors highlighted in Table 1 should certainly be explored in future research on hybrid water systems.

Table 1. *Authors by Documents and Citations (Scopus and WOS, 2024)*

	Scopus		**Web of Science**	
Author	**Documents**	**Citations**	**Documents**	**Citations**
Ghisi, E.	6	345	6	323
Chong, M.N.	2	135	2	115
Leong, J. Y. C.	2	135	2	115
Poh, P. E.	2	135	2	115
Stec, A.	3	85	2	62
Oviedo-Ocana, E.R.	2	70	2	59
Ward, S	2	70	2	59
Mo, W.	2	22	2	19

The bibliographic matching of authors in the studies obtained from the Scopus database is shown in Figure 2. In the analyses, the minimum number of publications for an author was selected as 2, and the minimum number of citations was selected as 1. 8 out of 120 authors provided the threshold values. The most substantial connection belongs to Ghisi, E., who is in the middle of the network centre. It was determined that the authors in the publications in the Scopus database formed two different clusters. Chong, M. M., Leong, J. Y. C., and Poh, P. E., who follow Ghisi, E. regarding publication and citation numbers, formed the green cluster. Other than these, Oviedo-Ocana, E. R., Ward, S. Mo, W. and Stec, A. formed the red cluster together with Ghisi, E. It is concluded from this that the authors with the most publications and citations have established a powerful academic connection with each other in their studies. It is understood that they have greatly influenced each other in their studies and that it is essential to review the works of these authors in the studies to be carried out in the following years.

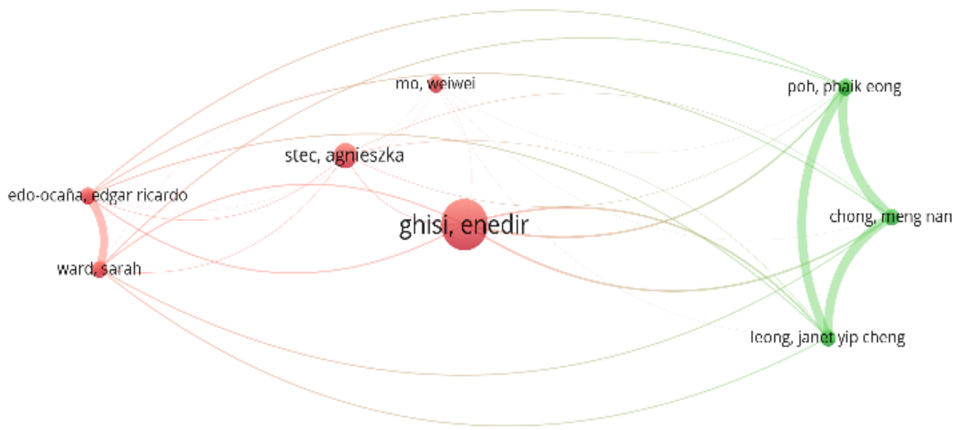

Figure 2. *Bibliographic coupling of authors (Scopus, 2024)*

Similar results are also seen in the Web of Science database analysis. 9 out of 99 authors met the threshold values of at least 2 publications and at least 1 citation. The bibliographic matching of authors of publications obtained from the Web of Science database is shown in Figure 3. These results formed 2 different clusters. The authors forming the green cluster are Chong, M. M., Leong, J. Y. C., and Poh, P. E., as in the results obtained from the Scopus database. The authors forming the red cluster are Ghisi, E., Oviedo-Ocana, E. R., Ward, S. Mo, W., and Stec, A., as in the results obtained from the Scopus database. In addition to these authors, Dominguez, I. is also included in the red cluster in the results obtained from the Web of Science database.

