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Water Resource Management in Sustainable Architecture: A Bibliometric Review of Green Buildings and Water Footprint Reduction

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Abstract

Water management has become a critical dimension of sustainable architecture, as buildings increasingly interact with limited freshwater resources and energy-intensive water treatment systems. In this context, the present study provides a comprehensive bibliometric analysis and review of scientific research addressing water management within sustainable buildings in order to assess the most important quantitative information about this topic and identify the most relevant research trends. A total of 3283 documents indexed in Scopus before 2024 were identified and analyzed through a two-stage approach combining bibliometric performance indicators and network analysis using SciMAT (v1.1.06). Publication trends, document types, leading countries, institutions, sources, and thematic distributions were examined, followed by analysis of the conceptual evolution of the field. Results revealed a sustained growth in scientific output, with engineering, environmental science, and materials science as the dominant subject areas. Keyword and cluster analyses identified construction materials and their water-related properties and water resource management as central research themes, while also highlighting the nexus between water, energy, and environmental impacts in building sustainability. Based on the bibliometric findings, a structured review of current research is presented following a circular-economy-oriented framework adapted to water, organized around three strategies: decreasing water demand, optimizing the use of non-conventional water resources, and retaining water through reuse.

Keywords: sustainable architecture; green building; sustainable construction; water footprint; water management; water saving; water reuse; bibliometric analysis

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1. Introduction

Sustainable architecture has become a key response to the growing environmental, social, and economic pressures on the construction sector. Driven by urban expansion and rising infrastructure demand, it promotes the efficient use of natural resources to reduce environmental impact [1]. This integrated and ethical approach emphasizes closed-loop resource cycles, recycling, and the use of non-toxic low-impact materials [2]. Within this context, consideration of water management has gained increasing relevance, as the construction industry interacts directly with limited freshwater supplies and indirectly with energy-intensive water treatment systems. Therefore, sustainable architecture must incorporate both quantitative and qualitative indicators related to water resource management, recognizing that water scarcity, climate variability, and stricter environmental regulations are reshaping construction practices worldwide. Water management is central to this framework, incorporating reduction, conservation, reuse, and innovative systems for the utilization of non-conventional water resources. Buildings are no longer understood solely as consumers of water but as active components of urban hydrological systems, capable of capturing, storing, and treating water flows [3]. This perspective reinforces the need to design infrastructures that are resilient under fluctuating water availability and capable of minimizing dependence on external supplies.

Responsible water management is critical for sustainable construction, as water is indispensable in numerous processes such as concrete production, curing, cleaning, and other essential activities. The construction sector, accounting for approximately 16% of global water consumption, faces the pressing challenge of reducing its impact on water resources [4]. Achieving this goal requires not only improving water-use efficiency but also preventing the contamination of natural sources, such as aquifers and surface waters [5]. Inadequate handling of construction residues, chemical additives, suspended solids, or cementitious materials can generate diffuse pollution that compromises ecological quality and human access to safe water supply. Consequently, preventive strategies (including site preparation, runoff control, sediment barriers, and adequate storage of hazardous products) become essential elements of sustainable practice. Material design and selection also play a crucial role since industrialized products, which require fewer on-site operations, generally consume less water than traditional systems [6]. Prefabrication, modular construction, and dry-assembly techniques reduce reliance on water-intensive tasks and rationalize construction schedules while lowering environmental impacts [7,8]. Furthermore, practices such as water reuse and use of non-conventional water resources are useful in minimizing water consumption in construction [9,10]. These measures broaden the portfolio of available water resources, enabling the use of non-potable supplies for cleaning, dust control, or concrete mixing when quality requirements permit. The adoption of these strategies supports a construction model better adapted to the challenges of water scarcity and climate change, where the optimization of water consumption is inseparable from energy efficiency, material circularity, and environmental protection.

Apart from direct water consumption in the construction sector, indirect water consumption constitutes a significant share of the overall environmental impact associated with building projects. This category includes the water used in the production of materials and components essential for construction, such as structural and architectural elements [11]. The water footprint of these materials varies considerably depending on raw material extraction, manufacturing processes, transportation distances, and the degree of industrialization. Careful evaluation of available materials and construction methods in the selection of materials with lower water intensity and the adoption of optimized manufacturing processes can form an effective strategy to reduce the environmental impact of construction projects. In this regard, materials such as recycled concrete, plastics, and

wood not only reduce waste generation but also require less water during production compared to conventional alternatives. Life-cycle thinking is therefore essential for accurately assessing impacts, as operational savings achieved through efficient building design may be counterbalanced by high embodied water if inappropriate materials are selected [12–14]. Integrating water footprint assessment into decision-making processes enables designers and project managers to identify critical hotspots and prioritize alternatives that contribute to a more responsible use of water resources. This reinforces the importance of transparent supply chains, updated environmental product declarations, and continuous monitoring of industrial processes to ensure that claimed reductions in water intensity are both verifiable and consistent over time. In addition to the direct and indirect water use associated with construction activities, other sources of water losses, such as non-revenue water, may also be considered when assessing overall water management. However, these aspects are beyond the scope of the present study and are therefore not addressed in this work. The published literature available on non-revenue water and related water loss assessment methodologies can be consulted [15,16].

The vast volume of scientific information currently available must be systematically examined, organized, and analyzed to obtain a global perspective that reveals the conceptual evolution of the field and the topics that have shaped and continue to define its development. In this context, bibliometrics has emerged as a particularly useful tool for synthesizing large volumes of scientific information and objectively describing the intellectual structure of a research area. Since its origins in the mid-twentieth century, bibliometrics is based on the quantitative analysis of publications, citations, and relationships among terms, authors, or institutions [17]. Through bibliometric indicators and scientific mapping techniques, it becomes possible to identify dominant topics, examine keyword co-occurrences, detect conceptual clusters, understand the temporal evolution of research areas, and recognize patterns of specialization or diversification [18]. These approaches help overcome the limitations of traditional narrative reviews and provide a more accurate representation of the growth, structure, and dynamics of the field. Several authors have published bibliometric studies related to green buildings [19–27], but none of them have been focused on the implications of water management in this framework. Therefore, the aim of this work is to conduct a bibliometric analysis of the literature indexed in Scopus until 2024 related to research on water management within the context of sustainable architecture. The retrieved documents were analyzed and assessed using several criteria to determine the quantitative features of global research activity in this field and to identify the most relevant current and prospective trends. The key emerging topics and unresolved research needs in this field were identified using bibliometric network analysis. The results were then used to produce a concise review of the main trends and the most significant research opportunities.

2. Methodology

Scopus was selected as the data source due to its extensive coverage of peer-reviewed publications. With more than 28,700 indexed journals and nearly 400,000 books, it offers one of the most complete and continuously updated records of global scientific activity [28]. The following search string was applied in the Article title, Abstract, and Keywords fields of the search engine: “water” AND (“green building” OR “green construction” OR “green architecture” OR “sustainable building” OR “sustainable construction” OR “sustainable architecture”). In addition, the search was limited to documents published before 2024 (2023 was the last complete year when the search was carried out in August 2024, so documents published in 2024 and the following years were not taken into account). This search resulted in 3283 documents. Filter counts and the full dataset were exported from

Scopus in CSV and RIS formats. The exported files contained fields such as title, authors, year, journal, citations, country, affiliation, language, document type, subject area, and keywords. These data were then organized in Excel to build a working dataset consistent with the study's criteria.

The methodology was structured in two phases: a bibliometric performance assessment and a bibliometric network analysis. The first phase summarized key features of the dataset using standard indicators applied to the Excel-based database. The second phase examined conceptual structures through a co-word analysis carried out with SciMAT software (the version v1.1.06 was used), selected because of its capacity to generate strategic and dynamic diagrams and detailed cluster networks [29].

Co-word analysis enabled the identification of keyword groups that were subsequently organized into clusters. Two indicators described each cluster: density, which captures the internal strength of association among its keywords, and centrality, which reflects its interaction with other themes and overall relevance within the domain [30]. The clusters were plotted in a strategic diagram, assigning density to the *y*-axis and centrality to the *x*-axis. Their distribution across this space leads to four classifications (Figure 1). Motor clusters occupy the upper right quadrant and denote well-structured and influential topics. Basic and transversal clusters are found in the lower right quadrant, involving important but not yet fully consolidated themes. Highly developed but isolated clusters appear in the upper left quadrant and correspond to specialized peripheral topics. Emerging or declining clusters fall in the lower left quadrant and represent nascent or marginal themes with low density and centrality [30].

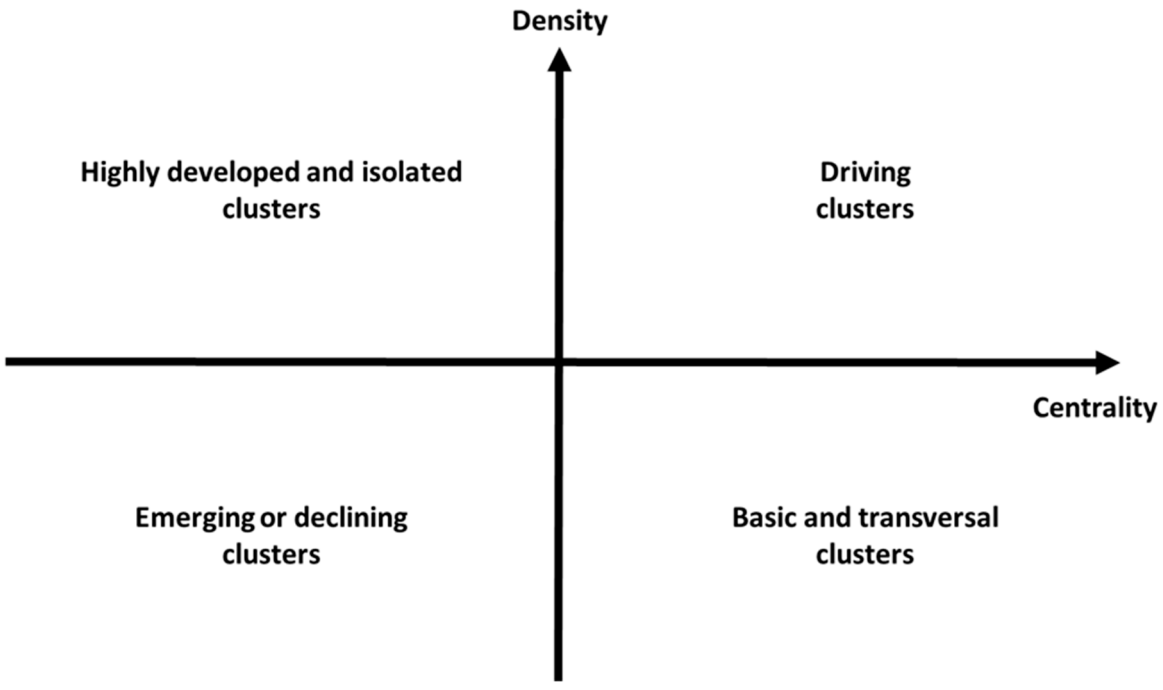


Figure 1. Schematic representation of a strategic diagram and classification of the clusters according to density and centrality values.

The dynamic diagram identifies thematic families of clusters that evolve over successive time intervals. Clusters may belong to one or several families depending on their interconnections. Solid lines indicate clusters sharing the same label or containing one another's label, whereas dashed lines represent links based on other shared elements. Line thickness reflects the inclusion index between clusters, and sphere size represents the number of associated documents. Within each cluster, thematic networks are formed

by keywords and their relationships. The central node corresponds to the most representative keyword, while node size indicates the number of associated documents. Line thickness between nodes represents the equivalence index, which depends on keyword co-occurrence.

The RIS-formatted bibliographic records exported from Scopus were imported into SciMAT to generate the database for the bibliometric network analysis. To reinforce data uniformity and reliability, a keyword normalization procedure was conducted, combining singular and plural versions, spelling variants between British and American English, and acronyms. The dataset was separated into three periods (1994–2014, 2015–2019, and 2020–2023) with an equivalent number of documents (1001, 869, and 1413 papers, respectively) to evaluate temporal shifts in scientific production. These intervals were selected to maintain similar document counts, allowing fair comparisons and reducing the risk of bias in the co-word analysis due to imbalanced datasets. The number of intervals was fixed equal to three because two intervals imply a very limited time evolution, while four intervals would drastically reduce the number of documents in each interval. The parameters required for scientific mapping were then defined in SciMAT, and the corresponding configuration is provided in Table 1.

Table 1. Parameter configuration used for the analysis by SciMAT.

