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Systematic Review

Water Supply and Wastewater Treatment and Reuse in Future Cities: A Systematic Literature Review

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Abstract: Due to climate emergencies, water stress, and fast-growing populations, many cities around the world are adopting wastewater reclamation and reuse to improve the water supply for their residents. The purpose of the paper was to investigate the effectiveness of expanding wastewater reclamation and reuse as a solution to water supply challenges for future cities. It used a systematic review of the literature to evaluate and synthesize the available evidence in support of wastewater reclamation and reuse for future cities. A model known as PRISMA was used to identify the most appropriate articles for inclusion in the study. Out of the 105 studies, a total of 46 articles were selected for analysis based on their relevance, content validity, and strength of evidence. The findings indicate that wastewater reclamation and reuse create additional sources of water for both domestic and industrial use, reducing the overall pressure on the natural water sources. Wastewater reclamation and reuse effectively increase water supply for future cities while minimizing pressure on natural resources and promoting environmental sustainability.

Keywords: megadrought; urban water systems; wastewater treatment; water reuse

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1. Introduction

1.1. Background and Scope of Study

As water becomes increasingly scarce for urban dwellers, cities will have to do more than their current efforts to achieve sustainable supply. Cities around the world have stretched their resources to secure water and prevent shortages that expose millions of people to various diseases, including cholera [1]. With a growing population, many cities are grappling with increasing consumption against a dwindling supply [1,2]. Climate change and natural calamities such as drought and floods continue to ravage various water sources that have kept many cities in steady supply [2]. Meyer [3] believes that cities must exceed their current efforts if they want to provide a sustainable supply of water for future populations. Apart from building dams and reclaiming wastewater, cities must double their efforts in discouraging wasteful consumption and unmeasured use [3]. It is also advisable for cities to explore ways in which innovative technologies such as microfiltration (MF), acoustic nanotubes, ultrafiltration (UF), and nanofiltration (NF) optimize water supply for future needs.

Water supply remains a consistent problem that cities have dealt with for years. Over 1700 years ago, the Romans built aqueducts to increase the water supply to the major cities and towns [4]. The aqueducts were built using a mixture of stone, brick, and volcanic cement that kept them strong, and this is the reason why most of them are still standing today [3,5]. During their reigns, emperors Augustus, Caligula, and Trajan were all concerned about the future of their cities and ordered the construction of the aqueducts [1,4,6]. The presence of these aqueducts today indicates the need for a futuristic approach to water supply and conservation to address urban needs. Apart from the Romans, the Mayans also constructed large underground water storage facilities to increase the water supply to their cities and farmlands [1,3,5,7]. Efforts by these traditional societies indicate that water supply has been a persistent issue over the centuries and that innovation has been a successful approach to achieving sustainable supply.

Modern cities use a portfolio of technologies to maintain a stable water supply and avoid potential crises. Some of the most remarkable technologies include the 60-story dam, centrifugal pumps, and ultrafiltration machines that convert wastewater into clean water for domestic and industrial use [8]. Dams have become essential both for water supply and power generation. The 60-story dam, for instance, has a power generation powerhouse where water passes through the turbines at an incredible speed of 85 miles per hour [5,7,9]. The generator inside the powerhouse is what converts kinetic energy into electric energy, enough to supply a city and its surrounding neighborhoods [7,10]. Investments in dams and other forms of reservoirs enable cities to provide sufficient water across the seasons. Technology also helps in developing accurate projections and tracking down the supply to enhance accountability [2,5,8,10]. However, future cities will have to do more than the current cities to maintain a stable supply.

Not long ago, many cities around the world experienced a water supply crisis, largely attributed to the increasing drought. For instance, in 2018, Cape Town (South Africa) nearly avoided a "Day Zero" where all the taps would have gone dry [11]. The city managed to push Day Zero forwards by more than 30 days by restricting the allocation of water to agricultural purposes [11]. The city also minimized heavy consumption by setting higher tariffs to avoid the use of water for nonessential purposes such as watering pools and lawns. Cape Town also installed a new water pressure system to avoid sending large volumes of water to both domestic and industrial consumers [11]. Away from South Africa, the Colorado River is also facing significant water shortages, exposing more than 40 million people to what may become one of the largest water crises in the American West [11]. As many parts of America face what has been described as a "megadrought" by meteorologists, cities must revise their water supply plans to accommodate the new difficulties.

The purpose of this paper is to evaluate and synthesize the available evidence in support of expanding reuse as a water supply solution for future cities. The introduction section provides background about the research problem and why it warrants a study. The paper examines underlying issues that may affect the water supply for both current and future cities. Apart from the challenges, the paper also examines various remedies that are used by modern cities to boost water supply. The methods section narrates various steps that were used in the selection and analysis of the sources. The results section provides a brief review of the findings in 46 articles. The discussion section provides a detailed analysis of the findings and explains how future cities can use the available evidence and strategies to boost the water supply. The conclusion section summarizes the findings and reiterates the paper's position on the research problem.

1.2. Underlying Issues

Climate change remains one of the biggest threats facing water supply in both current and future cities. The term "climate change" has been used many times to refer to the global warming phenomenon [12]. However, climate change also refers to the increase in extreme weather events, including flooding, tornadoes, wildfires, and hurricanes [12]. Collectively, the effects of climate change present significant challenges to water supply and wastewater treatment in both current and even future cities [13]. For instance, climate change has been largely associated with a growing challenge known as "megadrought." While drought refers to prolonged periods of dryness and low precipitation, megadrought refers to a drought that persists for decades [14]. Many cities within the American West and Southwest are facing megadrought situations. Other areas, such as the Sahara, Sub-Saharan Africa, and Asia, are also facing moderate to severe drought conditions [15–17]. This has led to a significant drop in water supply, with residents being forced to reduce their consumption levels to prevent a potential crisis.

Another significant challenge facing cities is the increased consumption caused by the growing urban population. As the city populations continue to grow, the demand for clean and safe water is more likely to exceed the supply [18]. The massive growth of the urban population is putting significant pressure on natural resources, including natural sources of clean water. Estimates by the World Bank, UNCTAD, and other international organizations indicate that the urban population is more likely to double by 2050 [19]. This means more than 4.4 billion people may become urban dwellers over the next two decades [20]. Further analysis indicates that about 7 out of 10 people will be living in the cities by 2050. Such a huge population would, no doubt, impose additional pressure on the current infrastructure that supports city dwellers [20,21]. For instance, the additional urban population indicates that more water pipes would have to be constructed to enhance supply, even to the remotely located populations.