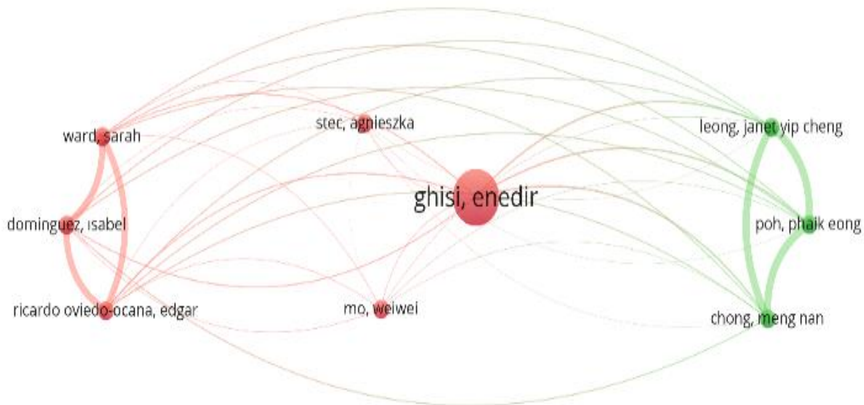

Figure 3. *Bibliographic coupling of authors (WOS, 2024)*

3.3. Analysis of Countries

Figure 4 illustrates the number of publications from various countries concerning the study topic. Brazil stands out as the leading country with 8 publications across both databases. The prominent factor contributing to Brazil's leadership in this study area is Ghisi, E., who also ranks highest in the author analysis. In the publication data from the Scopus database, the United Kingdom has 5 publications, followed by China and the USA, each with 4. Additionally, Australia, Colombia, Germany, Malaysia, and Poland contributed 3 publications on the topic. In the Web of Science database results show that China and the USA tied for second place with 5 publications, trailing behind Brazil. The United Kingdom follows with 4 publications, while Australia, Colombia, and Germany each have 3. The publication counts for these three countries are the same in both databases. Malaysia and Poland each have 2 publications, which are also equal. Czech Republic has 2 and 1 publications in Scopus and Web of Science databases, respectively.

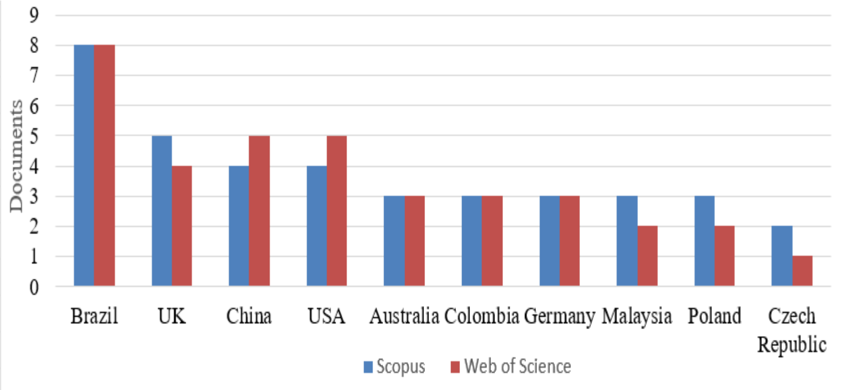

Figure 4. *Publications by Countries (Scopus and WOS, 2024)*

The connection between the countries where the most cited studies in the Scopus database were conducted is shown in Figure 5. The map was created according to the countries where at least 2 publications were made, and at least 1 citation was received. 8 out of 24 countries met the threshold values. Brazil, one of the countries with the most publications, is also at the centre of the map of the countries with the most citations and the most substantial network. Colombia, Australia, Poland and Great Britain are the other countries that make up the red cluster with Brazil. China, Malaysia and the USA are the countries that make up the green cluster.

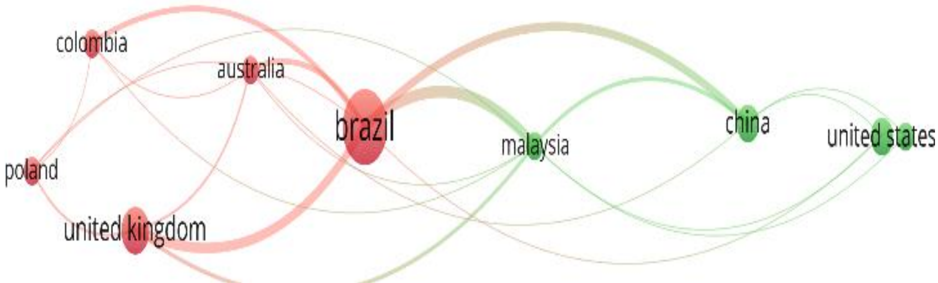

Figure 5. *Most Cited Countries (Scopus, 2024)*

The results in the Web of Science database are shown in Figure 6. In this database, 9 out of 20 countries met the threshold values. According to the results obtained from the Web of Science database, as in the results obtained from the Scopus database, two clusters, green and red, were formed in the connection map created according to the citations of the countries. In the graph, where Malaysia, China, the USA and Germany, which form the green cluster, have a strong connection, the interaction between Brazil, Australia, England, Poland and Colombia, which form the red cluster, is seen.