Parameter	Value
Unit of analysis	Words (author's words, source's words, added words)
Frequency reduction	5
Kind of matrix	Co-occurrence
Edge value reduction	2
Normalization measure	Equivalence index
Clustering algorithm	Simple centers
Maximum network size	11
Minimum network size	7
Evolution map measure	Jaccard's index

3. Results and Discussion

3.1. Bibliometric Performance Analysis

3.1.1. Publication Year and Document Type

The temporal evolution of the publications in Scopus regarding water management within sustainable architecture from 1994 (the year of the first document found) to 2023 is reported in Figure 2, with annual and cumulative series shown separately. The research field originated slowly in the last decade of the past century, with just twelve documents published before 2000. These foundational works include the pioneering efforts applied to sustainable development in construction, considering environmental protection, social aspects, and use of natural resources [31]. The main actors (such as architects, developers, contractors, and property managers) started pointing to their commitment to sustainable building and responsible resource management [32], advances in innovation in civil engineering and construction, and the training of professionals in sustainable management of the infrastructures [33]. The first proposals paid special attention to raw material consumption and reuse, energy and water saving, and reduction in waste to minimize environmental pollution [34,35]. Indeed, applying this innovative approach significantly reduced energy consumption, pollution, and waste in existing and new constructions, while simultaneously improving quality of life within buildings [36]. Two illustrative examples can be mentioned. First, Amsterdam planned the new IJburg housing estate with 18,000 homes for about 45,000 residents [37]. The project prioritized sustainability through water- and

energy-efficient design and the use of sustainable materials. Incorporating a dual water system (using reclaimed water for toilet flushing and laundry) significantly supported these goals. Second, the University of British Columbia in Vancouver (Canada) committed to the construction of a demonstrative sustainable building in 1992. The university held an initial workshop with consultants, users, and operators to set shared targets for ecology, energy, water, materials, and waste. The building met most predefined goals and included on-site wastewater treatment using composting toilets and a constructed wetland for graywater [38].

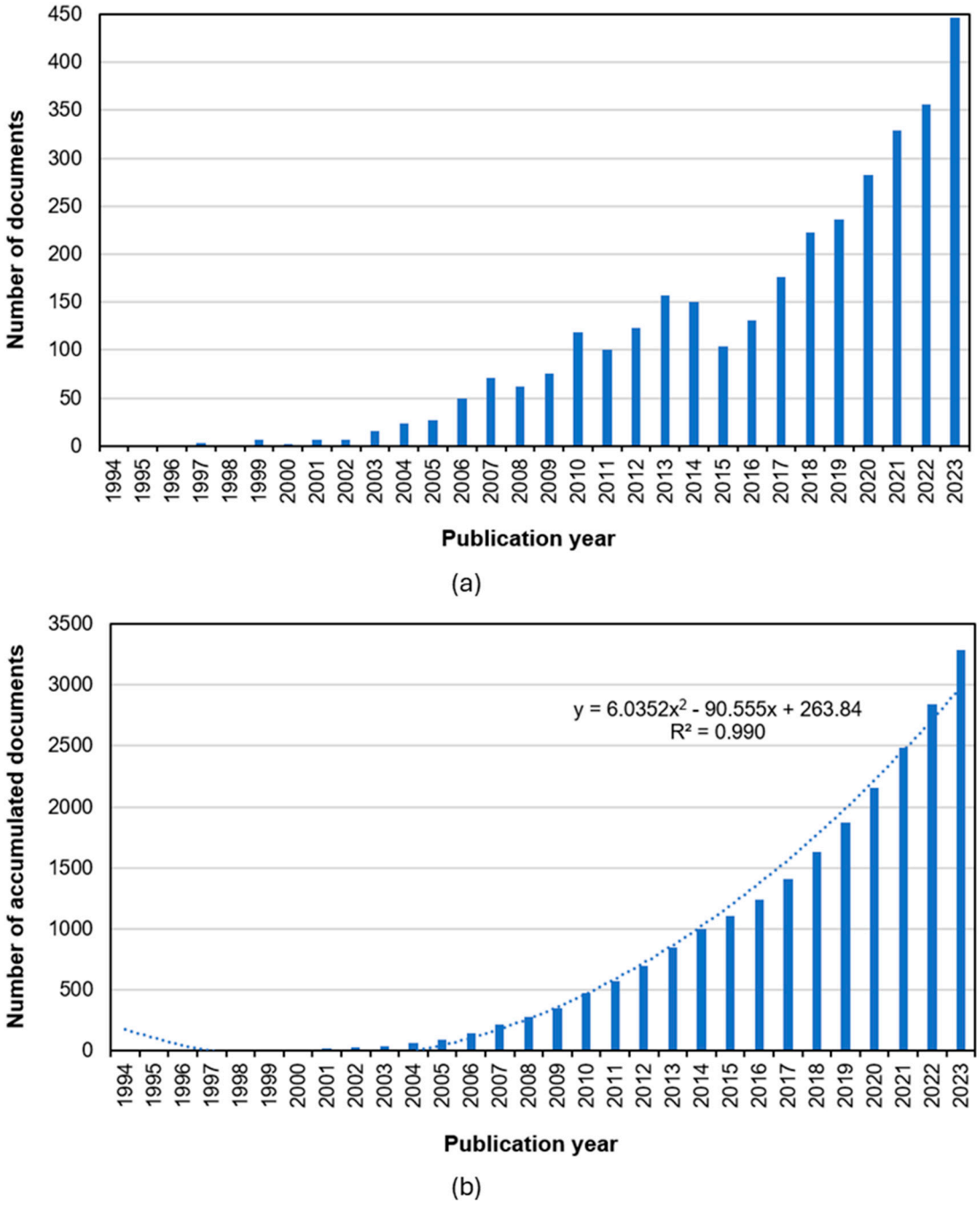


Figure 2. Annual (**a**) and accumulated (**b**) publication output. The line in the graph of the accumulated publication output represents the quadratic fitting.

During the first decade of the 21st century, scientific production increased steadily, exceeding 100 documents for the first time in 2010 (119 publications). This level was main-

tained until 2015, after which output grew almost linearly, reaching 282 documents in 2020 and 446 in 2023. Accordingly, accumulated production was best fitted by a quadratic model (R^2 = 0.990), outperforming potential and exponential models. Nevertheless, publication numbers in the last two years exceeded model predictions, suggesting renewed research interest. Despite this acceleration, the field has not yet experienced the exponential growth typical of major emerging research topics [39].

Table 2 shows that journal articles were the predominant document type, representing 54.92% (1803 documents), confirming journals as the main channel for scientific dissemination in databases such as Scopus. Conference papers ranked second with 28.72% (943 documents), reflecting the continuous development of research on water management and sustainable construction. Book chapters and reviews accounted for 5.15% (169 documents) and 4.81% (158 documents), respectively. The relatively low proportion of reviews is noteworthy given the large volume of publications available. Previous bibliometric studies have consistently identified reviews as the second or third most frequent document type in highly active water management research areas [40,41].

Table 2. Types of scientific documents published.

Type of Documents	Documents	Contribution (%)
Article	1803	54.92
Conference paper	943	28.72
Book chapter	169	5.15
Review	158	4.81
Conference review	141	4.29
Book	38	1.16
Short survey	10	0.30
Note	8	0.24
Retracted	6	0.18
Data paper	4	0.12
Editorial	3	0.09

The percentage of articles below 55% is suggestive of the potential bias that can be introduced when the literature searches of bibliometric analyses are restricted exclusively to journal articles. Other document types may be equally relevant in terms of both quantity and quality, so any such limitation should always be clearly justified.

3.1.2. Distribution of Languages, Countries, and Institutions

According to the ranking of the languages employed in the documents (Table 3), English was the dominant language, accounting for 97.38% of the papers (3197 documents), a pattern consistent with its role in facilitating broad international accessibility of research, as the international scientific communication has evolved from linguistic plurality toward the widespread primacy of English since the second half of the past century [42]. Chinese appeared in second place with 1.68% contribution (55 documents), reflecting the growing volume of research produced in that country, particularly on topics related to water [43]. Spanish (0.27% due to nine documents), Portuguese (0.18% due to six documents), and German (0.15% due to five documents) publications constituted minor contributions, while remaining languages were represented by only one or two documents, each below 0.1%.

Table 4 shows that the United States led scientific production with 15.78% of the overall contribution (518 documents), followed by China with 13.19% (433 documents) and India with 11.67% (383 documents), reflecting the scientific leadership of these countries [44,45]. Papers without a specified country represented 8.01%, ranking fourth, while Malaysia (fifth position) contributed 4.81% toward the overall productivity of the field (158 documents).

Among European countries, the United Kingdom accounted for 4.57% (150 documents), Italy 3.50% (115 documents), Spain 2.86% (94 documents), Portugal 1.77% (58 documents), Germany 1.71% (56 documents), and France 1.55% (51 documents), together representing 15.96%, exceeding the U.S. contribution. Countries experiencing severe water stress also showed significant output, including Australia (4.51%), Egypt (2.44%), Iran (2.13%), and Saudi Arabia (2.07%), highlighting the importance of sustainable water management research [46]. Other major contributors included Indonesia (2.89%), Brazil (2.10%), Nigeria (1.71%), and Hong Kong (1.55%), where sustainable housing remains a priority [47,48].

Table 3. Languages employed by the documents.

Languages	Documents	Contribution (%)
English	3197	97.38
Chinese	55	1.68
Spanish	9	0.27
Portuguese	6	0.18
German	5	0.15
French	2	0.06
Italian	2	0.06
Korean	2	0.06
Turkish	2	0.06
Croatian	1	0.03
Japanese	1	0.03
Persian	1	0.03

Table 4. The top 22 most productive countries (at least 50 documents).

Countries	Documents	Contribution (%)
United States	518	15.78
China	433	13.19
India	383	11.67
Undefined	263	8.01
Malaysia	158	4.81
United Kingdom	150	4.57
Australia	148	4.51
Italy	115	3.50
Indonesia	95	2.89
Spain	94	2.86
Canada	90	2.74
Egypt	80	2.44
Iran	70	2.13
Brazil	69	2.10
Saudi Arabia	68	2.07
Taiwan	65	1.98
Turkey	63	1.92
Portugal	58	1.77
Germany	56	1.71
Nigeria	56	1.71
Hong Kong	51	1.55
France	51	1.55

Table 5 lists the ten most prolific institutions, all with at least 10 publications. The Ministry of Education of the People's Republic of China ranked first with 49 documents (1.49%), followed by The Hong Kong Polytechnic University with 34 (1.04%) and Universiti Teknologi Malaysia with 25. These institutions have active research groups focused on

water resource management, sustainable construction, and building materials [49–55]. Four additional Asian universities also appeared among the top ten: Shanghai Jiao Tong University, Shenzhen University, Universiti Teknologi MARA, and Universiti Malaya. Although the United States produced the largest number of publications overall, its output was more evenly distributed across institutions, with Arizona State University (the most productive American institution) ranking tenth (18 documents). In contrast, research in the Czech Republic was more concentrated, as Czech Technical University in Prague ranked sixth with 21 documents despite the country not appearing among the most productive.

Table 5. The top 10 most productive institutions.

Institutions	Country	Documents	Contribution (%)
Ministry of Education	China	49	1.49
The Hong Kong Polytechnic University	Hong Kong	34	1.04
Universiti Teknologi Malaysia	Malaysia	25	0.76
Shanghai Jiao Tong University	China	24	0.73
Universiti Teknologi MARA	Malaysia	21	0.64
Czech Technical University in Prague	Czech Republic	20	0.61
Universiti Malaya	Malaysia	21	0.64
Shenzhen University	China	19	0.58
Universidad Politécnica de Madrid	Spain	19	0.58
Arizona State University	United States	18	0.55

3.1.3. Distribution of Output in Subject Categories and Sources

The distribution of subject categories compiled in Table 6 must take into consideration the non-exclusive nature of the classification, since a single document may fall under multiple areas and the cumulative percentage exceeds 100%. The predominant area was *Engineering* (58.36% contribution), which is noteworthy given that it encompasses three subcategories particularly relevant to this study: *Civil and Structural Engineering*, *Architecture*, and *Building and Construction*. *Environmental Science* followed with 30.28%, a proportion of which was associated with water resource management as sustainable water use within construction practices can be directly related to improved environmental conditions. The third position corresponded to *Energy*, representing an 18.49% contribution. Although the topic of this work points to water management, there is a strong relationship between energy and water saving, which are both two of the main objectives of the solutions derived from sustainable architecture [56]. Further down, in fourth place, *Materials Science* appeared as a relevant area (18.46% contribution) as material selection is a fundamental aspect of construction. The nature of the materials defines the amount of water required during their processing, and some specific properties determine their behavior when interacting with water, which has direct implications for water consumption in buildings [57,58]. *Social Sciences* occupied the fifth position in the ranking due to its 12.31% contribution. These sciences provide essential tools for understanding human behavior, a factor that critically shapes the adoption and effectiveness of water management practices in the construction sector [59]. They also allow rigorous assessment of social acceptability, ensuring that proposed measures align with community expectations and can be implemented sustainably [60].