The growing urban population is also presenting a significant challenge in laying down the infrastructure needed for sufficient water supply. As cities continue to grow, the low-income populations are usually pushed further outwards, into areas that may be difficult to reach by the pipes [22]. Most of the shanties are unplanned settlement schemes without a proper layout of water and sewerage infrastructure. One of the major challenges that future administrators may face is connecting the new settlements caused by the growing populations to the main grid to enhance the smooth and accountable supply of water [23]. Without connection, especially to the sewerage system, the risk of water pollution is significantly high and may expose millions of people to diseases such as cholera and dysentery [22–24]. As cities continue to grow, administrators need to examine ways in which they can control the structural and physical layout of the urban and suburban areas to support future infrastructural development.

The major intersecting trend of population growth and unsustainable water management remains a significant challenge facing both current and future cities. The growing urban population would not be a significant threat if cities had sufficient water management systems [25]. However, unsustainable water management has led to situations where the demand outweighs the supply in most urban centers. The management of the city water system has been subject to various challenges, including massive waste and challenges in accountability [26]. Most of the water that flows into the cities usually ends up fulfilling activities they were not designed to address [27]. Moreover, most of the water used in the major cities is poorly accounted for. For instance, there are so many unmetered connections that supply water but provide very little returns for the city administrators.

Another significant challenge that cities need to address is the aging or deteriorating infrastructure. Cities such as London have some of the oldest water supply infrastructure in the world [28]. Some of the pipes that supply water across major cities, including Paris, New York, and Mumbai, were constructed many centuries ago. While most of the old infrastructure is still in working condition, there are high chances of frequent breakdowns and the need to make repairs after losing a billion gallons of treated drinking water [29]. In the United States, for instance, an estimated 6 billion gallons of treated water are lost due to leaking pipes every day [30]. The statistics indicate that pipe breaks occur almost every 2 min [31]. Some of the pipe outbursts also damage related infrastructure, such as roads and railway lines. Apart from water loss, cities also lose about USD 14 billion almost daily in repairing the damages caused by the aging infrastructure.

The intense competition for water between different sectors is another challenge that affects the water supply in cities around the world. Water is needed for various purposes, including agriculture, industrialization, business, and domestic use [31]. The growing urban population has led to intense competition for water as various sectors of the city try to meet the needs of the population. Industries demand more water for processing goods that are needed by the urban population [31]. Various business activities such as carwash, carpet cleaning, and other outdoor business activities also demand significant amounts of water, despite most of it going to waste [32,33]. The suburban population is also competing for water with urban dwellers to meet various needs, including irrigation [34]. The intense competition leaves very little amount of water that people can consume at home. The intense competition may expose city dwellers to constant rationing as the administrators try to balance consumption across different sectors.

1.3. Expanding Reuse of Marginal Waters

Wastewater reclamation and reuse remain one of the best strategies that can be used to maintain supply without depleting the natural sources of water. Wastewater treatment involves the removal of suspended solids and chemicals so that the remaining effluent can be discharged back into the environment for consumption [35]. The treatment process involves primary, secondary, and tertiary stages, depending on the intended use of the final product. Once the pollutants and chemicals are removed from the wastewater, the final product, known as effluent, can be discharged back into circulation to boost the water supply [36]. One of the main advantages of wastewater treatment is that it increases the supply of water in urban areas without imposing excessive pressure on natural resources. Rather than letting wastewater go to waste, it can be converted into useful products, including clean and safe water for domestic use [37]. Wastewater treatment also protects the reservoirs around the city from potential depletion.

The intense competition for water among different sectors can be minimized through wastewater treatment. The treated wastewater can be an important source of both moisture and nutrients for crops [38]. The sewage, which forms the largest component of wastewater, contains nitrogen in the form of ammonia. During the treatment process, a method known as air-stripping can be used to convert wastewater into fertilizer [39]. The process results in clean water and a byproduct that can be used in farms to enhance crop yields. Based on the high level of nutrients, wastewater is more effective in agriculture than clean water from reservoirs [40]. The treatment to purpose also enables cities to provide water that is fit for the intended purpose. Sewage contains nitrogen in the form of ammonia. Removing the ammonia via air-stripping, a method that converts wastewater into fertilizer, would shorten the water treatment process and create a valuable byproduct [41]. By providing alternative sources of water, wastewater is likely to provide a more viable solution to the intense pressure on clean sources of water.

Another potential solution to the growing water challenges in the cities is building better infrastructure. Lessons can be drawn from cities such as New Orleans (Louisiana), Santa Barbara (California), and Alameda (California), which have become leading benchmarks for water management [41]. According to Petrinic et al. [41], cities such as New Orleans are located next to some of the largest water masses in the country. While most of the surrounding water may not be safe for drinking and other forms of human consumption, these cities excel in transforming the raw water into a form that can be used to serve various needs. For example, in the quest to alleviate water crises and foster the development of cleaner production and a circular economy, the positive cycle enabled by wastewater reuse emerges as a significant opportunity. By augmenting the water supply and diminishing the release of pollutants into surrounding water bodies, this cycle offers the potential to break free from the existing constraints. [42]. In Santa Barbara, for instance, water from the sea undergoes a treatment process to protect consumers from waterborne and sewage-related infectious bacteria, parasites, toxic chemicals, and viruses. It also concerns industrial consumers [43]. The city is aware of the pollutants that are usually swept into the sea by the runoffs during rain or floods [44]. By constantly improving the water supply system, cities can minimize both the current and future challenges they may face in addressing the needs of their populations.

1.4. Resilient Urban Water Systems

Future solutions to water supply should focus on increasing territories with raw water resources, creating alternative sources of water, and integrating water consumption with environmental sustainability policies [45]. Although 75% of the Earth is made up of water, accessing it has always been a challenge for most cities [46]. The distant locations away from the natural sources of water remain a significant challenge that urban administrators need to overcome. One of the potential solutions is increasing territories with raw water sources. This includes building more reservoirs, protecting natural sources such as rivers and lakes, and digging boreholes [47–49]. The reservoirs have proven effective in the sustainable supply of water in major cities across the world. Many cities that are located hundreds of miles away from major sources of water, such as lakes, have to rely on reservoirs, including artificial lakes, to improve water supply [50]. For instance, Toledo Bend Lake is the largest human-made reservoir in the south, serving both Louisiana and Texas.

Cities must also create alternative sources of water to minimize intense pressure on their reservoirs. Wastewater treatment is one of the most sustainable alternatives that cities can use to reduce pressure on natural sources [51]. The alternatives can be developed in many ways, including reducing waste and converting wastewater into useful products. Cities must work towards reducing waste by educating their residents about the economic use of water. In South Africa, for instance, the city of Cape Town took various measures, including educating the public and heavy punishments to reduce water waste [52]. Public education enables city dwellers to plan effectively with the little water they receive through metered connections [53]. Connecting water use to the economic impact on every household may improve public consciousness against waste. Imposing heavy punishment may also prevent the use of water for non-intended purposes, including watering lawns and washing cars [54]. Cities that have closely avoided day zero understand the difficulties brought by wasteful consumption to urban residents.