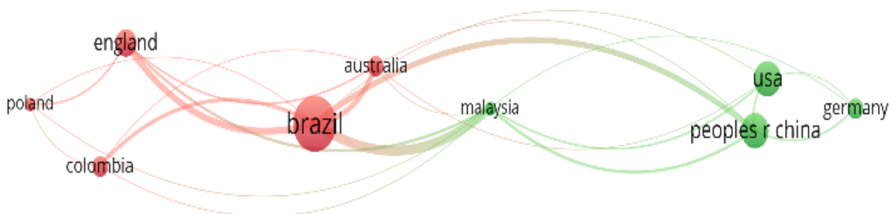

Figure 6. *Most Cited Countries (WOS, 2024)*

3.4. Co-occurrence of Keywords

Figure 7 displays a map of keywords that appear in at least two publications from the Scopus database studies. Out of 134 keywords, 21 exceeded the threshold value. These 21 identified keywords were reviewed for any duplicates or spelling mistakes. The terms rainwater, greywater, rainwater harvesting, and greywater reuse are prevalent across nearly all clusters. Additionally, the red cluster includes terms such as potable water savings, final water consumption, and financial analysis. A similar pattern is found in the green cluster, where stormwater management and greywater reuse keywords are accompanied by water conservation and minimization of wastewater. The blue cluster comprises rainwater harvesting and greywater recycling, along with water savings and green roofs. Other significant keywords pertinent to hybrid water system research include environmental impact, financial feasibility, sustainability, greywater treatment, and domestic water supply. This leads to the conclusion that many studies focus on economic analyses and environmental impact assessments related to water savings through alternative water sources.

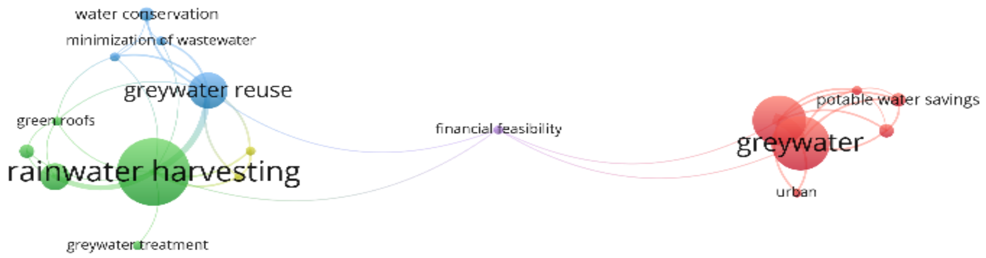

Figure 7. *Co-occurrence of keywords (Scopus, 2024)*

Figure 8 shows the mapping of keywords found in at least 2 different studies in the Web of Science database according to the number of citations. 18 words out of 119 provided threshold values. Similar clusters formed by the results in the Scopus database are also found in the results obtained from the Web of Science database. The red cluster consists of rainwater, greywater, urban, water end-uses, potable water savings, and financial analysis. The blue cluster consists of greywater reuse, stormwater management, minimization of wastewater, and water conservation. The green cluster consists of green roofs and water savings, greywater recycling, and rainwater harvesting. In addition, similar to the results obtained from the Scopus database, the words life cycle assessment, environmental impact, financial feasibility and greywater treatment are other keywords used in hybrid water system studies.

Figure 8. *Co-occurrence of keywords (WOS, 2024)*

3.5. Analysis of Sources

The first five sources of documents related to the research topic, ranked according to both publication and citation numbers, are given in Table 2. While the Journal of Cleaner Production leads in the number of publications, the Building and Environment source has a higher citation count. This pair of sources is succeeded by Water (Switzerland), Desalination, and Urban Water Journal. Similar to Scopus, the Journal of Cleaner Production also ranks first in publications within the Web of Science database. Thus, it is evident that the Journal of Cleaner Production is one of the key journals related to this subject. It has also been determined that the journals listed in the top five are prevalent across both databases.