Regarding the main sources, Table 7 shows the number of documents published by the most frequent sources. As indicators of their relevance, the corresponding SCimago Journal Ranking indexes (SJR), Impact Factors (IFs), and the Journal Citation Indicators (JCIs) of

the top 18 sources, the only ones that published at least 22 documents, were included. *Construction and Building Materials* was the leading source, providing 127 documents (3.87% contribution), followed by *Sustainability* with 93 documents (2.83% contribution) in the second position, while the third position was shared by both the *Journal of Cleaner Production* and *IOP Conference Series Earth and Environmental Science* (both with 83 documents and a 2.53% contribution). Whereas the leader journal *Construction and Building Materials* is specifically dedicated to the investigation and innovative use of materials in construction, the second-ranking journal, *Sustainability*, has a much broader scope, as it covers technical, environmental, cultural, economic, and social aspects of sustainability. The *Journal of Cleaner Production* is also a more general journal, and pays attention to theoretical and practical aspects of cleaner production (encompassing environmental and sustainability issues in corporations, governments, educational institutions, regions, and societies), so not focused exclusively on the architecture and construction sectors. The rest of the journals included in Table 7 can be directly related to buildings and building materials, with no journals explicitly devoted to water research. The journal with the highest IF value was the *Journal of Cleaner Production* (9.7), also corresponding to the maximal SJR (2.058). However, five of the nine journals with assigned IFs presented values above 6.5, a fact that confirmed the high relevance of the journals publishing works about water management in sustainable buildings. When the JCI values were revised, the case of the *Journal of Green Building* must be highlighted, as it presented the highest value (1.60) despite being classified within the Architecture category in the Web of Science, characterized by low IF values. Apart from the journals, the presence of nine other sources (most of them related to conferences) must be mentioned. The *IOP Conference Series Earth and Environmental Science* was the most productive one among them, occupying a shared third position, but the next two positions in the ranking also corresponded to proceedings and post-proceedings, such as *Lecture Notes in Civil Engineering* (63 documents) and *Advanced Materials Research* (61 documents).

Table 6. The top 10 most popular subject categories.

Institutions	Documents	Contribution (%)
Engineering	1916	58.36
Environmental Science	994	30.28
Energy	607	18.49
Materials Science	606	18.46
Social Sciences	404	12.31
Earth and Planetary Sciences	273	8.32
Computer Science	265	8.07
Business, Management, and Accounting	215	6.55
Physics and Astronomy	181	5.51
Chemical Engineering	139	4.23

Table 7. The top 18 most popular scientific sources (at least 22 documents).

Source	Documents	Contribution (%)	IF (2023)	JCI (2023)	SJR (2023)
Construction and Building Materials	127	3.87	7.4	1.43	1.999
Sustainability	93	2.83	3.3	0.68	0.672
Journal of Cleaner Production	83	2.53	9.7	1.52	2.058
IOP Conference Series Earth and Environmental Science	83	2.53	-	-	0.199
Lecture Notes in Civil Engineering	63	1.92	-	-	0.162
Advanced Materials Research	61	1.86	-	-	0.121
Journal of Building Engineering	50	1.52	6.7	1.39	1.397

Table 7. *Cont.*

Source	Documents	Contribution (%)	IF (2023)	JCI (2023)	SJR (2023)
Journal of Green Building	48	1.46	0.7	1.60	0.281
Materials Today Proceedings	47	1.43	-	-	0.473
Materials	44	1.34	3.1	0.58	0.565
Applied Mechanics and Materials	41	1.25	-	-	0.112
Buildings	40	1.22	3.1	0.72	0.575
IOP Conference Series Materials Science and Engineering	40	1.22	-	-	0.249
E3s Web of Conferences	36	1.10	-	-	0.182
Energy and Buildings	32	0.97	6.6	1.22	1.632
AIP Conference Proceedings	32	0.97	-	-	0.152
Building and Environment	25	0.76	7.1	1.24	1.647
WIT Transactions on Ecology and the Environment	22	0.67	-	-	0.176

3.1.4. Most Frequently Cited Documents

The ten most-cited documents are presented in Table 8. Citation counts ranged from 279 for the document in tenth position to 1178 for the leader document. Although a more detailed discussion of the most important research trends will be covered in the next subsection concerning keyword analysis, and especially in the next section with the complete bibliometric network analysis, these highly cited publications can already provide a valuable insight into the topics that have attracted attention from the scientific community. Four main topics were identified: sustainable concrete, other sustainable construction materials, green roofs, and assessment of environmental impacts.

Table 8. The top 10 most cited papers.

Ranking	Document	Number of Cites
1	**The greening of the concrete industry** Author(s): Meyer, C. Source: Cement and Concrete Composites Year: 2009	1178
2	**TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0** Author(s): Bare, J. Source: Clean Technologies and Environmental Policy Year: 2011	588
3	**State-of-the-art analysis of the environmental benefits of green roofs** Author(s): Berardi, U.; GhaffarianHoseini, A.; GhaffarianHoseini, A. Source: Applied Energy Year: 2014	562
4	**Application of agro-waste for sustainable construction materials: A review** Author(s): Madurwar, M.V.; Ralegaonkar, R.V.; Mandavgane, S.A. Source: Construction and Building Materials Year: 2013	419
5	**Influence of the amount of recycled coarse aggregate in concrete design and durability properties** Author(s): Kwan, W. H.; Ramli, M.B.; Kam, K.J.; Sulieman, M.Z. Source: Construction and Building Materials Year: 2012	401

Table 8. *Cont.*

Ranking	Document	Number of Cites
6	**Advances and challenges in sustainable tourism toward a green economy** Author(s): Pan, S.Y.; Gao, M.; Kim, H.; Shah, K.J.; Pei, S.; Chiang, P. Source: Science of the Total Environment Year: 2018	340
7	**Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks** Author(s): Raut, S.P.; Ralegaonkar, R.V.; Mandavgane, S.A. Source: Construction and Building Materials Year: 2011	331
8	**Sustainability assessment in the construction sector: Rating systems and rated buildings** Author(s): Berardi, U. Source: Sustainable Development Year: 2012	295
9	**Green roof energy and water related performance in the Mediterranean climate** Author(s): Fioretti, R.; Palla, A.; Lanza, L.G; Principi, P. Source: Building and Environment Year: 2010	280
10	**Engineered mycelium composite construction materials from fungal biorefineries: A critical review** Author(s): Jones, M.P.; Mautner, A.; Luenco, S.; Bismarck, A.; John, S.J. Source: Materials and Design Year: 2020	279

The most cited document reviewed the potential to increase the environmental sustainability of the concrete industry, mainly by incorporation of different wastes and by-products [61]. The effects of these new formulations on water consumption and absorption were taken into account. Furthermore, the document in the fifth position evaluated the addition of recycled coarse aggregates (RCAs) in more sustainable concrete formulations [62]. Their properties were investigated, including water absorption tests, demonstrating that water absorption was directly proportional to the level of RCA replacement. Apart from concrete, the study of other sustainable construction materials has been a hot topic, covered by three documents included in Table 8. Firstly, the document in the fourth position reviewed the application of agricultural wastes for sustainable construction materials [63]. Once again, the water absorption of these innovative materials was deeply investigated. Secondly, the development of sustainable construction material using industrial waste as well as agricultural waste was reviewed by the document in the seventh position of the ranking [64]. As previously mentioned, water absorption was among the most important characteristics of the new materials requiring detailed investigation. Thirdly, the paper in the tenth position of the ranking was a review about the construction materials derived from fungal biorefineries, as mycelium composites have recently emerged as economically and environmentally sustainable materials [65]. However, the predisposition of mycelium composites to absorb large amounts of water over short time periods represents a critical drawback for their use in construction. Regarding green roofs, the document in the third position reviewed the environmental benefits of green roofs [66], while the one in the ninth position focused on the performance of green roofs under Mediterranean climatic conditions [67]. Both works confirmed that green roofs significantly mitigate rainwater runoff generation. Lastly, sustainability assessment in the construction sector was the central topic of two papers from Table 8. On the one hand, the document in the second position presented TRACI 2.0 (the Tool for the Reduction and Assessment of Chemical and

other environmental Impacts 2.0), developed by USEPA for life-cycle impact assessment and employed in many prestigious applications, including examples in the construction sector, such as the US Green Building Council's LEED Certification or the National Institute of Standards and Technology's BEES (Building for Environment and Economic Sustainability) [68]. On the other hand, the rating systems used for sustainability assessment in the construction sector were reviewed by the paper in the eighth position, discussing the construction characteristics of rated buildings [69]. Although the specific inclusion of standards was not considered in this bibliometric analysis, some documents, including these two among the most cited ones, were clearly linked to different local, national, or sectorial standards and rating systems. Indeed, these standards can serve as a key driver for research and practice in this field. While energy performance has been the most important criterion in sustainability rating systems for buildings, other performance ratings, such as water efficiency or indoor air quality, have increased their relevance. Apart from LEED and BEES, other famous standards and rating systems can be mentioned, such as the British Building Research Establishment Environmental Assessment Method (BREEAM), the Japanese Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), the Chinese Three Star, the Australian Building Greenhouse Rating (ABGR), or the Global Sustainability Assessment System (GSAS), particularly developed for the Gulf region [70]. Many of these certification systems prioritize water efficiency through measures such as reducing indoor and outdoor water consumption, reusing graywater and rainwater, and implementing water metering and leak detection systems. LEED awards credits for achieving at least a 20% reduction in water use compared with baseline standards, while BREEAM assesses stormwater management and flood risk. In contrast, systems developed for arid conditions place greater emphasis on water efficiency, enforcing strict indoor water consumption limits and promoting innovative technologies for water conservation and reuse. While building energy performance has been the most important criterion in sustainability rating systems, other performance ratings, such as water efficiency or indoor air quality, have increased their relevance.

3.1.5. Distribution Analysis of Keywords

Analysis of the most frequent keywords from the identified research papers revealed that the main keyword was *Sustainable development*, which appeared in 1065 documents, followed by *Green buildings* with 501 documents in the second position and closely followed by *Sustainable construction* in the third position, appearing in 494 documents (Figure 3). While both expressions occupying the second and third positions were directly taken into consideration in the defined search string employed in the database, the expression *Sustainable development* was not considered. This fact indicates the high relevance of this concept with the contexts of green architecture and construction [71–73].

The detailed study of the keywords allowed us to associate specific keywords with relevant areas within the research topic. In general terms, these keywords can be grouped into four major areas:

- Green architecture and construction. This group comprised keywords associated with the integration and optimization of sustainable principles to enhance the connection between the built environment and constructions. Examples included *Intelligent Buildings* (463 times), *Green Building* (320), *Construction Industry* (298), *Sustainable Building* (260), *Architectural Design* (228), *Building* (150), *Construction* (139), *Office Buildings* (116), and *Historic Preservation* (100). These keywords reflect the progressive consolidation of sustainability as a core principle in the architecture, engineering, and construction sectors, moving beyond isolated design strategies toward comprehensive approaches that integrate environmental, social, and economic performance. They also reveal the grow-

ing influence of broader trends such as circular economy principles, resource-efficient construction, material innovation, and the increasing need to address water scarcity and climate resilience through the design and operation of buildings. Furthermore, the strong presence of terms related to intelligent and green buildings suggests that recent research has shifted from conceptual discussions toward the implementation of advanced technologies and performance-based solutions aimed at improving building efficiency while reducing environmental impacts throughout the life-cycle, where water reuse is expected to play a key role [74].