Cities should also transform their policies to align both water supply and environmental sustainability. There is a very thin line between water conservation and environmental sustainability. Water is one of the natural resources contributing to the stability of the natural ecosystem [55]. Water provides moisture and nutrients that support nearly every form of life on the planet [56]. However, there has always been a tendency for policymakers to treat water conservation differently from other environmental sustainability policies [57–60]. Various rules governing carbon emissions and pollution should also be tied to water conservation to increase awareness of pollution. Studies have shown that water pollution remains the biggest threat to supply and sustainability [61–63]. Other challenges, such as climate change, also stem from the misuse and exploitation of natural resources, including water. Increasing awareness of pollution will help conserve the reservoirs and protect residents against various diseases associated with water pollution.

2. Methods

To find relevant studies for the review, the author conducted an extensive search on both physical and online databases. Some of the conference papers used in the systematic review were obtained from the physical libraries, while the articles were obtained from two main databases and indexes: ProQuest Aquatic Science Collection, Scopus, WATERnetBASE: Water References Online, Nature, and Water Resources Abstracts. These databases were chosen because of their vast collection of studies on various topics related to water conservation and sustainability. The author used at least five databases due to the large number of articles needed for the review. The studies found in the selected databases have also undergone sufficient peer review to enhance their authenticity, reliability, and validity.

A systematic review was selected for this study because it is precise in stating the outcomes, explicit in methodology, comprehensive, and reproducible [64]. A systematic review is suitable when a researcher is looking for specific answers to a research question [64]. For example, a researcher can use systematic reviews to determine if a particular intervention treats a given disease. In this case, systematic reviews can provide specific answers to the benefits of expanding water reuse to future cities [65]. Researchers can also use a systematic review to determine if there is a correlation between an intervention and the outcomes [66]. For this study, the specificity and comprehensive nature of the systematic review made it an appropriate approach for answering the research questions.

The methods used in systematic reviews are carefully planned and deliberated. Each stage of the systematic review is usually defined in detail, enabling readers to evaluate the impact of each step used in the methodology on the outcomes [67]. According to Drawson et al. [67], the methods used in collecting and analyzing data are crucial in determining both the validity and reliability of a study. Questions can be formulated using various logics, including the PICO (population, intervention, comparison, outcomes) and CIMO (context, intervention, mechanisms, and outcomes) approaches [68]. The selected articles are also subjected to deliberate eligibility criteria to determine whether they are appropriate for the study or not. Systematic reviews make research transparent and easy to reproduce [69]. Those who want to verify the outcomes can follow the same methodology to generate the same results.

A systematic review was selected because it is comprehensive and exhaustive. Researchers can use either quantitative or textual narratives to analyze and present the results [70]. The quantitative approach, such as a meta-analysis, relies on statistics to determine correlations or relationships between variables [70]. Meta-analysis can be used to evaluate the results from various randomized controlled trials to determine if there is a correlation between variables [65]. In this study, the selected systematic review approach is the textual narrations of the results. This includes presenting a table with summaries of the results from the selected studies. All the studies presented in the table underwent scrutiny and met the eligibility requirements [69]. It is also easier for the researchers to remove or add additional studies to the table if they discover new evidence.

The systematic review approach also provides reliable and accurate results. The depth of evidence presented in the systematic reviews enables researchers to investigate issues beyond a reasonable doubt [64]. Systematic reviews evaluate results from primary studies and can help researchers determine if there is consistency in the outcomes [70]. Whenever the outcomes are not consistent, researchers can gain significant authority to inform readers about disagreements among researchers. Evidence from systematic reviews is also ranked highly because it comes from various primary studies [66]. The researchers can also evaluate the quality of the outcomes using the standardized GRADE approach [67]. While there could be more effective methodologies for similar studies, the systematic review proved more suitable in this study based on its comprehension, accuracy, and reliability.

2.1. Question Formulation

For the question formulation, an exploratory approach was adopted to identify challenges facing water supply in future cities. The formulation of the research question began with reviewing the topic to determine its focus and relevance to the underlying issue. The topic for this study is water supply and wastewater treatment and reuse in future cities. Since the topic is general, the author narrowed it down to a specific issue: "expanding water reuse in the future cities." Since water supply is a general problem, it was focused on how cities can expand their water reclamation and reuse to provide more water for their current and future populations. Narrowing the topic to a specific issue enabled the development of a more focused research question.

The second step in the formulation of the research question involved researching to determine if there is sufficient information or if there is a need for more studies. The general research on the topic found sufficient studies conducted from as early as the 1920s. However, there seemed to be different positions adopted by the previous researchers about the effectiveness of water reuse. While some researchers supported investments in wastewater reclamation and reuse, others pointed out several challenges that prevent most cities from reclaiming and supplying clean and safe water for domestic and industrial use [70]. Among the challenges pointed out by the previous researchers include budgetary constraints, inadequate staff and training, excessive energy consumption, and difficulties in sludge management [69]. The research question would be drafted in a way that reflects both the benefits and challenges facing the expansion of water reuse to meet the needs of the urban population.

The third step in the question formulation focused on the needs of the audience. Williams [70] argues that a researcher should contextualize the audience's needs when developing research questions to enhance relevancy. Researchers should question how their efforts would address the challenges facing society [67]. This may help in refining the research question further to make it more relevant to the current needs. Thinking about the audience also helps in creating an engaging question that readers can also use in conducting their own investigations [69]. After making all the relevant considerations, the final research question read as follows: "How effective is expanding water reuse as a solution to water supply for future cities?" The research question was also used as a criterion for selecting or rejecting articles for the study.

2.2. Source Identification

The methods used in obtaining the articles included Boolean search and snowballing sampling. The Boolean search is achieved by using keywords extracted from the research question. The keywords are typed into search boxes of the selected database to obtain the articles. A single search may return more than 1000 articles depending on the depth of the database and the popularity of the topic among researchers. It is upon the researchers to reduce the number of articles by refining the keywords, making them more specific and accurate. The Boolean operators become effective when researchers want specific results from several keywords. Researchers can broaden their search using related keywords while limiting the results to specific areas.