Table 2. *Top 5 Sources by Documents and Citations (Scopus and WOS, 2024)*

	Scopus		Web of Science	
Journal	**Documents**	**Citations**	**Documents**	**Citations**
Building and Environment	2	299	2	283
Journal of Cleaner Production	5	247	8	261
Water (Switzerland)	3	81	4	65
Desalination	2	207	2	176
Urban Water Journal	2	14	3	73

Figure 9 shows the bibliographic coupling of the sources where the studies in the Scopus database are published. The red cluster consists of the sources that form 3 different clusters: Journal of Cleaner Production, Water (Switzerland), Urban Water Journal and Resources, Conservation, and Reuse. The blue cluster comprises Water Science and Technology and Desalination, while the green cluster comprises Building and Environment and Water Science and Technology.

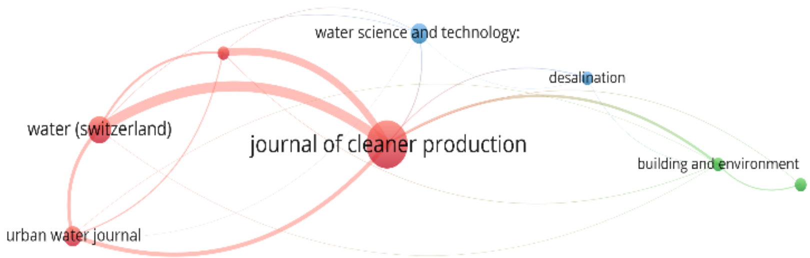

Figure 9. *Bibliographic coupling of sources (Scopus, 2024)*

According to sources, Figure 10 illustrates the bibliographic coupling of publications in the Web of Science database. Similar to the results in the Scopus database, the Journal of Cleaner Production is again at the centre of the network. In addition, other sources that make up the red cluster are Urban Water Journal, Water (Switzerland), and Water Science and Technology. Resources, Conservation and Reuse and Building and Environment are other notable sources.

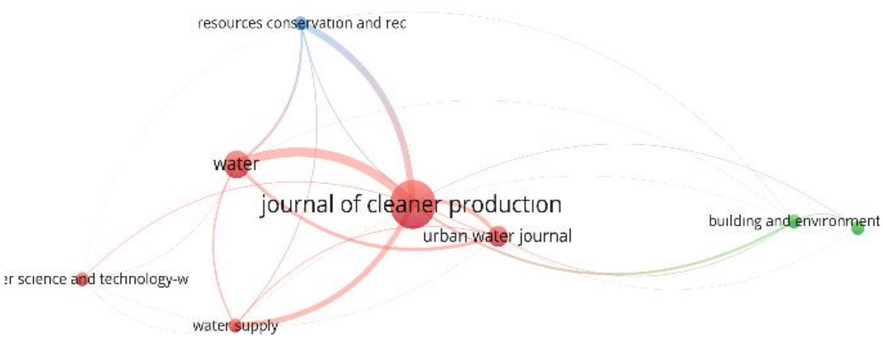

Figure 10. *Bibliographic coupling of sources (WOS, 2024)*

3.6. Research Areas

Table 3 includes the publication numbers and percentages of studies obtained from the Scopus database according to their fields of study. Studies on hybrid systems are included in the fields of Environmental Science, Engineering, Social Sciences and Energy. The number of documents in the table is higher than the total number of studies obtained because a document falls into more than one research field.

Table 3. *Research Area Categories (Scopus, 2024)*

Research Area	Documents	Percentage
Environmental Science	37	38.5%
Engineering	14	14.6%
Social Sciences	12	12.5%
Energy	8	8.3%
Business, Management and Accounting	7	7.3%
Agricultural and Biological Sciences	4	4.2%
Biochemistry, Genetics and Molecular Biology	4	4.2%
Chemical Engineering	2	2.7%
Chemistry	2	2.1%
Economics, Econometrics and Finance	2	2.1%
Other	2	2.7%

A similar situation is seen in the results in Table 4 obtained from Web of Science. Engineering, Environmental Sciences Ecology, and Water Resources research areas are where hybrid water systems studies are published the most. In addition to these areas, Construction Building Technology, Geography and Geology fields are included in the research areas of hybrid rainwater harvesting-greywater recycling systems studies.