- Water resource management. This group of keywords was related to water quality, conservation, and use, pointing to reduced environmental footprints. Accordingly, this category included examples such as *Water Conservation* (228), *Water Supply* (140), *Water Management* (96), and *Water Pollution* (92). The increasing recognition of water resources as a critical component of sustainable construction reflects the sector's response to growing concerns over water scarcity and resource depletion. Improved sustainable water use in the construction sector requires moving beyond conventional freshwater sources toward the integration of non-conventional water resources. The adoption of these alternative water resources has become closely linked to the development of sustainable construction practices, reducing dependence on potable water supplies while improving resource efficiency and supporting the long-term environmental performance of buildings [75].
- Construction materials and their physical properties. This group included keywords related to the physical (mainly mechanical and thermal) properties of construction materials. Representative examples were *Compressive Strength* (470), *Water Absorption* (317), *Fly Ash* (177), *Cements* (168), *Durability* (154), *Concrete Aggregates* (120), *Thermal Conductivity* (117), *Mechanical Properties* (108), *Portland Cement* (103), *Tensile Strength* (100), *Mortar* (96), *Brick* (94), *Thermal Insulation* (88), and *Concrete Mixtures* (85). In addition to the conventional evaluation of the mechanical and thermal performance of construction materials, material innovation has emerged as a key research direction in the development of multifunctional materials that simultaneously enhance structural performance and environmental sustainability. The selection of appropriate construction materials can substantially reduce both direct and indirect water consumption through lower embodied water, improved durability, enhanced water efficiency during operation, and greater compatibility with water reuse systems [76].
- Energy and environmental effects. This group encompassed keywords related to energy consumption, carbon footprint, and environmental consequences, although the search string was defined to prioritize water-related research. Representative terms included *Energy Efficiency* (399), *Energy Utilization* (254), *Environmental Impact* (217), *Energy Conservation* (196), *Environmental Protection* (137), *Climate Change* (127), *Carbon Dioxide* (123), *Greenhouse Gases* (113), *Global Warming* (99), and *Environmental Management* (82). Although the scope of the present study was deliberately defined to prioritize water-related research, the intrinsic coupling between water, energy, and environmental performance in the built environment results in the presence of several terms directly related to energy and carbon emissions. Therefore, the observed thematic overlap highlights how water management strategies in construction are frequently embedded within broader sustainability agendas, even when the main driver of the research is the optimization of water resources and the promotion of water-efficient building systems [77].

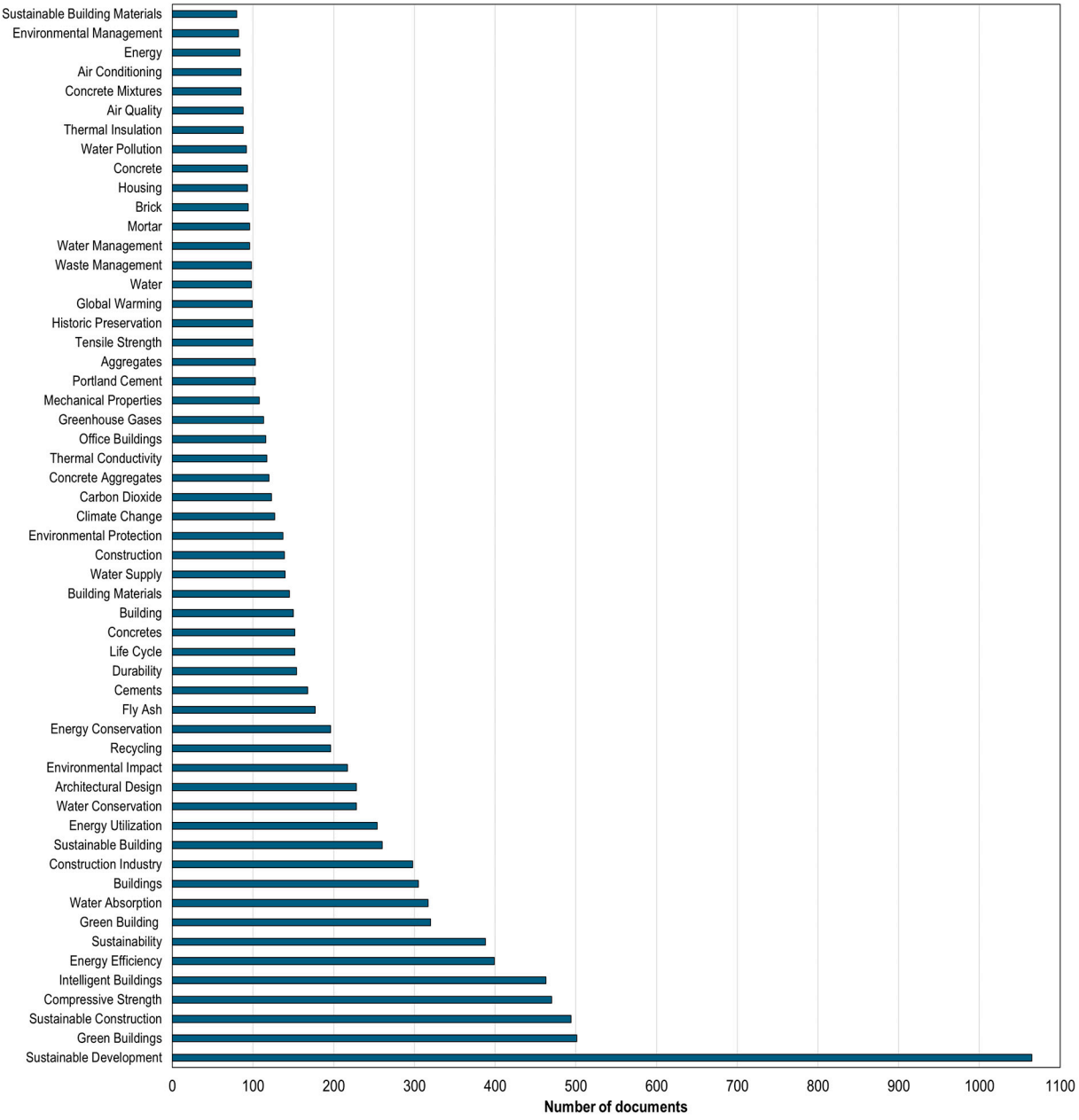


Figure 3. The top 55 most frequently used keywords (selected by at least 80 documents).

3.2. Bibliometric Network Analysis

As previously mentioned, the analyzed time interval ranged from 1994 to 2023 and was divided into three periods: Subperiod 1 from 1994 to 2014, Subperiod 2 from 2015 to 2019, and Subperiod 3 from 2020 to 2023. Based on this division, a dynamic evolution map was obtained, and is shown in Figure 4. From this map, several main cluster families can be identified. To complement this dynamic diagram, the corresponding strategic diagrams of each defined subperiod are shown: 1994–2014 (Figure 5), 2015–2019 (Figure 6), and 2020–2023 (Figure 7). The detailed structure of each cluster can be observed in Figures S1–S25 in the Supplementary Material.

The first family (marked in red in Figure 4) was formed by the cluster "*Sustainable Development*" during the first two subperiods and by "*Compressive Strength*" in the third subperiod. These three clusters were the ones with the highest number of documents, with 454, 424, and 410 papers, respectively. The analysis of the structure of the cluster "*Sustainable Development*" from both Subperiods 1 (Figure S1) and 2 (Figure S10) revealed the presence

of several keywords that were previously classified into the group termed "Green architecture and construction" during the review of the most frequently used keywords, such as *Intelligent Buildings*, *Green Building*, *Building*, *Sustainable Building*, *Architectural Design*, and *Construction Industry*. In addition, other related terms were identified too, like *Sustainability*, *Sustainable Construction*, and *Sustainable Development*. Although the keywords *Sustainable Development* and *Sustainable Construction* were included in the cluster "*Compressive Strength*" from Subperiod 3 (Figure S16), this cluster presented several keywords directly related to the group "Construction materials and their physical properties" defined in the previous subsection. These keywords included *Cement*, *Concrete Mixtures*, *Concrete Aggregates*, *Brick*, *Tensile Strength*, *Water Absorption*, and *Durability*. This presence confirmed the predominance that concrete and cement still have in the context of construction materials and the research efforts to improve their sustainability [78,79]. Moreover, water absorption is one of the main properties related to concrete durability. The higher the water absorption, the higher its porosity and exposure to aggressive agents and, consequently, the lower its stability [80]. The three clusters of this family were located in the upper right quadrant (Figures 5–7), so they must be considered motor themes. Indeed, they presented the highest centrality values in each period.

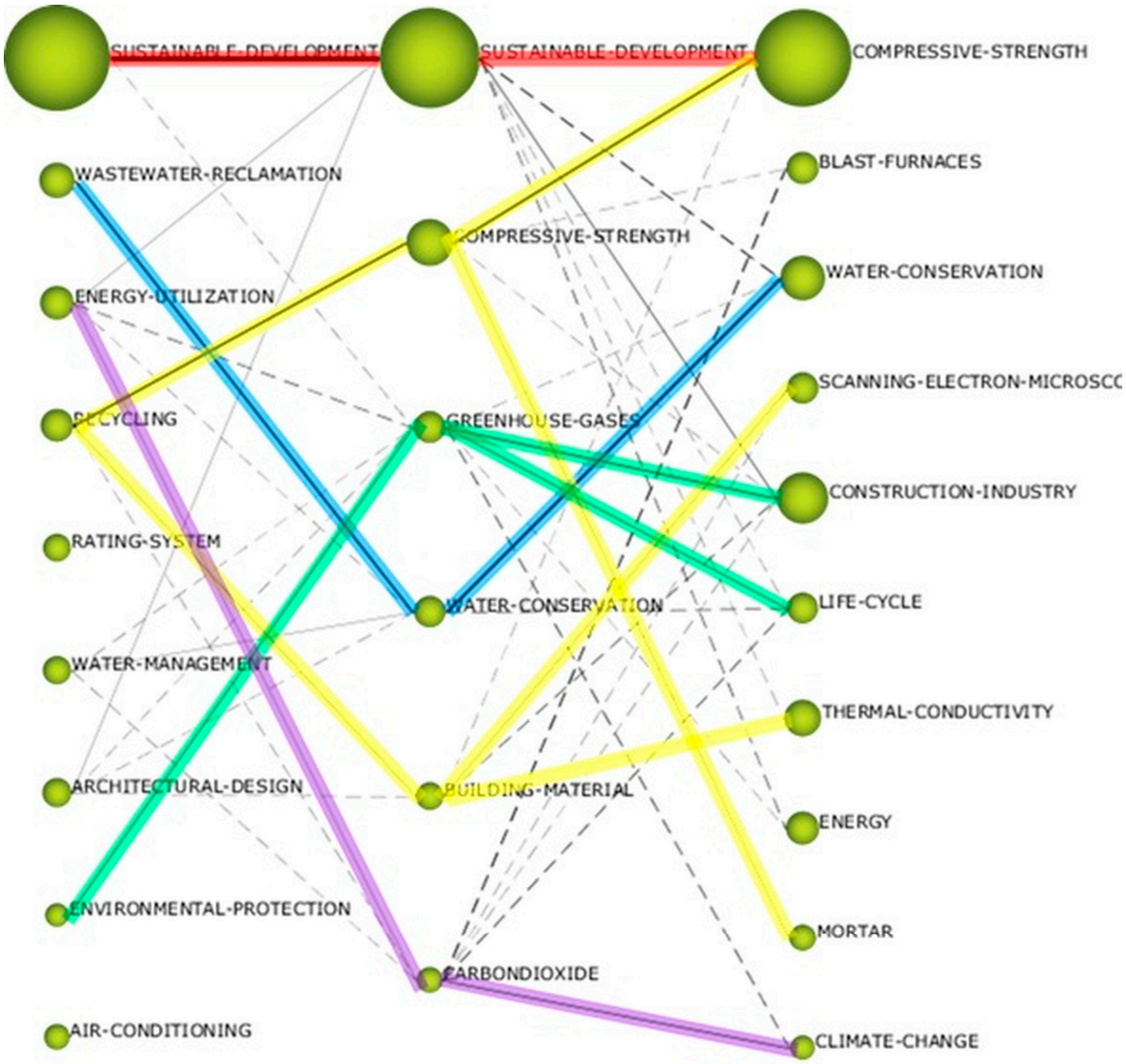


Figure 4. Thematic evolution structure of the clusters in the research related to water management within sustainable architecture (1994–2023).