Although Boolean operators provide results that are directly related to the keywords, there are situations where researchers may want to obtain more articles within or outside the used keywords. Snowball sampling enables obtaining results that are not directly related to the keywords [64]. This is where the researcher uses the already available reference list to find more articles that are related to the ones they have already [66]. Snowball sampling was used in this study to find more articles that are related to mainstream references to build a more comprehensive reference list [67]. However, one may note that conducting snowball sampling presents additional challenges and may be unnecessary in a case where the required articles can be easily obtained using the keywords [68]. It may only be appropriate to use snowball sampling where additional articles are needed to meet the required threshold.

Getting the right articles for review was not a challenging task because the author had clearly outlined the criteria for the task. The work began by examining the originality of each article needed for further analysis. Originality was defined as an independent work whose major findings add substantial new knowledge to the already existing literature [69]. By going through the abstracts, the author was able to discern the originality of the studies based on their research approach and their findings. The author also relied on peer-reviewed articles to ensure the originality was tested before publishing [70]. Originality was deemed crucial because the purpose of research is to add new information or build on the existing literature to solve a problem affecting society [70]. Focusing on originality also prevents redundancy, which is a significant impediment to the growth of information literacy.

The second factor to consider was the relevance between the presented literature and the research topic. The selected articles had to be relevant to the research topic to enhance accuracy and reliability [69]. All the studies that were selected for further analysis met this criterion. The author examined if the selected studies covered all the required areas of the topic and whether the information provided was redundant or complementary to the existing literature. By focusing on the abstract and methodologies used in the studies, the author could determine how the findings were relevant to the topic under investigation. The aim was not to maintain similarity but to ensure that the provided information did not deviate significantly from the field of study. The author also noted specific areas where the results seemed conflicting and excluded outcomes that were considered to be outliers.

The author also considered the methods used in collecting and analyzing data in each article. This was crucial given that the methods used in data collection and analysis determine the overall accuracy of the study [65]. The methods also determine both reliability and validity of the study. Validity ensures that all the procedures needed for data collection and analysis are followed, and the overall results are factual [69]. Reliability ensures that similar results would be obtained if the same methodology and population were used in a different study [70]. The abstract and methodology sections of each article provided relevant information needed to determine the accuracy of the selected articles. According to Hammarberg et al. [68], examining the research methods also prevents the chances of repeating the same mistakes made by the previous researchers.

The fourth consideration focused on the connection between the conclusions made in the selected article and other sections of the study. It was crucial to consider the conclusions made because they not only summarize the main findings but also point toward challenges that may have impacted the overall quality of the findings [65]. Most authors present their conclusions in the form of recommendations, including a potential direction for future studies [67]. The conclusion may help in identifying gaps that could not be fulfilled and how they can be addressed in future studies [70]. It was also important to examine how researchers tie their arguments to ensure readers understand their work and future directions.

The fifth consideration was the objectives of the study. Using the abstracts, introduction, and results sections of the selected articles, the author was able to determine whether the authors met their stated objectives or failed to do so [64]. The objectives generally guide the contents of a study. Researchers usually set out key objectives to meet at the end of their study [65]. The objectives also outline the key problems that a study seeks to address [66]. A study that fails to meet its objectives may be considered incomplete and requires additional research. All the studies that were selected for further analysis met all the stated objectives. In most studies, the researchers even went beyond the stated objectives by addressing issues related to their main topic, such as suggesting recommendations at the end of the conclusion.

The sixth and final consideration focused on the overall quality of communication in the selected materials. The author focused on various aspects of communication, including content clarity, conciseness, and comprehension. Clarity examines whether the words used in communication were simple enough for readers to understand. Most researchers avoid using technical terms to make their work easier to understand, even for those who do not have technical knowledge in their field of study. For instance, breaking down all the technical terms related to water supply helps even those with inadequate knowledge of the topic to understand and even contribute towards building a better topic. Conciseness examines whether the authors stated their points clearly and without unnecessary verbosity. It was also crucial to examine how deep the authors went in explaining their points to enhance understanding. All six considerations helped in building a comprehensive list of articles that provides sufficient answers to the research question.

2.3. Source Selection and Evaluation

The first step involved screening the abstracts to determine the background of the study, objectives, methods, findings, and conclusion. The abstract is the comprehensive summary of the study, usually written in less than 200 words. The researchers use abstracts to inform readers about the background of their study, the main objectives, and the methods they used in collecting and analyzing data. The abstract also explains the tools that were used in collecting data and their effectiveness in providing a more reliable result. The abstract also explains the major conclusions drawn by the researchers based on their findings. The abstract screening was used to determine whether an article should be included or excluded from the study. The abstract also helped in isolating studies that were either irrelevant or did not fall within the required year of publication. The second phase ensured that the articles met all the requirements in the inclusion criteria, including the year of publication (2001 and 2023), relevant keywords, peer review journals, and reliable data.

The author also examined the impact of his biases and how they may influence the types of articles they select for the study. The main types of biases that were considered include publication bias, information bias, and selection bias. Information bias occurs when the researchers are looking for particular information in the selected studies. This may prevent an objective review of the other viable data that may add new knowledge on a topic. Selection bias occurs when the study population or articles used in the study are selected based on the researchers' preferences or beliefs rather than objective facts. The author avoided both information and selection biases by focusing on the inclusion and exclusion criteria. Publication bias occurs when researchers select only publications that confirm their beliefs, ignoring those with differing views.

As shown in Figure 1, the author also used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach to synthesize and select the most appropriate studies [70]. The PRISMA checklist document is provided in the Supplementary Materials (See Table S1). The research on the selected databases returned more than 450 studies. However, not all of them met the eligibility criteria, as some fell below the required year of publication. A total of 60 articles were published between 1995 and 1999, falling below the 2000 and 2023 range. Although the old publications have important elements, it was not considered appropriate to include them due to the analysis carried out with PRISMA. More than 286 articles were rejected for various reasons, including being duplicates or irrelevant to the research topic. This left a total of 105 articles to be used in the research, including an additional reference on the PRISMA method presented in Table S1 from the supplementary material. Out of this number, a total of 46 articles met the required inclusion criteria for analysis, while the remaining 59 articles were included in the references.