Table 4. *Research Area Categories (WOS, 2024)*

Research Area	Documents	Percentage
Environmental Sciences Ecology	23	67.6%
Engineering	22	64.7%
Water Resources	17	50%
Science Tech. Other Topic	7	20.6%
Construction Building Technology	2	5.9%
Geography	1	2.9%
Geology	1	2.94%

3.7. Analysis of Affiliations

The affiliations to which the authors of the studies on hybrid water systems are affiliated are listed in Table 5. Since many organisations are related to this study topic, the first 5 organisations with the most publications are included in the table. According to the results in the two databases, hybrid system studies appear the most prevalent in Universidade Federal de Santa Catarina, with 7 publications. The main reason is that Ghisi, E. works in this organisation. The University of Exeter has the same number of publications in both databases, with 3. Politechnika Rzeszowska im. Ignacego Łukasiewicza and Universidad Industrial de Santander have 3 and 2 publications in Scopus and Web of Science databases, respectively. Monash University Malaysia is ranked 5th in both databases with 2 publications.

Table 5. *Affiliations by Documents (WOS, 2024)*

Research Area	Scopus	WoS
Universidade Federal de Santa Catarina	7	7
University of Exeter	3	3
Politechnika Rzeszowska im. Ignacego Łukasiewicza	3	2
Universidad Industrial de Santander	3	2
Monash University Malaysia	2	2

3.8. Description of Studies

Alternative water source systems have been the subject of many studies in the literature from social, economic and environmental perspectives. In addition, there are studies in the literature examining the quality of these resources.

Several studies have noted that water saving effectiveness has been evaluated in the context of environmental or economic evaluations of alternative water supply systems. This focus is due to the fact that the primary aim of these systems is to help decrease water usage or, in simpler terms, to conserve water.

One of the basic components of alternative water source systems is the storage tank. Tank design dramatically affects the performance of alternative water source systems both environmentally and economically. Another critical component of these systems is the treatment method. Especially the fact that greywater is more polluted than rainwater has led to the development and increase of greywater treatment technologies. Treatment methods affect alternative water source systems both environmentally and economically and in terms of water quality. Therefore, selecting the proper treatment method affects the system's performance as much as the tank sizing.

Table 6 presents research on evaluating alternative water resources, focusing on environmental, social, and quality factors. These studies explored various treatment techniques or assessed water quality without any treatment. The findings indicated that rainwater necessitates less treatment because it is cleaner than greywater. After the first flush separation, rainwater can be utilised for washing vehicles, washing clothes, irrigation, cleaning floors, cooling towers, fire hydrants, emergency tanks, and toilet flushing. Following a series of treatment processes, greywater can be employed for toilet flushing and irrigation, which do not require drinking water standards. Different studies applied chemical, physical, and biological treatment methods either in combination or individually. It was determined that while extending the greywater treatment process improves water quality, it tends to diminish both environmental and economic efficiency.

When the studies that addressed the issue from an environmental perspective were examined, it was seen that greywater recycling systems were considered independent of the climate. Greywater is produced regularly and reducing the load on sewage systems. Additionally, when a treatment method such as an artificial wetland is used, it can have less environmental impact than rainwater harvesting systems. [24, 27]. The most significant environmental contributions of alternative water sources are the reduction of water consumption and the load on the urban sewage and rainwater infrastructure networks.

On the other hand, Table 6 includes studies on the perspectives of suppliers, local administrators, and users who are stakeholders of alternative water resources. In these studies, it has been determined that users generally have a more positive view of rainwater than greywater. In studies on water quality, basic methods used to treat greywater have been included. It has also been observed that the desire to use alternative water resources varies in different cultures and countries. Therefore, the storage volume and treatment method must be user-oriented when designing alternative water resources systems.

Table 6. *Studies examining alternative water resources in terms of quality, environmental and social aspects*