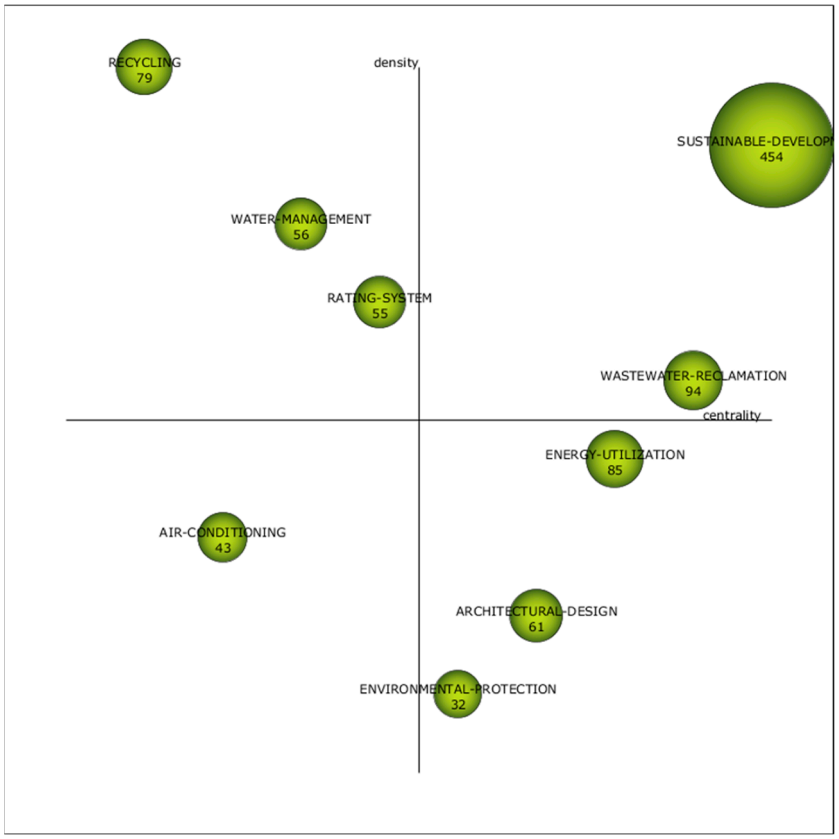


Figure 5. Strategic diagram of the clusters of Subperiod 1 (1994–2014).

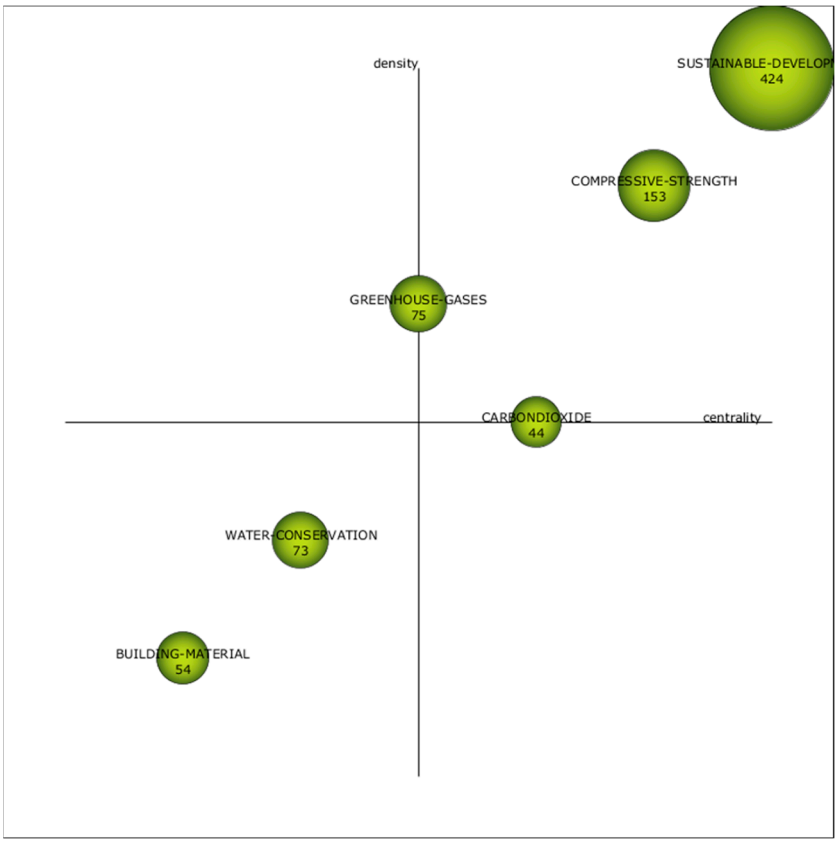


Figure 6. Strategic diagram of the clusters of Subperiod 2 (2015–2019).

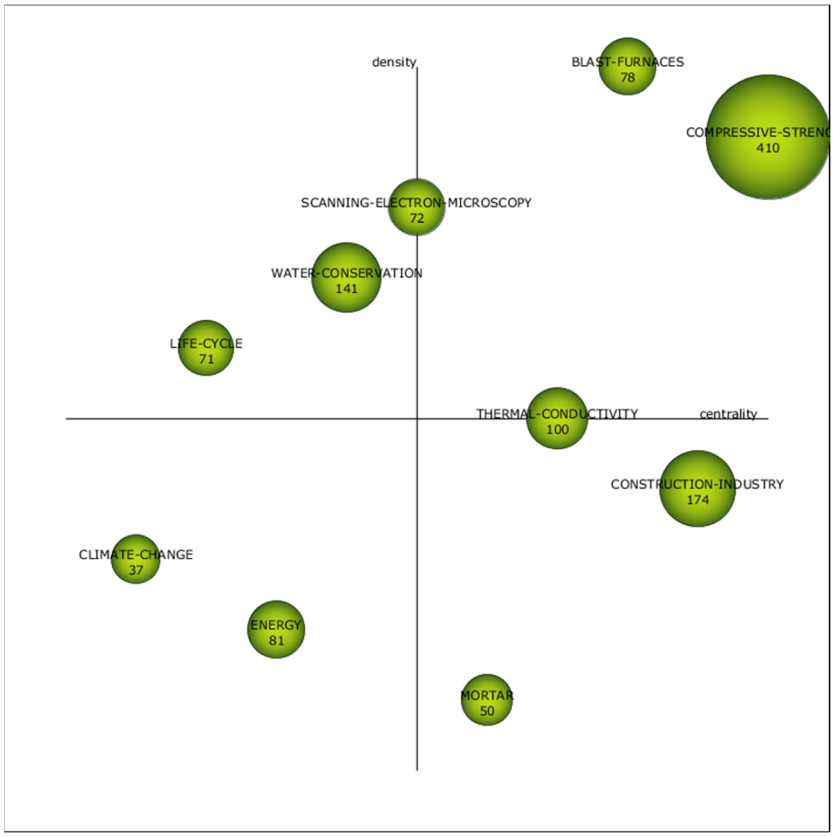


Figure 7. Strategic diagram of the clusters of Subperiod 3 (2020–2023).

The cluster "*Compressive Strength*" from Subperiod 3 was also linked to a second family of clusters. As observed in Figure 4, the family marked in yellow presented a strong relationship between the cluster "*Recycling*" from Subperiod 1 and the cluster "*Compressive Strength*" from Subperiods 2 and 3. These clusters of the yellow family in the first two subperiods shared most of the keywords related to the group "Construction materials and their physical properties" linked to the cluster "*Compressive Strength*" from Subperiod 3, as observed in Figure S4 for the cluster "*Recycling*" from Subperiod 1 and Figure S11 for "*Compressive Strength*" from Subperiod 2. The use of more sustainable material must be considered a priority within the green architecture context, and some of their physical characteristics are critical to achieve reduced environmental impacts [81–83]. Moreover, other clusters directed related to construction materials and properties also belonged to this family (although without so strong a relationship), like "*Building Material*" from Subperiod 2 (with keywords like *Construction Material*, *Green Building Material*, *Sustainable Building Material*, *Lime*, and *Durability*, as observed in Figure S14), "*Scanning Electron Microscopy*" from Subperiod 3 (with keywords like *Lime*, *Hydrated Lime*, and *Microstructure*, as observed in Figure S19), "*Thermal Conductivity*" from Subperiod 3 (with keywords like *Building Material*, *Porosity*, *Density*, and *Moisture,* as observed in Figure S22), and "*Mortar*" from Subperiod 3 (with keywords like *Cementitious Material*, *Fine Aggregate*, *Recycled Aggregate*, and *Mechanical Property*, as observed in Figure S24). While the cluster "*Recycling*" appeared as a highly developed but isolated cluster in the upper left quadrant during Subperiod 1, which presented the highest density (Figure 5), the cluster "*Compressive Strength*" evolved to become a motor theme in Subperiod 2. This progression implied a growing relevance of this topic related to materials and their properties, confirmed by the evolution of the cluster "*Building Material*" from an emerging theme in Subperiod 2 to the clusters "*Scanning Electron Microscopy*" and "*Thermal Conductivity*" in the borders of the upper right quadrant in Subperiod 3.

A third family, marked in blue in Figure 4, was directly related to water management, including the clusters "*Wastewater Reclamation*" from Subperiod 1 and "*Water Conservation*" from Subperiod 2 and 3. The structure of the cluster "*Wastewater Reclamation*" revealed the presence of keywords such as *Wastewater*, *Wastewater Reclamation*, *Water Supply*, *Water Recycling*, *Water Quality*, *Water Conservation*, and *Stormwater*, all of them strongly linked to the management of water resources and most of them previously identified in the group "Water resource management" defined in the previous subsection (Figure S2). Some of these keywords were also present in the structure of the cluster "*Water Conservation*" from Subperiod 2, such as *Water Supply*, *Water Recycling*, and *Water Conservation*, which were complemented with new keywords, such as *Water Management* and *Wastewater Treatment* (Figure S13). In the case of the cluster "*Water Conservation*" from Subperiod 3, *Water Supply* and *Water Conservation* were also included as keywords in the corresponding structure (Figure S18), where the keyword *Water resource* also appeared. The sustainable management of water resources must constitute a central pillar of green architecture, as it directly conditions the environmental performance, resilience, and long-term viability of the built environment [84,85]. While the cluster "*Wastewater Reclamation*" from Subperiod 1 appeared as a motor theme in the upper right quadrant with the second highest value of centrality (Figure 5), the importance of the cluster "*Water Conservation*" from Subperiod 2 was significantly reduced until it became a declining topic in the lower left quadrant (Figure 6). However, the cluster "*Water Conservation*" from Subperiod 3 was situated in the upper left quadrant as a highly developed but isolated cluster (Figure 7). Therefore, the relevance of this topic rebounded in the last subperiod, so the suffered decline was temporal and the topic gained relevance during later years.

Two other families were identified in the dynamic evolution map. On the one hand, the family marked in purple in Figure 4 included the clusters "*Energy Utilization*" from Subperiod 1, "*Carbon Dioxide*" from Subperiod 2, and "*Climate Change*" from Subperiod 3. On the other hand, the family marked in green in Figure 4 included the clusters "*Environmental Protection*" from Subperiod 1, "*Greenhouse Gases*" from Subperiod 2, and "*Construction Industry*" and "*Life-Cycle*" from Subperiod 3. Both clusters from Subperiod 1 were situated in the lower right quadrant, so they can be considered basic and transversal topics (Figure 5). During Subperiod 2, both clusters were located in the borders of the upper right quadrant. While the cluster "*Carbon Dioxide*" was located in the transition from the upper right quadrant to the lower right quadrant, the cluster "*Greenhouse Gases*" was located in the transition from the upper right quadrant to the upper left quadrant (Figure 6). The cluster "*Climate Change*" from Subperiod 3 lost relevance, and its lower centrality and density values implied its classification as a declining topic in the lower left quadrant (Figure 7). However, the clusters of the green family in this last subperiod presented higher relevance, with "*Construction Industry*" being located in the lower right quadrant and "*Life-Cycle*" in the upper left quadrant. The relevance of this topic increased again during the last subperiod, indicating that the previous decline was temporary rather than persistent. Both families of clusters presented keywords in their structures that can be related to those from the group "Energy and environmental effects" identified in the previous subsection: *Energy Use*, *Energy Consumption*, and *Energy Consumption* in the cluster "*Energy Utilization*" (Figure S3); *Climate Change* in the cluster "*Carbon Dioxide*" (Figure S15); *Global Warming* and *Carbon Dioxide* in the cluster "*Climate Change*" (Figure S25); *Greenhouse Gases* and *Life-Cycle* in the cluster "*Environmental Protection*" (Figure S8); *Global Warming* and *Life-Cycle Assessment* in the cluster "*Greenhouse Gases*" (Figure S12); *Greenhouse Gases* and *Environmental Impact* in the cluster "*Construction Industry*" (Figure S20); and *Life-Cycle Analysis*, *Life-Cycle Assessment*, *Carbon Emission*, and *Energy Efficiency* in the cluster "*Life-Cycle*" (Figure S21). Although this work centered on water resource management, these two cluster families

linked to energy and environmental impacts, especially carbon emissions, highlighted that energy remains a dominant priority in efforts to enhance building sustainability [86,87].

3.3. Review of the Most Relevant Hot Topics

Water is a vital resource in the construction industry, essential for numerous processes throughout a project's life-cycle. Depending on its use, water can be regarded as a resource, a product, or a service, underscoring the need for its efficient and sustainable management. In the context of increasing water scarcity and pollution, integrating circular economy principles into water use within construction is crucial to ensure the sector's sustainability.