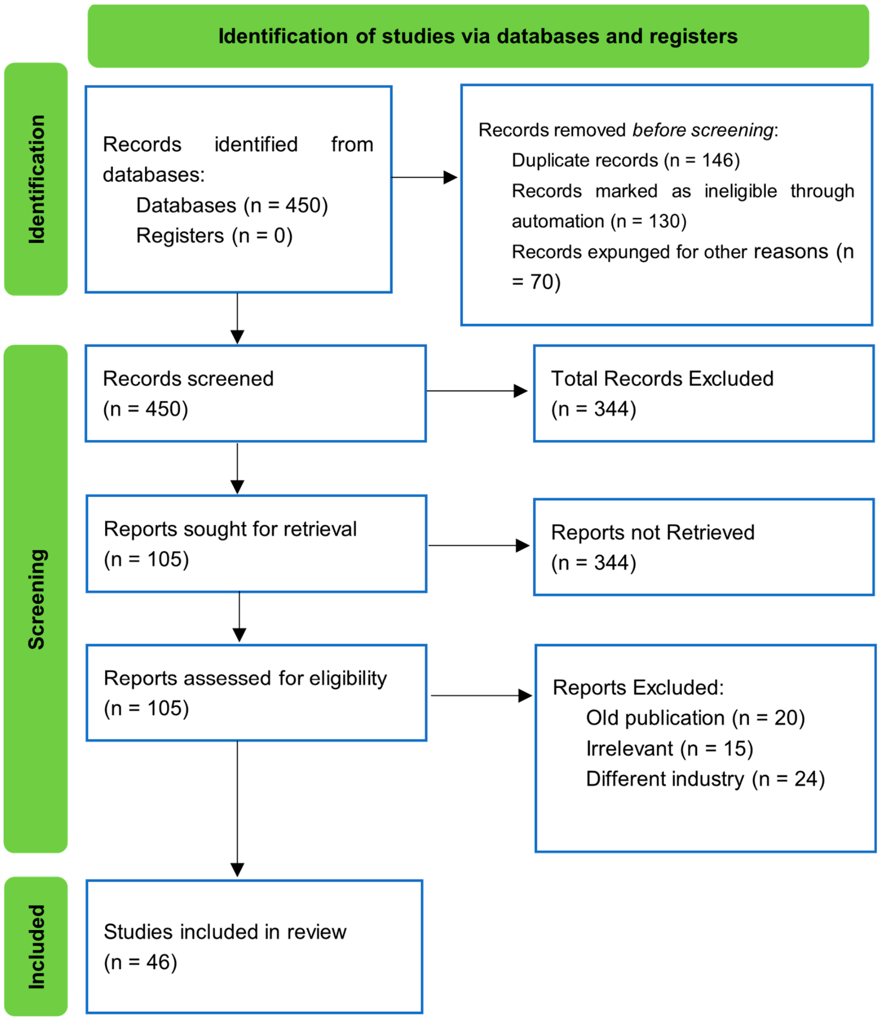

Figure 1. PRISMA flowchart describing the source selection and evaluation process.

2.4. Data Analysis

The 46 articles retrieved from the search results were subjected to further analysis and synthesis. The results were then displayed in a table in accordance with the title of the study, document type, authors, and main findings. While the table mainly summarizes what the author found, a detailed discussion of the results has been given in the discussion section. The analysis helps in building comprehensive support for the topic. The table has also been cross-examined to remove errors such as repeated articles or incorrect numbering.

3. Results

The PRISMA model enabled the author to narrow down the results to identify the most accurate sources to be included for analysis. It also uses content validity to ensure that the sources included in the table are accurate and effective. The summary of the findings is shown in Table 1.

Table 1. Selected articles.

Title	Type of Document	Authors and Date	Findings
The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review.	Journal Article	Kivaisi, 2002 [18]	The study describes wastewater treatment as a deliberate step towards a sustainable water supply in the future. The study also discusses other benefits of wastewater treatment, including irrigation and a source of clean energy.
Wastewater engineering: treatment and reuse.	Journal Article	Tchobanoglus et al., 2003 [19]	The study found that wastewater treatment improves water supply while protecting natural sources from potential overconsumption.
Municipal-treated wastewater reuse for plant nursery irrigation.	Journal Article	Lubello et al., 2004 [20]	Found that wastewater treatment provides alternative sources of water for irrigation and industrial use.
Developments in wastewater treatment methods.	Journal Article	Sonune and Ghate 2005 [21]	The authors talk about new developments in wastewater treatment methods, including the use of reverse osmosis, decentralization, and innovative technologies.
The role of membrane processes in municipal wastewater reclamation and reuse.	Journal Article	Wintgens et al., 2005 [22]	Describes how reverse osmosis treats wastewater by removing suspended materials by forcing water through a semi-permeable membrane.
Membrane bioreactor technology for wastewater treatment and reuse.	Journal Article	Melin et al., 2006 [23]	The authors discuss the use of membrane bioreactor technology in treating wastewater and boosting supply to the cities.
Wastewater treatment in dairy industries—the possibility of reuse.	Journal Article	Sarkar et al., 2006 [24]	Discusses how dairy farms rely on wastewater treatment to provide sufficient water for the animals throughout the year.
Aspects of municipal wastewater reclamation and reuse for future water resource shortages in Taiwan.	Journal Article	Chiou et al., 2007 [25]	Discusses how municipal wastewater reclamation and reuse are addressing water shortages in Taiwanese cities.
Photocatalytic TiO2 films and membranes for the development of efficient wastewater treatment and reuse systems.	Journal Article	Choi et al., 2007 [26]	The researchers examined the use of semi-permeable membranes in wastewater treatment, a process known as reverse osmosis.
Feasibility study on petrochemical wastewater treatment and reuse using submerged MBR.	Journal Article	Qin et al., 2007 [27]	Highlights challenges in treating petrochemical wastewater for industrial and domestic use.

Table 1. *Cont.*

Title	Type of Document	Authors and Date	Findings
Wastewater treatment and reuse. In Arab environment: water: sustainable management of a scarce resource.	Journal Article	Choukr-Allah, 2010 [28]	Found that wastewater treatment and reuse are enabling Arab countries and cities to overcome water shortages caused by arid conditions.
Hybrid-constructed wetlands for wastewater treatment and reuse in the Canary Islands.	Journal Article	Melián et al., 2010 [29]	Found a unique way of wastewater treatment by using wetlands, such as the case of the Canary Islands.
Global challenges to wastewater reclamation and reuse.	Journal Article	Bahri and Asano, 2011 [30]	Found that excessive energy consumption, diseases, lack of skills, and budgetary constraints are the main challenges affecting wastewater reclamation and reuse. The authors also described ways in which cities can overcome the mentioned challenges.
The potential of wastewater reclamation to reduce fresh water stress in Ho Chi Minh City-Vietnam.	Journal Article	Dan et al., 2011 [31]	Found that wastewater reclamation and reuse have been used effectively in Ho Chi Minh City (Vietnam) to improve water supply.
Fenton and biological-Fenton coupled processes for textile wastewater treatment and reuse.	Journal Article	Blanco et al., 2012 [32]	Found that treating wastewater from the textile industry reduces waste and cost of production and minimizes pressure on natural resources.
Energy and sustainability of operation of a wastewater treatment plant.	Journal Article	Bodik and Kubaska, 2013 [33]	Describes wastewater treatment and reuse as an effective source of water and energy for both domestic and industrial purposes.
Review of cost versus scale: water and wastewater treatment and reuse processes.	Journal Article	Guo et al., 2014 [34]	While the authors support the use of wastewater treatment to increase supply for the cities, they raise concerns regarding the high cost of operations and how it prevents many cities from rolling out large-scale wastewater treatment plants.
Wastewater treatment for reuse in urban agriculture; the case of Moshi Municipality, Tanzania.	Journal Article	Kihila et al., 2014 [35]	Found that wastewater reclamation and reuse are assisting the city of Moshi in Tanzania to increase water supply and generate energy for domestic use.
Review of wastewater treatment and reuse in the Morocco: Aspects and perspectives.	Journal Article	Salama et al., 2014 [36]	The study found that wastewater treatment and reclamation enable cities located in arid and semi-arid regions to boost supply and provide sufficient water for their populations.