Study	Aim	Findings
[16]	Quality (Comparing rainwater and greywater quality)	There are many pollutants found in reservoirs fed with greywater. Rainwater and mains water are of similar quality.
[17]	Quality (Impact of rainwater and greywater treatment methods in office buildings)	Rainwater treatment has been found to be more economical and effective than greywater treatment.
[18]	Quality (Quality status of alternative water sources after treatment)	It has been determined that greywater can be used after basic treatment and that rainwater will require less treatment.
[19]	Social (Socio-economic motivation for using alternative water sources)	A survey conducted over the Internet has concluded that women and low-income households use alternative water sources more.
[20]	Social (User and manager perspectives on alternative water sources)	The surveys conducted with managers and users have found that the perspective on greywater is negative due to health risks.
[21]	Social (User perspectives on greywater and rainwater systems)	A survey conducted in 200 households has concluded that 80% of the participants would be willing to use the systems if the necessary incentives were provided.
[22]	Social (Motivation for using alternative water sources)	As a result of the surveys, it has been concluded that the number of households and low income increase the use of alternative water sources.
[23]	Social (Acceptability of alternative water sources)	A survey conducted with 1200 participants in 12 countries has concluded that 75% of the participants would be willing to use the systems if there is an economic incentive.
[24]	Environmental (Energy saving potential of rainwater and greywater systems)	The greywater system has shown 50% better energy performance than rainwater due to the use of artificial wetlands in treatment.
[25]	Environmental (Environmental performance of hybrid systems)	Hybrid systems provided 41.9% water savings and 40% wastewater reduction.
[26]	Environmental (Impact of green roof system on greywater treatment and rainwater collection)	The green roof improved greywater quality and reduced rainwater runoff.
[27]	Environmental (Environmental performance of alternative water sources)	Since the greywater system does not consider treatment, the greywater system provided 3 times more energy savings than the rainwater system.

Table 7 includes studies examining alternative water source systems economically. Different building types across various countries have produced varying outcomes in these studies. The reason for the different results is that there are many variables affecting the performance of these systems. Variables such as location, building type, number of users, rainwater demand, where rainwater will be collected, and the tank size of the rainwater harvesting system affect the investment cost. On the other hand, end-uses constituting the greywater source, greywater demand, and greywater treatment methods also affect the investment cost of the greywater recycling system as well as the operating and maintenance costs.

Another factor affecting the economic performance of the systems is the economic status of the countries. Although different financial indicators are selected in different studies when evaluating economic performance, net present value, payback period, internal rate of return, and benefit/cost are the most frequently selected indicators. While some research suggests that alternative water sources are financially feasible [32, 29, 28, 33, 36, 30, 35], other studies have determined that they are not economically favourable [37, 9]. Although the climate zone where the system will be installed, different purification methods, the economic situation of the countries, water prices, and electricity prices reveal this difference, it can be said that the most critical factor affecting the economic attractiveness of the systems is the investment cost.

Table 7. *Studies examining the economical performance of alternative water sources*

Study	Aim	Finacial Indicators	Findings
[9]	Economic analysis of rainwater and greywater systems	[1]PP, [2]NPV	The payback periods of the systems were found to be high. They are not economically attractive.
[28]	Economic analysis of rainwater and greywater systems in multi-storey residential buildings	PP, NPV	The payback periods of hybrid systems were found to be less than 8 years.
[29]	Life cycle cost analysis of rainwater and greywater systems	NPV, PP	Although the systems were high-cost, they were found to be economically viable.
[30]	Economic analysis of hybrid system in university building	[3]B/C, PP	48% water savings were achieved with the hybrid system. A payback period of 6 years was found.
[31]	Economic analysis of rainwater and greywater systems	PP, NPV, B/C, [4]IRR	It was concluded that only greywater and hybrid systems could be applied, and the rainwater system alone was not economical.
[32]	Economic evaluation of rainwater and greywater systems	PP, NPV, B/C	Hybrid systems were found to be more economically viable.
[33]	Water saving and economic analysis of hybrid system	PP, NPV	The hybrid system saved 51.6% of water. A payback period of 5.25 years was found.
[34]	Life cycle cost analysis of greywater and rainwater systems	PP	It was concluded that the greywater system had a demand meeting rate of 70-90% and the rainwater system had a demand meeting rate of 50-70%.
[27]	Economic performance of alternative water sources	NPV	The greywater system provided 10 times more net present value than the rainwater system, depending on the treatment system.
[35]	Economic performance of hybrid systems	PP	It was concluded that the hybrid system had a payback period of less than 5 years.
[36]	Economic evaluation of hybrid water system	NPV, IRR, PP	The hybrid system provided 38% water savings. The payback period was found to be slightly more than 10 years.
[37]	Economic analysis of hybrid water systems	NPV, B/C, PP	It was concluded that the hybrid system was not economically attractive due to high investment costs.
[38]	Economic analysis of rainwater and greywater systems	NPV, PP, IRR	It was concluded that the payback periods of hybrid systems vary between 89-132 months.