The common definition of the circular economy does not adequately address the multiple characteristics of water. For this reason, the most frequently cited R-Strategies in circular economy literature (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) are not fully applicable to water management [88]. In fact, a complete recalibration of these strategies in order to adapt them to water has been proposed, which can be grouped in three main categories: decreasing, optimizing, and retaining [89]. This same scheme was followed to review the most relevant hot topics related to water management in sustainable construction in this work, with a specific subsection devoted to each of these categories, since it can be easily adapted to the trends identified from the bibliometric findings. Firstly, water decreasing can be linked to the yellow family from the bibliometric network analysis and the group "Construction materials and properties" from the review of the most frequently used keywords. Secondly, water optimizing can be related to the blue family from the bibliometric network analysis and the group "Water resource management" from the keyword review. Thirdly, water retaining can be connected to the red family from the bibliometric network analysis and the group "Green architecture and construction" from the keyword review.

3.3.1. Decreasing: Water Saving in Sustainable Construction

The construction industry is making significant efforts toward more efficient water use [90]. It is essential to recognize that water is not only used during the operational phase but also plays a crucial role throughout all stages of the project life-cycle in multiple ways. During the design phase, initiatives focus on minimizing water consumption within buildings. Efforts aim to implement low-consumption fixtures and promote practices that reduce potable water use. The actions carried out during the operational phase are closely linked to the work undertaken during the design phase. Raising awareness and training end users regarding the decisions made in the initial design phase become critical, since this ensures that they possess the knowledge required to properly use the implemented systems and installations, thereby promoting more efficient water use and enhancing the project's sustainability throughout its lifespan.

Between the design and operation phases, the construction phase has gained attention, driven by growing awareness of the need to optimize water use. This phase involves several activities where significant efficiency gains can be achieved. Key water-consuming actions include earthworks (where water is used for soil compaction and dust control), equipment and vehicle cleaning, pollution control through surface wetting, and water consumption by workers for hygiene and drinking. Additionally, many materials and processes, such as concrete curing and mortar preparation, depend on water, as do testing operations for plumbing systems and sanitation fixtures. Water is also required for maintaining site cleanliness and safety. Leakage represents a critical issue that must be promptly addressed to prevent waste and save water. Examples of measures to save water during the construction phase include using recycled or non-potable water for dust suppression and soil compaction, employing biodegradable dust suppressants that require less water, implementing

closed-loop systems for equipment and vehicle washing, adopting water-efficient curing methods such as membrane curing or curing compounds instead of continuous spraying, collecting and reusing graywater from site facilities, installing temporary leak detection systems, and promoting worker-awareness campaigns on responsible water use [91,92].

The production of construction materials can represent one of the main sources of water consumption within the building sector, making them a critical factor for sustainable water management in this field. From the extraction of raw materials to their transportation, use, and eventual dismantling, every stage influences water use. It has been demonstrated that more than 95% of the water consumed in construction projects is embedded in the production processes of the construction materials employed [93]. The water footprint is a key indicator that measures the total amount of water used, both directly and indirectly, for the production and consumption of goods and services throughout their life-cycle. It therefore accounts for water directly used in the construction and operation of a building (site preparation, concrete mixing, or cleaning activities) as well as water indirectly required (production of steel, cement, and timber or electricity generation). Three components are commonly distinguished within the water footprint [94]. The blue water footprint accounts for freshwater withdrawn from surface and groundwater sources, the green water footprint refers to rainwater stored in the soil or absorbed by vegetation, and the gray water footprint represents the volume of freshwater required to dilute pollutants to meet natural background levels and water quality standards. Analysis based on the water footprint reveals the deep interconnections between the construction sector and water resources, helping to propose sustainable strategies that minimize its impact. Consequently, the assessment of the water footprint of different construction materials [95,96], individual buildings [97,98], or even the construction sector as a whole, is gaining increasing relevance [99,100].

Regarding the calculation of the water footprint of construction materials, the most widely used ones, such as cement and steel, have been the most extensively studied [101]. Steel and other metallic materials are characterized by high water footprints, with the gray component being more significant than the blue one. Metals require large amounts of water during deep mining operations for their extraction, as well as during subsequent processing steps for their separation. Moreover, the water used in mining becomes loaded with fine particles and various dissolved metallic by-products, explaining the high contribution of the gray water footprint. The use of recycled metal in construction products can substantially reduce the water footprint, as most water consumption is associated with primary mining activities [102]. In the case of cement, whose manufacturing process is highly energy-intensive, the largest blue water consumptions are linked to the energy required for clinker pyroprocessing and for cement grinding and blending. The amount of water consumed in concrete preparation is considerably lower than that required for cement production. The use of supplementary materials as clinker substitutes in cement production reduces energy demand, thereby decreasing the water footprint associated with the energy used in pyroprocessing [103].

Various stone materials must be extracted from deep underground sources, requiring large-scale machinery and equipment capable of excavating and cutting massive slabs. These operations demand water for dust suppression and cooling. Natural sand, used along with other aggregates as fine material in concrete, exerts significant pressure on natural resources, particularly water resources when river sand is involved. Its extraction from riverbeds can cause water pollution, bed degradation, and a decrease in groundwater levels, resulting in a very high water footprint for these aggregates [98]. Consequently, replacing such aggregates, which are required in large quantities for construction projects, with alternative solids obtained as by-products or residues from other industrial processes (such as slags, fly ash, quarry dust, or plant-based residues), leads to a reduction in the

construction's water footprint [104–106]. The washing and filtration of clay to remove impurities are essential for producing masonry products (bricks, adobes, and other blocks), and water is also required for cooling in kilns and during curing stages.

Wood-based buildings consume less fuel, water, heat, and electricity throughout their life-cycle than those made of cement or brick [107]. Specifically, their water footprint can be more than ten times lower. Wood is a natural material, and its cultivation often requires no irrigation beyond soil moisture and rainfall, making the green component the dominant part of its water footprint. However, the use of fertilizers and pesticides during cultivation introduces a minor gray component, although far below the green one. Additionally, wood and similar materials such as bamboo undergo several supply-chain processes before being used in construction. Pre- and post-sawing treatments, such as water immersion, cooling, or steaming, contribute to the blue water footprint. Studies have shown that recycling wood products from demolished buildings and reusing them for flooring or paneling slightly reduces the overall water footprint of these materials [108].

Finishing materials, such as glass, plywood, polymers, textiles, paints, and varnishes, are required in much smaller quantities than structural materials, yet their overall contribution to a building's water footprint can exceed that of cement [109]. Glass manufacturing involves several water-dependent steps and requires substantial thermal energy for vitrification, contributing significantly to its water footprint. In particular, float glass, the most common type used in buildings, undergoes a controlled cooling process that consumes large volumes of water [110]. Synthetic polymer production often involves solvents, sometimes high-purity water, and in cases such as fluoropolymers, the high toxicity of raw materials implies intensive wastewater treatment, leading to a high gray water footprint. Textile production is also highly water-intensive, especially during dyeing, generating considerable wastewater volumes. Thus, both polymers and textiles are characterized by large gray components. Many building insulation materials rely on polymeric foams such as polyisocyanurate or expanded polystyrene (EPS), but significant potential exists for producing insulation from recycled or waste-derived sources, such as post-consumer EPS, textile residues, paper by-products, or plant fibers [111–114] in order to reduce raw material extraction and associated water footprints.

Assessment of the water footprint of construction materials must be adapted to the specific context in which they are produced and used, considering technical, environmental, geographical, and social factors such as the availability of raw materials and water resources, local extraction and preparation practices, construction techniques, building performance requirements, and regional climatic conditions. Moreover, the energy sources employed and the management of waste and wastewater affect the relative proportions of blue, green, and gray water footprints. Therefore, analyses should adopt a holistic approach that accounts for these variations to develop context-specific strategies and policies aimed at reducing water-related impacts.

3.3.2. Optimizing: Non-Conventional Water Resources in Sustainable Construction

Water conservation is a critical aspect of sustainable construction and a fundamental strategy to effectively address the current challenge of water scarcity. It involves the management of both water availability and consumption. Beyond strategies aimed at reducing water use, sustainable building design can also enhance water supply by harnessing non-conventional sources such as rainwater, atmospheric water, and urban runoff.

The proper implementation of rainwater harvesting systems can enable the use of this resource as a valuable water supply. Although this approach is not new, since it has been practiced for at least 4000 years [115], its adaptation to 21st century sustainable construction offers significant potential. Rainwater harvesting contributes not only to reducing potable

water demand but also to mitigating urban flooding, lowering urban runoff. When properly designed and integrated into building water management strategies, these systems can substantially reduce the environmental footprint of urban developments [116–118]. Their implementation aligns with global sustainability goals, particularly those related to water resource conservation, climate change adaptation, and resilience of cities to hydrological variability.

The main component of a rainwater harvesting system is a tank or reservoir that allows the storage and treatment of the collected rainwater. Typically, the collection surface is the building's roof [119,120], although other impermeable surfaces associated with the structure, like walls, can also be connected to the tank [121–123]. During rainfall events, the harvested rainwater is directed to the tank through the collection system, usually consisting of gutters and downpipes, and temporarily stored to meet indoor and outdoor water demands. A separate piping network is generally required to connect the rainwater tank to the points of use, supported by a pump to maintain adequate pressure. Auxiliary devices for water quality control include first-flush diverters, debris screens, and filters. Diverters isolate and discharge the most contaminated initial portion of the collection surface runoff into the sewer system, while screens and filters are used to intercept solids (sediments, debris, leaves, etc.) and particulate matter to prevent their entry into the tank. Recent innovations in rainwater harvesting design have led to more sophisticated systems adapted to contemporary needs. Examples include modular and collapsible storage systems, gutter-based or other high-efficiency low-energy collection, and storage designs [124,125].

The potential for potable water savings through the use of rainwater has been widely studied [126]. Such savings depend on the proportion of potable water that can be replaced by rainwater, which in turn is determined by the intended end uses of this alternative source. Additionally, this variable is influenced by local rainfall patterns, the available catchment area and its characteristics, as well as the respective demands for rainwater and potable water [127–130]. Therefore, the design and sizing of rainwater storage tanks must take all these factors into account. The presence of contaminants in the atmosphere and on collection surfaces can affect the quality of harvested rainwater. Hence, specific water quality parameters must be met to protect users' health and ensure the long-term functionality of the rainwater harvesting system, even when the collected water is used for non-potable purposes. Although no internationally recognized standard regulates rainwater quality for non-potable uses, rainwater may require treatment prior to storage and use [131]. Such treatment may range from simple filtration to physicochemical and biological processes or even disinfection [132,133].

The atmosphere contains a considerable amount of water, as each kilogram of air can hold more than 10 g of water, even in arid desert regions [134]. Therefore, extracting water from ubiquitous atmospheric humidity presents immense potential to address the pressing water scarcity in various regions. Several alternatives exist for atmospheric water harvesting in buildings, such as fog harvesting using fog collectors, dew harvesting through condensers, or moisture extraction from air using hygroscopic surfaces based on sorbent materials [135,136].

Fog harvesting is a simple, low-cost, and sustainable technique. However, the occurrence of fog is not common in all locations, which limits its applicability, though many sites with favorable topography and climatic conditions have successfully implemented and demonstrated this technology [137,138]. Water extraction from fog requires the interception of its visible aerosols, composed of liquid droplets, onto a fog collector mesh or net, which is generally installed in a vertical orientation. The efficiency of the collection process depends on factors such as the nature of the collector device, the water content of the fog, wind speed, topography, and site altitude, among others. Consequently, fog collection is highly

variable, and the daily water extraction rate ranges from 1.5 to 30 L/m^2 [139]. Recent research focuses on developing new advanced materials for fog harvesting [140–143] and optimizing the design of collectors and their interaction with fog [144–148].

Dew forms as a result of the condensation of invisible atmospheric water vapor onto a substrate, and is minimally affected by the climatic and geographical limitations that constrain fog harvesting. Early research primarily focused on passive radiative condensers, which do not require additional energy input [149]. In these systems, the dew point temperature necessary to initiate atmospheric water vapor condensation is achieved through passive radiative cooling of the substrate, which dissipates its heat [150]. These condensers typically operate during nighttime, since solar radiation during the day generally raises the surface temperature above the required level (Figure 8). Depending on the available radiative cooling capacity for condensation, the upper limit of daily dew collection is approximately 1 L/m^2. Active condensers have been designed as an alternative method for dew harvesting, capable of producing larger amounts of water through additional energy input [151]. Active condensers operate similarly to dehumidifiers, extracting water from air, and the use of solar energy has been proposed to meet the additional power demand of these active systems [152].