Table 1. *Cont.*

Title	Type of Document	Authors and Date	Findings
A mini-review on the impacts of climate change on wastewater reclamation and reuse.	Journal Article	Vo et al., 2014 [37]	A systematic review of data found sufficient evidence in support of wastewater reclamation and reuse as an effective source of water for urban residents.
Wastewater treatment and reuse: Past, present, and future.	Journal Article	Angelakis and Snyder, 2015 [38]	Examined the past, present, and future prospects of wastewater reclamation and reuse, arguing that the future depends on alternative sources of water other than the natural aquifers.
Emerging organic contaminant removal in a full-scale hybrid constructed wetland system for wastewater treatment and reuse.	Journal Article	Ávila et al., 2015 [39]	Supports wastewater reclamation and reuse and provides strategies for removing the organic contaminants that can make the treated water not safe for drinking, cooking, or laundry work.
Dissolved effluent organic matter: characteristics and potential implications in wastewater treatment and reuse applications.	Journal Article	Michael-Kordatou et al., 2015 [40]	Found that cities can use wastewater reclamation and reuse to increase supply for the current and future populations. Highlights dissolved effluent organic matter as a potential challenge that cities should address.
A feasibility study of ultrafiltration/reverse osmosis (UF/RO)-based wastewater treatment and reuse in the metal finishing industry.	Journal Article	Petrinic et al., 2015 [41]	The feasibility study found that reverse osmosis is an effective technology for removing suspended solid particles in wastewater.
Wastewater reclamation and reuse in China: Opportunities and challenges.	Journal Article	Lyu et al., 2016 [42]	Found that China is one of the leading countries in the implementation of wastewater reclamation and reuse to increase water supply for the urban population.
Bioaugmentation: an emerging strategy of industrial wastewater treatment for reuse and discharge.	Journal Article	Nzila et al., 2016 [43]	Found that bioaugmentation is one of the most effective strategies for improving wastewater reclamation and reuse.
Evaluation of the energy efficiency of a large wastewater treatment plant in Italy.	Journal Article	Panepinto et al., 2016 [44]	Found energy efficiency remains a major challenge for large-scale implementation of wastewater reclamation and reuse, although the problem can be addressed using a combination of innovative technologies and alternative sources of energy.

Table 1. *Cont.*

Title	Type of Document	Authors and Date	Findings
Characteristics of water quality of municipal wastewater treatment plants in China: implications for resources utilization and management.	Journal Article	Sun et al., 2016 [45]	Found that cities can use wastewater reclamation and reuse to avoid potential crises in water supply while minimizing pressure on the natural sources.
Wastewater treatment and reuse-The future source of water supply.	Journal Article	Ding, 2017 [46]	The study found that wastewater reuse and reclamation offer effective solutions to the future supply of water in major cities around the world.
Wastewater treatment and reuse, theory and design examples, volume 1: Principles and basic treatment.	Journal Article	Qasim and Zhu, 2017 [47]	The study found that wastewater reuse and reclamation is a sustainable approach to increasing water supply, conserving the environment, and improving agricultural production.
Wastewater treatment and reuse in the food industry.	Book	Barbera and Gurnari, 2018 [48]	The authors found that wastewater reclamation and reuse provide a sustainable supply of water and nutrients needed for large-scale food production.
Recent advances in energy recovery from wastewater sludge. Direct thermochemical liquefaction for energy applications.	Journal Article	Nazari et al., 2018 [49]	The researchers argue that recent advancements in sludge management may assist cities in overcoming difficulties in managing sludge and providing sufficient water to their residents.
Circular economy in wastewater treatment plant–challenges and barriers.	Journal Article	Neczaj and Grosser, 2018 [50]	Found that wastewater treatment and reuse contribute to the circular economy by reducing waste, protecting natural resources, and increasing biodiversity.
Wastewater treatment and water reuse.	Journal Article	Salgot and Folch, 2018 [51]	The researchers found that wastewater treatment and reuse provide alternative sources of water and reduce dependence on natural sources.
Wastewater treatment and water reuse in Spain. Current situation and perspectives.	Journal Article	Jodar-Abellan et al., 2019 [52]	Describes how countries such as Spain have been relying on wastewater reclamation and reuse to increase water supply and lessons that can be drawn from their best practices.
Wastewater reclamation and reuse trends in Turkey: Opportunities and challenges.	Journal Article	Maryam and Büyükgüngör, 2019 [53]	Found that Turkey is another country where wastewater reclamation and reuse provide alternative sources of water, preventing shortages and supporting agricultural production.

Table 1. *Cont.*

Title	Type of Document	Authors and Date	Findings
Reuse of domestic wastewater by membrane technologies towards sustainable city development.	Journal Article	Raharjo et al., 2019 [54]	Argues that domestic wastewater reclamation and reuse is still underutilized despite its effectiveness in reducing wasteful consumption in the cities.
Wastewater reclamation holds a key for water sustainability in future urban development of Phoenix Metropolitan Area.	Journal Article	Wang et al., 2019 [55]	The researchers found that wastewater reclamation and reuse provide alternative sources of water to those who live in the city of Phoenix and its Metropolitan area.
Water reuse in India: Current perspective and future potential in advances in chemical pollution, environmental management, and protection.	Journal Article	Kumar and Goyal, 2020 [56]	The researchers draw several lessons from the Indian wastewater reuse, including the use of technology to expand the treatment plants without the need for additional real estate.
Governance arrangements for the scaling up of small-scale wastewater treatment and reuse systems–lessons from India.	Journal Article	Reymond et al., 2020 [57]	Uses a case of India to explain how effective governance can improve wastewater collection, treatment, and discharge back into circulation and reasonable costs to the taxpayers.
Wastewater treatment and resource recovery technologies in the brewery industry: Current trends and emerging practices.	Journal Article	Ashraf et al., 2021 [58]	Found that wastewater treatment can help in reducing overconsumption in industries such as alcohol brewery that uses a significant amount of water to produce the final products.
Optimization of an electrocoagulation-flotation system for domestic wastewater treatment and reuse.	Journal Article	Bracher et al., 2021 [59]	Explored potential technologies, including electrocoagulation-flotation systems, that can be used in domestic wastewater treatment and reuse.
Wastewater reclamation and reuse potentials in agriculture: towards environmental sustainability.	Journal Article	Fito and Van Hulle, 2021 [60]	Found that wastewater treatment and reclamation can provide the water needed for agriculture and industrial purposes, reducing intense competition for water among different sectors.
Wastewater treatment and reuse situations and influential factors in major Asian countries.	Journal Article	Liao et al., 2021 [61]	The study found that wastewater reclamation and reuse are influenced by several situations, including climate emergencies, fast-growing urban populations, and the expansion of desert conditions into areas that were once considered wetlands.