[1]PP: Payback Period, [2]NPV: Net Present Value, [3]B/C: Benefit/Cost, [4]IRR: İnternal Rate of Return

Table 8 includes studies examining alternative water sources in terms of water-saving potential. Most studies revealed that hybrid rainwater harvesting-greywater recycling systems provide more water savings compared to systems where the sources are used alone. When two different sources are compared, only one study was found where the water-saving potential of the rainwater system was better than that of the greywater system [24]. Compared to other studies, the greywater system was superior to the rainwater system regarding water saving. The most important reason for this is that the greywater system is not dependent on the climate. The rainwater harvesting system has more unknowns compared to the greywater recycling system. For this reason, it has fallen chiefly behind the greywater system in terms of efficiency.

Table 8. *Studies examining the water saving performance of alternative water sources*

Study	Aim	Findings
[39]	Performance and efficiency of hybrid systems	It was concluded that adding a rainwater system to a greywater system had no effect in terms of water efficiency.
[40]	Evaluation of the potential of alternative water sources	Greywater was found to be more advantageous than rainwater due to its independence from climate.
[41]	Systems that can solve water shortages due to climate change	The importance of alternative water sources was emphasized.
[42]	Environmental impact of green roof, rainwater, and greywater systems	The highest level of water saving was achieved when greywater and rainwater were used together.
[30]	Performance of hybrid system in university building	The hybrid system provided 48% water saving and 59% wastewater reduction.
[24]	Water saving potential of rainwater and greywater systems	In terms of water saving, the rainwater system provided twice as much savings as the greywater system.
[43]	Reservoir design for alternative water sources in Ankara	Around 40-46% of water saving was achieved with the hybrid system.
[44]	Performance analysis of alternative water sources	The hybrid system provided more water savings than when alternative water sources were used alone.
[45]	Hybrid system performance in residential and commercial buildings	Hybrid systems were found to be more effective than when alternative water sources were used alone.
[46]	Performance of hybrid system in office building	The hybrid system reduced water consumption and wastewater discharge.
[47]	Evaluation of the efficiency of alternative water sources	It was determined that greywater was more effective in areas with high populations.

Table 9 includes information on the rainfall data, discount rates, and storage tank design methods used in studies examining alternative water sources from environmental, economic, and social perspectives. It also includes information on the final consumptions that constitute the greywater source and the purposes for which the alternative water sources are used. It is observed that most studies use at least 10 years of precipitation data. Since the discount rates are selected according to the economic conditions of the countries, different rates have been evaluated in different studies. In the studies examined, end-uses that constitute the greywater source were selected as the water coming from the bathroom, sink, and washing machine, which is relatively less polluted. On the other hand, alternative water sources were generally used for purposes such as toilet flushing, cleaning, irrigation, and emergency tanks that do not require drinking water quality [48]. Different software and methods were used in different studies to select the storage capacity of the alternative water source [49]. These methods are mainly based on the water balance model.

Table 9. *Studies examining the water-saving performance of alternative water sources*

Study	Rainfall Data (Year)	Discount Rate (%)	Greywater Supply	Greywater Demand	Rainwater Demand	Tank Design Method
[9]	34	1, 5, 10	[1]S., [2]L., [3]W.M.	[4]T.	T.	Neptune software
[28]	3	N.A.	S., L., W.M.	T.	T., W.M.	Neptune software
[40]	80	N.A.	S.	W.M., T., [5]I.	T.	UVQ tool (WBM)
[30]	30	3	S., L., W.M.	T., I.	T., I.	[9]WBM
[43]	45	N.A.	S., L., W.M.	T., I.	T., I.	Rippl Method
[31]	24	3.5	L. ve S.	T.	I., [6]C., W.M.	Trial and error method
[44]	13	N.A.	B., L., W.M.	T., I.	T., I.	SWMM software
[32]	15	6.05	B.	T., I.	T., I., Te., W.M.	Trial and error method
[45]	35	N.A.	B., L., W.M.	T., I.	T., I.	RainTANK tool (WBM)
[33]	10	2.88	W.M.	T.	Ç.M.	Netuno software
[34]	10	0-6	B., L., W.M.	T., I.	T., I.	Vensim software (WBM)
[27]	30	3	B., L., W.M.	T., I.	T., I.	Python software (WBM)
[37]	20	3.5	L.	T.	I., [7]E.T., [8]C.T.	WBM
[38]	12	6.73, 11.73, 16.73	B. ve L.	T.	W.M.	Netuno software