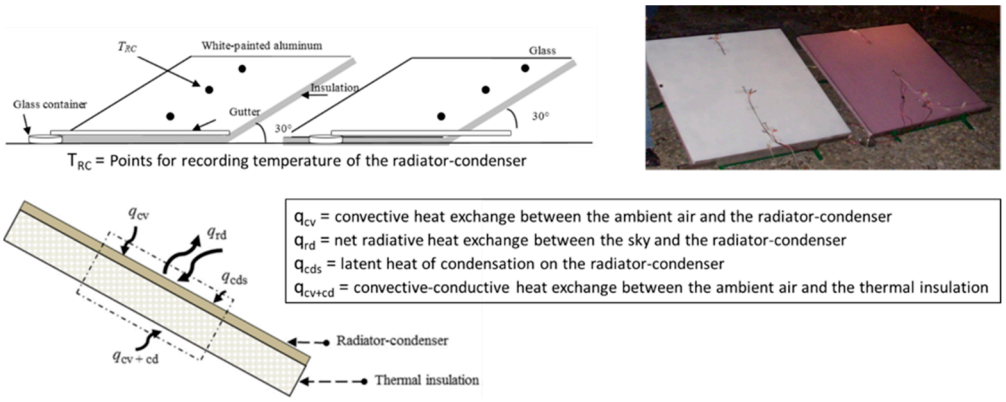


Figure 8. View of two dew-harvesting panels and the corresponding energy balance [153].

Atmospheric water harvesting based on sorption exploits the strong affinity of specific sorbents to capture water molecules even from air with low humidity [154]. In a typical passive system employing this technology, the sorbent captures water vapor from the surrounding air and releases it upon heating, leading to condensation and subsequent collection, usually on a relatively cool surface (Figure 9). The development of hygroscopic materials such as metal–organic frameworks (MOFs), polymer gels, and composite materials with embedded hygroscopic salts has enabled the advancement of this technology [155–165], giving rise to different operating modes, including single-cycle and multi-cycle sorption/desorption processes and batch operation. As a result, sorption-based atmospheric water harvesting systems have achieved daily water production rates of up to 2 L per kilogram of sorbent. Furthermore, active systems, which employ heat pumps, desiccant heat exchangers, electric heating modules, fans, and regeneration condensers, have demonstrated more stable and higher water production rates, reaching between 20 and 30 L per day.

An effective urban runoff harvesting system must account for the capture, treatment, storage, distribution, and reuse of rainwater runoff that flows across roads, pavements, and other predominantly impervious urban surfaces [167]. The accumulation of pollutants on these surfaces between rainfall events is often significant, so runoff can dissolve and transport contaminants, particularly during the initial phase after precipitation (known as

the first flush). Consequently, its treatment is far more critical than in the case of rainwater or atmospheric water, which typically contain much lower contaminant levels [168,169].

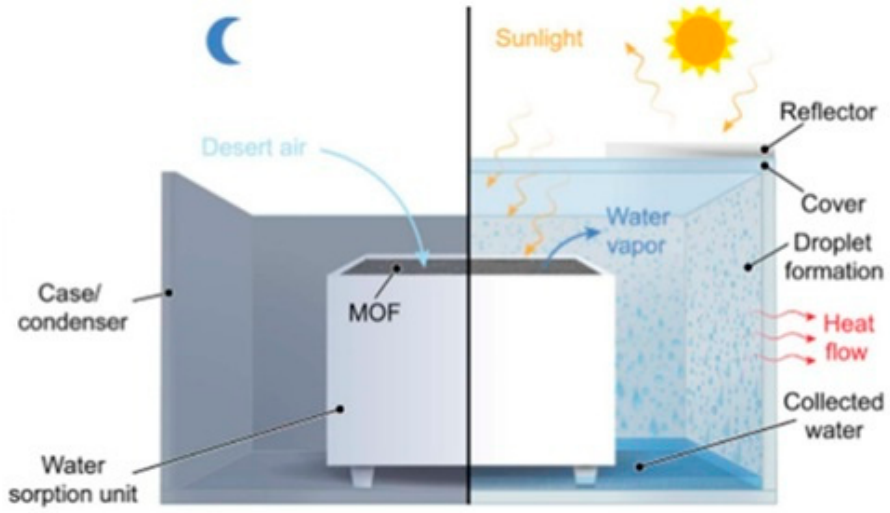


Figure 9. Schematic representation of the operation of a passive atmospheric water harvesting system based on sorption using a metal–organic framework (MOF) as sorbent [166].

Commonly used systems for runoff water collection may be classified as traditional (networks of gutters, pipes, channels, and ditches), specific (porous pavements), or nature-based (constructed wetlands, rain gardens, and other vegetated structures such as filter strips or swales) [170–172]. Nature-based solutions offer the advantage of serving as pre-treatment or direct treatment for runoff water. Specific systems based on porous pavements can also be employed to treat water as it infiltrates through them. Although more advanced technologies, such as advanced oxidation processes or membrane technologies, have been reported for such treatments, their complexity and high operational costs make them suitable only in very limited cases (for example, the removal of highly specific contaminants) [173–176].

Some nature-based systems also have potential for use as storage units, such as ponds and constructed wetlands [177,178], but the construction of underground tanks remains the most common option for storing treated runoff water, although direct aquifer recharge can also be considered [179,180]. Determining the optimal storage volume is one of the most critical research topics related to storage systems, as it directly influences overall system performance. For instance, an oversized storage system, designed without consideration of demand or environmental conditions, may result in excessively long retention periods and interfere with the hydrological cycle, whereas insufficient capacity may fail to meet demand. While a runoff water distribution system can be integrated with an existing potable water network, this requires advanced treatment measures to ensure water quality. Therefore, although cost reductions may be achieved by sharing existing infrastructure, it is more common to install a separate system to provide a safer alternative. This system must guarantee water quality at the point of use, depending on the intended application (Table 9) [181].

3.3.3. Retaining: Water Reuse in Sustainable Construction

Sustainable construction holds significant potential to promote water reuse, particularly through the integration of systems that enable the recovery and treatment of domestic wastewater within buildings. Domestic wastewater discharges can be divided into two categories: blackwater and graywater. The former refers to toilet effluents containing fecal matter and a high microbial load, whereas the latter comprises discharges from washing

machines, sinks, showers, and washbasins, characterized by a lower microbial content and, therefore, higher potential for reuse. Although microbial concentrations in graywater are relatively low, coliform levels may exceed $1 \cdot 10^6$ CFU/100 mL, which could pose potential health risks upon reuse without treatment [182]. Several technologies have enabled graywater treatment and reuse for applications such as garden irrigation, toilet flushing, and laundry washing [183–185]. Incorporation of decentralized treatment units enables a reduction in freshwater consumption and minimizes the volume of wastewater requiring treatment in centralized facilities. However, to fully exploit this potential, adaptation of building design is necessary to facilitate source segregation of domestic wastewater by means of dual plumbing networks, allowing efficient separation of graywater and blackwater streams for subsequent treatment and reuse [186].

Table 9. Compilation of applications for treated urban runoff water.

Types of Proposed Uses	Applied Examples
Domestic uses	Toilet flushing, laundry, vehicle washing, plant irrigation, pet washing, supply for bathrooms and showers, pool refilling, food preparation, drinking water production
Urban uses	Irrigation of golf courses and other sports facilities, watering of parks and gardens, street cleaning, supply for ornamental fountains
Industrial uses	Agricultural irrigation, cooling, electricity generation, applications in the construction industry, applications in the food industry
Environmental uses	Aquifer and groundwater recharge, support of aquatic ecosystems

Among commercially established technologies, membrane bioreactors (MBRs) stand out, combining physical separation of colloidal substances with aerobic biological treatment of dissolved organic matter. MBRs can remove up to 80% of chemical oxygen demand (COD) and reduce biological oxygen demand (BOD) to below 5 mg/L [187]. A schematic representation of an MBR module operation is shown in Figure 10a. Constructed wetlands are another widely recognized technology, appreciated for their simplicity, very low energy requirements, and minimal maintenance needs (Figure 10b) [188]. However, one major limitation of constructed wetlands is the space required for their installation. In this regard, vertical-flow constructed wetlands [189] have emerged as a promising nature-based solution for graywater treatment. These systems effectively remove organic matter, nitrogen, phosphorus, and pathogens through microbial activity within the wetland matrix, being also particularly efficient in removing emerging contaminants [190]. Currently, simple systems can be implemented to collect graywater, treat it through sand filters, and reuse it for irrigation purposes. A simple concept consisting of graywater collection, subsequent treatment through vertical constructed wetlands integrated into a wall, and storage in a holding tank is shown in Figure 10c [191].

Therefore, such solutions make it possible to generate treated water for daily domestic activities. However, the installation of any of these technologies requires structural modifications that allow for the capture of graywater, the separation of graywater and blackwater streams, the design of storage systems that prevent long retention times of treated water, and its subsequent recycling into household activities where graywater can be reused. It is important to note that, due to the characteristics of graywater, untreated water should not be stored for more than 24 h to prevent bacterial and pathogen growth and the development of unpleasant odors [194,195]. Decentralized treatment systems have been predominantly developed for graywater, as its lower contamination levels facilitate

simpler and safer on-site management. In contrast, decentralized blackwater treatment remains less widespread due to its higher organic and pathogen content, which demands more complex technologies and stringent health safeguards. Nevertheless, examples of decentralized systems for the in situ treatment and reuse of blackwater have also been proposed [196–198].

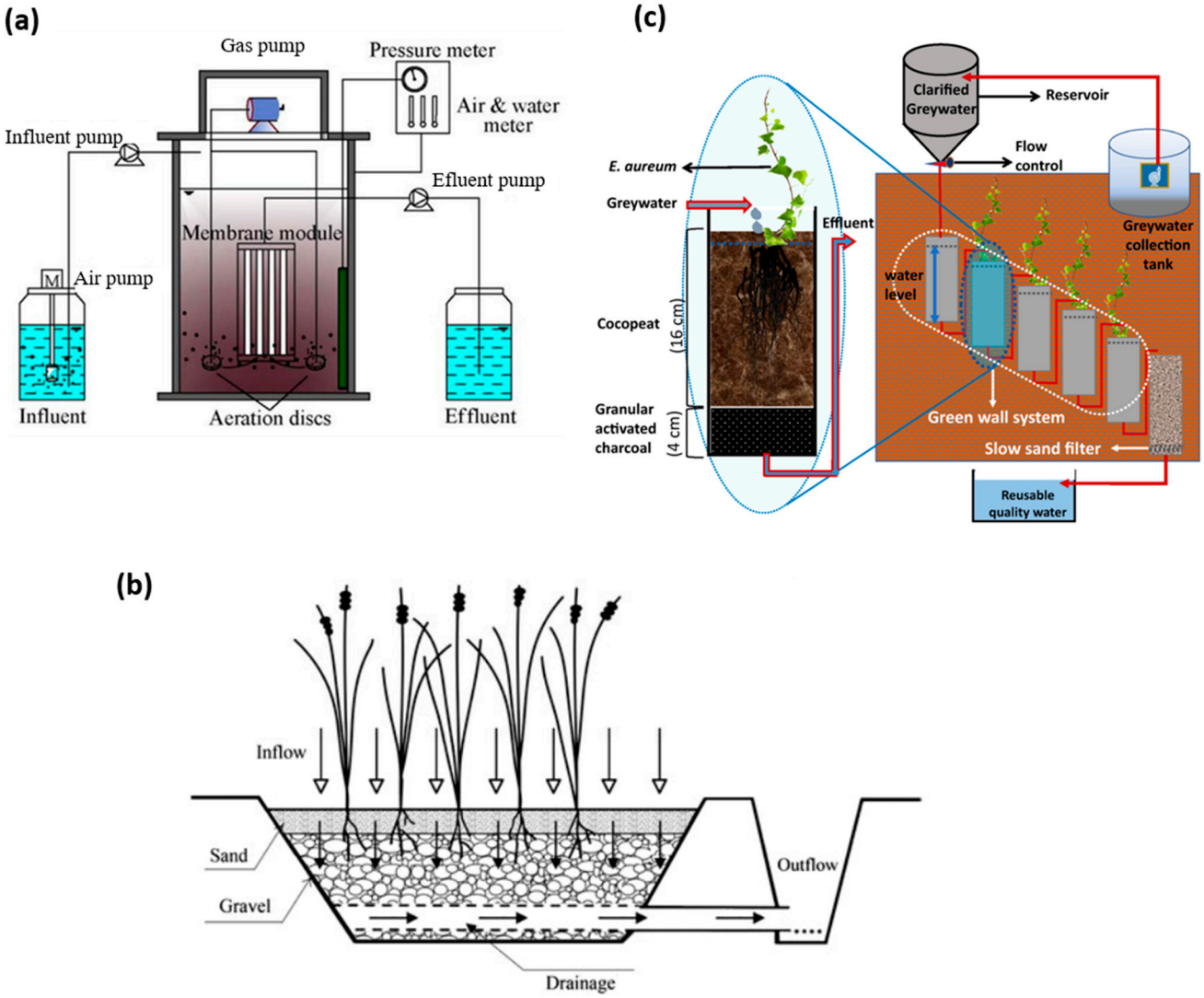


Figure 10. Schematic representation of the operation of a membrane bioreactor (MBR) system (**a**) [192], a vertical-flow constructed wetland (**b**) [193], and a system installed on a wall using vertical constructed wetlands (**c**) [191].