Table 1. *Cont.*

Title	Type of Document	Authors and Date	Findings
Membrane distillation bioreactor (MDBR) for wastewater treatment, water reuse, and resource recovery: A review.	Journal Article	Kharraz et al., 2022 [62]	The researchers examined the use of the membrane distillation bioreactor (MDBR) to improve wastewater treatment and provide more water for both domestic consumption and agricultural purposes. Membrane distillation bioreactor (MDBR) is a form of reverse osmosis and can be used even domestically to treat wastewater.
Wastewater treatment and sludge management strategies for environmental sustainability.	Journal Article	Sharma et al., 2022 [63]	The researchers found the use of technology and innovation as effective strategies that can help municipalities improve both sludge management and wastewater treatment for environmental sustainability.

4. Discussion

4.1. Expanding Wastewater Reclamation and Reuse

The findings indicate that wastewater reuse increases water supply by providing alternative sources of water for industrial and domestic use [23,45,71]. Wastewater reuse is effective in reducing the overall pressure on natural resources, allowing cities to plan effectively for their current and future populations [44,72]. The findings also indicate that the main drivers for wastewater reuse include water stress, fast-growing populations, and climate emergencies [73]. The findings also indicate that major innovations such as potable reuse and decentralized systems may help cities expand water reuse to meet future needs [73]. However, there are still major challenges that cities need to overcome to maximize their capacity to scale up wastewater reuse [74]. Some of the main challenges include excessive energy consumption, budgetary constraints, inadequate skills, and difficulties in managing sludge.

However, the idea of wastewater reuse has often been met with relentless skepticism among the urban and even non-urban populations. Wastewater reuse has often been considered a "yuck" idea because of the potential dangers involved [25,31,75]. Not many people are willing to reuse water from their toilets or sinks because of the natural fear of potential diseases [76]. People are naturally squeamish about wastewater reuse because they cannot imagine how to convert water from the toilets and sinks back into circulation without exposing consumers to potential waterborne illnesses, including typhoid, cholera, and dysentery [77]. The general skepticism towards wastewater reuse is also driven by the fact that most cities do not have sufficient technologies to clean wastewater so that it can be avoidable for reuse, especially drinking and other forms of domestic consumption [78]. The general skepticism also affects domestic initiatives that people can use to increase their water supply at home without relying on government solutions.

Cities can expand water reuse by investing in both potable and non-potable reuse projects. The potable reuse project refers to the advanced treatment of reclaimed wastewater to augment the urban water supply system, including providing clean and safe water for drinking [78,79]. The non-potable reuse project refers to the treatment of reclaimed wastewater for various purposes, including agriculture and industrial use [79]. Comparatively, potable reuse projects are more expensive because of the technology required to remove all the suspended materials and chemicals present in the reclaimed wastewater to make it safe for drinking and other domestic needs [15,22,31,80]. Potable reuse projects also consume more energy than non-potable reuse projects due to the prolonged treatment processes needed to produce clean and safe water for domestic purposes [81]. Cities need to make significant investments in potable reuse projects to meet all the water quality requirements and minimize the chances of spreading diseases.

Non-potable water reuse projects typically have lower quality objectives than potable projects. The level of treatment also depends on the intended use. For instance, water that is needed for cooling the machine parts or cleaning surfaces may not require significant investments in technology and expertise because of the intended use [82]. For agricultural purposes, the aim is to provide water that is high in nutrients and low in organic chemicals that can affect the soil composition and overall crop yield [55,83]. Significant work goes into both potable and non-potable reuse projects to ensure the final product is free from potential hazards that can cause harm to consumers [84]. Both potable and non-potable water reuse projects can assist cities in generating clean sources of energy, including methane gas, for industrial and domestic use [85]. However, more investments are still needed in both training and production to enhance the capacity needed for efficient wastewater reclamation and reuse.

As cities continue to grow in size and population, many administrations are warming up to the idea of converting wastewater from toilets, sinks, runoffs, and factories into clean and safe water for drinking and industrial use [86]. Those who are leading the way have developed elaborate designs to increase the water supply for the next generations. In Durban (South Africa's third largest city), for instance, huge amounts of wastewater equivalent to about 13 Olympic-size swimming pools have been treated and discharged back into the paper refinery industry since 2001 [25,43,47,55,59,87]. The city has also been expanding its water reuse system to meet both current and future needs [88]. Through public-private partnership (PPP), Durban can build sufficient wastewater treatment plants needed to provide sufficient water for industrial use and reduce pressure on the natural sources of water, including reservoirs around the city [89]. Durban is demonstrating how wastewater reuse can provide alternative sources of water and reduce the intense competition that is facing many cities around the world.

Durban is not the only city that is leading efforts in wastewater reuse. London draws a significant amount of its drinking water from recycled water from the River Thames [88]. The river that flows through London provides sufficient water for both industrial and domestic use. However, recycling has been essential in converting more water from the river into domestic use and reducing pressure on other sources [89]. The water recycling facilities along the River Thames indicate efforts that London is taking to address potential challenges that may affect the overall volume of water from the river [90]. For instance, during drought seasons, the river experiences a significant drop in the water volume. Excessive consumption may lead to situations where London loses not just a significant source of water but also one of its greatest sources of biodiversity [88,91]. Other cities around the world, including Windhoek in Namibia, have been recycling water from the rivers since 1965.

In places such as India and Singapore, wastewater reuse provides alternative sources of water for power plants, factories, and refineries. This reduces demand for the limited natural sources of water. For instance, wastewater reuse has been a significant source of water for many power plants across India, especially the ones located near its urban populations [90,91]. The same trend has been witnessed in Singapore, where wastewater provides a valuable source of water for factories and refineries [92]. Rather than relying on natural sources, power plants and factories can use recycled water for cooling machines, cleaning surfaces, and production of goods. Wastewater recycling is also sustainable because nothing goes to waste [93]. The same water that has been used in cooling machines is treated and returned to circulation, ensuring very little or nothing goes to waste [94]. Since most cities are also experiencing intense competition between water for domestic and industrial use, wastewater reuse can solve the problem by providing enough water for industrial purposes.