[1]S: Shower, [2]L: Lavatories, [3]W.M.: Washing Machine, [4]T: Toilet cistern, [5]I: Irrigation, [6]C: Cleaning, [7]E.T.: Emergency Water Tank, [8]C.T.: Cooling Tower, [9]WBM: Water Balance Model

4. CONCLUSION AND RECOMMENDATIONS

The aim of this research is to investigate the importance and role of hybrid water systems combining rainwater and greywater for purposes where drinking water quality is not required in buildings. Previous research on this topic was reviewed using the Scopus and Web of Science databases with the search terms "rainwater harvesting and greywater recycling." After filtering, 33 studies were identified in the Scopus database and 32 in the Web of Science database. It was found that 29 of these studies were present in both databases, resulting in a total of 36 distinct studies. These studies were evaluated based on the year of publication, country of publication, author(s), research area, source of publication, and the affiliation where they were published. The findings were gathered from the databases concerning these categories.

Due to the limited number of studies on this topic, no year filtering was conducted. Aside from the period between 2012 and 2018, there were no active years concerning hybrid water systems. Consequently, it was determined that this topic has not yet garnered significant interest from researchers. However, it was found that a substantial number of publications originated from countries like Brazil, Great Britain, China, and the USA, despite them not being leading nations in the field of hybrid water systems.

The primary research domains concerning hybrid rainwater harvesting and greywater recycling systems include environmental science, engineering, social sciences, and energy research. Following these are disciplines like water resources and chemistry. The Journal of Cleaner Production and Building and Environment are prominent publications in this area. Other significant sources for studies on hybrid water systems include water-focused journals such as Water (Switzerland), Desalination, and Urban Water Journal.

When the affiliations are examined, Universidade Federal de Santa Catarina and Monash University Malaysia lead the way in hybrid water systems studies. Apart from these, no other noteworthy affiliation was found. It was determined that Ghisi, E., who works for Universidade Federal de Santa Catarina, is the leading author in this field. Brazil is at the top among the countries with the most publications thanks to Ghisi, E., who has 6 documents in both Scopus and Web of Science databases. When the authors with the most publications and citations were examined, it was revealed that the 6 authors following Ghisi, E. have the same number of publications with 2.

The keywords "rainwater harvesting, greywater recycling, potable water saving" were found together in the analyses, and "financial analysis, economic analysis" emerged remarkably. This situation emphasises the importance of economic feasibility studies regarding hybrid water systems. Hybrid water systems at the building scale have been the subject of many studies in terms of environmental, economic, and social aspects. Except for a few studies, it has been concluded that alternative water sources are generally economically feasible. It has been determined that the most critical environmental contributions of alternative water sources are water saving and reducing the load on the sewage and rainwater network infrastructure. The studies conducted from the perspective of alternative water sources determined that the participants were mainly reluctant to use greywater. It has been determined that the perspective on rainwater is better compared to greywater.

It has been observed that in studies where economic analyses of alternative water resources are made, at least 10 years of rainfall data are used, and the discount rate is selected according to the economic situation of the country where the research is conducted. During the design phase, the selection of where to obtain and where to use rainwater and greywater systems is made. It has been seen that various software is used to determine the volume of the tank, which is one of the essential components of alternative water resources systems. All of these software are based on the water balance model.

Alternative water systems vary in economic and environmental aspects depending on many factors such as location, size, building type, treatment method, number of users. Each situation is unique. Therefore, each needs to be designed and examined from environmental and economic perspectives. Which alternative water source will be used and how it will be used is determined during the design phase. Thus, the more efficient one is selected during the operation phase.

Future studies to improve and develop the feasibility of hybrid water systems are of great importance. Specifically, the design of storage tanks and treatment methods are fundamental elements that influence the utilization of alternative water sources across environmental, economic, and social dimensions. The social acceptability and financial feasibility of the proposed research on these components will play a direct role in minimizing environmental impacts. Last but not least, future research on advancing storage tank design and treatment techniques is expected to facilitate using alternative water resources.

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