The implementation of green walls and roofs constitutes a key strategy to enhance water efficiency in sustainable buildings. The use of these vegetated systems has been promoted as decentralized on-site treatment technologies capable of managing graywater and even blackwater in combination with urban runoff. Such systems are increasingly being integrated into urban buildings, where green roofs in particular can play a relevant role in improving water quality through purification processes [199]. In addition, the multilayer structure of green roofs enables water storage that can be reused during dry periods, thereby improving the water resilience of urban infrastructures [67]. Nevertheless, the irrigation of green walls and roofs emerges as a suitable option for the reuse of recovered graywater, regardless of the selected treatment approach.

Two main types of green walls can be distinguished. The first corresponds to climbing green walls, which use climbing plants that progressively attach to walls or support structures. These systems require low maintenance, are simple, lightweight, and relatively inexpensive to install. The second type, known as living green walls, consists of plants that require containers, substrates, and more robust metallic structures. These systems are more complex and heavier, so they demand more specific maintenance [200]. Green roofs comprise several superimposed layers, each fulfilling a specific function to optimize overall performance. The upper layer consists of vegetation; beneath it lies a soil layer that serves as a growth medium and retains a fraction of the rainfall. This is followed by a filter layer, which prevents soil particles from clogging the drainage system, and finally a drainage layer that ensures adequate conveyance of excess water toward collection or discharge systems. This stratified configuration maximizes water-use efficiency and improves runoff water quality, positioning green roofs as a key technology for sustainable construction [201].

One of the most remarkable attributes of green walls and roofs is their role as thermal insulators. During winter, they help increase indoor temperatures by providing effective thermal insulation, whereas in summer they reduce indoor temperatures by minimizing heat transfer into buildings, thereby contributing to energy savings. This approach mitigates the impact of urban infrastructures on the local microclimate and promotes biodiversity by providing habitats for plants and animals in densely populated areas. The adoption of green walls and roofs is therefore a key strategy for sustainability, improving environmental conditions in modern cities [202]. The benefits associated with the installation of green walls and roofs are extensive, as these systems can also be used for urban wastewater treatment, enabling the removal of contaminants, and even being specifically designed for the ecological treatment of domestic wastewater while maintaining water quality within acceptable limits [203].

In parallel with the advances achieved in local domestic wastewater recovery and reuse, an emerging and highly promising option within the context of sustainable construction is the reuse of wastewater in the production of concrete. The construction industry is a water-intensive sector, requiring approximately 150 L of water per m^3 of concrete produced, but this value can increase to 500 L per m^3 when washing and losses during the production and transportation stages are considered [204]. This demand represents a significant share of the global water footprint of urban development and exacerbates the effects of water scarcity. From a sustainability perspective, the use of both domestic and industrial wastewaters constitutes a practical strategy to alleviate pressure on freshwater resources while simultaneously reducing the environmental burden associated with effluent discharge. These advantages have promoted research efforts in this field and several reviews compiling the main results have been published [205–212].

The potential for wastewater reuse in concrete production depends largely on the physical and chemical characteristics of the effluent. Several studies have documented the feasibility of employing water streams, such as those from ready-mixed concrete plants [213], domestic wastewater, and various industrial effluents [214], provided that their pH and contents of solids, chlorides, sulfates, carbonates, and metals remain within the limits prescribed by international standards, such as ASTM C1602 and EN 1008 [209]. Nevertheless, the reuse of treated wastewater for concrete production presents both opportunities and risks that must be carefully managed.

In the fresh state, excessive salinity or the presence of organic matter may interfere with cement hydration, extend setting time, and increase the risk of corrosion of steel reinforcement [215–219]. These effects arise mainly from the interference of dissolved salts and organic compounds with the early formation of calcium-silicate-hydrate (C-S-H) gel and from the alteration of ionic equilibrium in the pore solution [220]. Adequate pretreat-

ment with wastewater can significantly reduce these effects. In the hardened state, mixes produced with wastewater have demonstrated compressive strength and microstructural integrity comparable to those produced with potable water. Reported strength losses are generally below 10%, and in certain cases the use of high-quality treated wastewater has even resulted in strength gains [221,222]. Conversely, workability can decline moderately due to higher suspended-solid contents, although with suitable treatment and mixing ratios, both mechanical strength and durability can be preserved [223,224]. Durability is highly influenced by the concentration of aggressive ions. Moderate chloride and sulfate levels may reduce permeability by promoting secondary hydration reactions and pore refinement, thereby slightly improving resistance to water ingress [225,226]. However, when chloride concentrations exceed safe thresholds, the passive film on embedded steel can be destabilized, leading to localized corrosion, while excessive sulfate contents can react with hydrated phases to form expansive products such as ettringite and gypsum, ultimately causing cracking and loss of mechanical integrity [227].

The reuse of treated wastewater in concrete production offers significant economic and environmental advantages [228,229]. It reduces freshwater consumption and wastewater discharge, thereby lowering operational costs in batching plants and contributing to the conservation of limited water resources. Additionally, by integrating reclaimed water into concrete manufacturing, the overall environmental footprint of the construction sector is diminished through decreased energy use for water treatment and reduced ecological impact associated with freshwater extraction. Future research should focus on developing unified testing protocols, identifying potential risks associated with contaminant accumulation, and quantifying the economic and environmental life-cycle benefits to consolidate wastewater reuse as a mainstream component of sustainable concrete production.

4. Conclusions

The bibliometric performance analysis revealed sustained and increasingly consolidated research activity on water management within sustainable architecture. Scientific output has grown steadily since the mid-1990s, with a marked acceleration after 2015, although without reaching the exponential growth typical of emerging disruptive fields. Journal articles dominated dissemination, while the relatively low share of review papers indicates room for further synthesis efforts. Research was led by the United States, China, and India, with strong contributions from other countries facing water stress, reflecting the practical relevance of the topic. Engineering, environmental science, and materials science concentrated most publications, confirming the technical orientation of the field. Keyword and cluster analyses highlighted construction materials, water-related physical properties, water conservation, and wastewater reclamation as central themes, while energy and environmental impacts remained strongly interconnected with water-focused research.

Research addressing the reduction in water demand emphasized that the largest opportunities for water savings lie beyond operational consumption. Water use during construction activities, and, above all, the embodied water associated with construction materials, dominate the overall water footprint of buildings. Cement, steel, aggregates, and finishing materials account for the highest indirect water consumption, largely driven by energy-intensive production processes and pollution-related gray water footprints. Substitution with recycled materials, increased use of supplementary cementitious materials, alternative aggregates, and bio-based products consistently emerge as effective strategies to reduce water demand. These findings stress the importance of integrating water footprint assessment into material selection and life-cycle decision-making, rather than focusing exclusively on on-site water savings.

Optimization strategies based on non-conventional water resources were shown to be increasingly diverse and context-dependent. Rainwater harvesting remained the most mature and widely applicable option, while atmospheric water harvesting and urban runoff recovery have gained attention due to advances in materials, system design, and nature-based solutions. However, their performance is highly sensitive to local climatic, urban, and regulatory conditions. The literature consistently indicated that improper sizing, insufficient treatment, or lack of integration with building demand can limit their effectiveness. Consequently, future progress depends less on technological novelty than on system integration, adaptive design, and alignment between water quality requirements and intended uses within buildings.

Water retention through reuse constituted the most transformative strategy for improving water efficiency in sustainable construction. Decentralized graywater treatment, green roofs and walls, and wastewater reuse in concrete production have demonstrated substantial potential to reduce freshwater demand and wastewater discharge simultaneously. Membrane bioreactors and nature-based systems dominated building-scale applications, while wastewater reuse in concrete has shown promising mechanical performance when quality constraints are respected. Nevertheless, risks related to contaminant accumulation, durability, and health must be carefully managed. The literature indicated that widespread adoption requires clearer regulatory frameworks, standardized testing protocols, and life-cycle evaluations to ensure that water reuse solutions deliver robust environmental benefits without transferring risks across system boundaries.

This work provides a comprehensive framework for understanding the evolution of research on water management in sustainable buildings and identifying the main scientific trends that are shaping the field. From a theoretical perspective, the integration of bibliometric mapping with a structured review based on the circular-economy-oriented framework for water (decreasing, optimizing, and retaining) offers an organized perspective that connects the intellectual development of the field with its main technological approaches. From a practical perspective, the results may assist architects, engineers, policymakers, and building managers in prioritizing water-saving measures, selecting suitable non-conventional water resources, and promoting water reuse strategies according to local environmental and regulatory conditions.

Several limitations should be considered when interpreting the findings derived from this work. First, the bibliometric analysis was based exclusively on the Scopus database, which, despite its extensive coverage, does not include all existing publications indexed in other scientific databases or gray literature. Second, the search strategy was intentionally focused on water management within the context of sustainable architecture and buildings, which may have excluded related studies addressing water efficiency from broader urban, industrial, or infrastructure perspectives. Third, the bibliometric analysis reflects the state of the literature up to 2023 and, therefore, does not capture the most recent developments in this field. Finally, although the review identified the dominant research themes and synthesized the available evidence, it did not quantitatively compare the technical, economic, or environmental performance of the different water management strategies, as this was beyond the scope of the present work.

Future studies should move beyond descriptive analyses and place greater emphasis on the quantitative assessment of the effectiveness of water management strategies under different climatic, economic, and regulatory contexts. Greater integration of water footprint assessment with life-cycle assessment, carbon footprint, and energy analyses would strengthen holistic sustainability evaluations. Additional research is also needed on digital water management technologies, smart monitoring systems, artificial intelligence for water optimization, and the integration of nature-based solutions into building design.

In addition, further work should address the harmonization of performance indicators and assessment methodologies to facilitate comparisons between studies and accelerate the transfer of research outcomes into engineering practice and sustainable building policies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16142849/s1, Figure S1: Structure of the cluster Sustainable Development in Subperiod 1 (1994–2014). Figure S2: Structure of the cluster Wastewater Reclamation in Subperiod 1 (1994–2014). Figure S3: Structure of the cluster Energy Utilization in Subperiod 1 (1994–2014). Figure S4: Structure of the cluster Recycling in Subperiod 1 (1994–2014). Figure S5: Structure of the cluster Rating System in Subperiod 1 (1994–2014). Figure S6: Structure of the cluster Water Management in Subperiod 1 (1994–2014). Figure S7: Structure of the cluster Architectural Design in Subperiod 1 (1994–2014). Figure S8: Structure of the cluster Environmental Protection in Subperiod 1 (1994–2014). Figure S9: Structure of the cluster Air Conditioning in Subperiod 1 (1994–2014). Figure S10: Structure of the cluster Sustainable Development in Subperiod 2 (2015–2019). Figure S11: Structure of the cluster Compressive Strength in Subperiod 2 (2015–2019). Figure S12: Structure of the cluster Greenhouse Gases in Subperiod 2 (2015–2019). Figure S13: Structure of the cluster Water Conservation in Subperiod 2 (2015–2019). Figure S14: Structure of the cluster Building Material in Subperiod 2 (2015–2019). Figure S15: Structure of the cluster Carbon Dioxide in Subperiod 2 (2015–2019). Figure S16: Structure of the cluster Compressive Strength in Subperiod 3 (2020–2023). Figure S17: Structure of the cluster Blast Furnaces in Subperiod 3 (2020–2023). Figure S18: Structure of the cluster Water Conservation in Subperiod 3 (2020–2023). Figure S19: Structure of the cluster Scanning Electron Microscopy in Subperiod 3 (2020–2023). Figure S20: Structure of the cluster Construction Industry in Subperiod 3 (2020–2023). Figure S21: Structure of the cluster Life Cycle in Subperiod 3 (2020–2023). Figure S22: Structure of the cluster Thermal Conductivity in Subperiod 3 (2020–2023). Figure S23: Structure of the cluster Energy in Subperiod 3 (2020–2023). Figure S24: Structure of the cluster Mortar in Subperiod 3 (2020–2023). Figure S25: Structure of the cluster Climate Change in Subperiod 3 (2020–2023).

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