The circular economy model advocates for waste reduction as one of the core principles of sustainability. The circular economy approach ensures that nothing goes to waste by ensuring the used products and materials are recycled and brought back into circulation to reduce pressure on natural resources [95]. As the city populations continue to grow, there is an even greater need to adopt the circular economy model to minimize waste and ensure there is sufficient water to meet the current and future needs [96]. Wastewater reclamation provides a sufficient amount of water for agriculture and industrial purposes at lower investment costs and energy consumption [97]. This is much better compared to traditional approaches such as desalination and inter-basin water transfer. According to estimates, it costs about USD 0.32 per cubic meter to produce non-potable recycled water [98]. However, it costs about USD 0.50 to produce clean water through the desalination of water from the oceans [99]. This indicates that cities would save resources by adopting wastewater reclamation instead of traditional approaches such as desalination.

Expanding water reuse also enables cities to adapt quickly to the effects of climate change. The growing empirical evidence indicates that climate change is largely associated with adverse weather conditions, such as prolonged droughts, and natural disasters such as floods [100]. Cities that are located in arid and semi-arid regions are already experiencing frequent water shortages due to prolonged droughts [88,100]. If not mitigated, climate change may lead to serious water shortages for urban populations [10,14,59,100]. Wastewater reclamation addresses the challenge by providing alternative sources of clean water for domestic and industrial use. Wastewater reclamation can also prevent the growth of climate change by creating more grounds for hydro-circulation [88]. Cities can also use the savings drawn from the reclaimed wastewater to meet other investment needs, including building more reservoirs [98]. Expanding water reuse creates a sustainable pathway toward a future where people are conscious of the need to create more sources of clean and safe water rather than depleting the natural sources.

Sufficient water supply may also require additional investments in building more reservoirs, discouraging wasteful use, and enhancing accountability. Research indicates that cities cannot depend on single sources of water for an efficient future [101]. The current challenges indicate that depending on single sources of water supply can easily lead to day zero and other potential challenges [89,91,97,101]. However, building more reservoirs around cities creates additional pathways for boosting water supply. Across the United States Southwest, there have been significant efforts to boost water supply by building large reservoirs that also serve as hydroelectric generation facilities [102]. The Toledo Bend Lake in Louisiana is an example of a water reservoir providing both water and electricity to the surrounding cities in both Louisiana and Texas [99]. The state of California has also witnessed increased efforts in building more water reservoirs in the past decades to boost the supply of water and electricity.

As cities struggle to provide more water for their residents, additional efforts should be channeled toward reducing wasteful consumption. In South Africa, the city of Cape Town faced a dire situation in 2018 when it narrowly avoided day zero [100]. One of the measures that assisted the city in avoiding the catastrophe is reducing wasteful consumption [88]. The city imposed various measures and higher tariffs for those with heavy consumption. The use of higher tariffs reduced wasteful consumption by forcing residents to restrict their overall water use to a few cubic meters per day [18,45,76]. The heavy tariffs meant that those who use water for non-essential needs, such as watering their lawns, would pay heavily for the luxurious consumption [77,88,101]. Educating the city about the need to conserve water and the challenges facing the supply networks may also discourage heavy consumption [103,104]. The city residents need to understand the potential challenges they face and the need to use only a reasonable amount of water to ensure there is more for the future.

Management of the water supply also requires sufficient accountability from the city administrators. One of the challenges facing most cities is the heavy amount of water that is supplied but never accounted for. The use of illegal connections enables some unscrupulous residents and business facilities to avoid paying for their water consumption [103]. Illegal connections also put additional pressure on the city to supply more water without compensation or accountability [103]. One of the strategies that cities can use to enhance accountability is auditing their systems to ensure all the connection terminals are billed appropriately at the end of the consumption period [74,79]. Proper auditing may also assist administrators in identifying illegal pipes that are connected to their systems and the total losses they cause every month or year [88]. Conducting regular audits may also help in identifying potential cracks within the grid that can cause massive loss of water if not mitigated.

Technology has also become an essential tool that cities can use to properly manage their water supply and consumption. Many cities are moving towards adopting smart technologies to help them improve both water supply and response to potential challenges [89]. Enterprise resource planning (ERP) is one of the technologies that cities can use to reduce waste, improve supply, and generate more revenue [90]. The ERP system relies on artificial intelligence technology to collect data, analyze data, and enable timely decision-making [91]. The use of AI technology to automate services enables cities to prevent frequent breakages that lead to a massive amount of water loss through leakages [92,97,98,102]. Technology may also seal all the loopholes used by businesses and residents to avoid paying for the water they receive [103]. It is no longer possible for cities to provide sufficient services without automating tasks that can lead to errors [104]. Technology can perform regular repetitive tasks, leaving humans with more technical or analytical duties to prevent potential errors.

Technology should also help cities to effectively plan for their populations. Data analytic tools, including the use of artificial intelligence, may help cities improve the accuracy of their forecasts [88]. Cities usually conduct a census of their populations every ten years. The results from the census enable cities to plan effectively for their current and future populations [21]. One of the significant aspects of the census is the population growth rate and changing needs. For an efficient water supply, cities need to understand the overall population growth rate and how it would impact resources in the future [89]. Developing accurate forecasts would enable cities to determine the number of cubic meters of water they need to add to their grids annually to meet future needs [77]. This will also support gradual improvement in the infrastructure to meet future needs. Accurate forecasts also enable cities to create sustainable budgets that can be funded over time to achieve future demands.

4.2. Drivers of Wastewater Reuse

Wastewater reclamation and reuse is a challenging plan that requires significant planning and funding. The high cost of wastewater reclamation has prevented many cities from laying out their plans [11,19,22]. Other cities have developed sufficient proposals but lack individuals and organizations that can fund the projects [29]. However, based on the various challenges facing modern cities, wastewater reclamation and reuse are becoming a necessity than just a plan. Most future city plans would have to include a comprehensive plan on how to reclaim and reuse wastewater drawn from various sources, including factories and residential areas [77]. The high cost of wastewater reclamation and reuse also depends on the overall population of a city [99]. Those with high populations, such as London and New York, have to invest more in reclaiming enough wastewater to augment the water supply system.

The main drivers of water reuse include water stress, a fast-growing population, and climate emergencies. Water stress is a global problem that has been worsening over the past decades. Water stress or scarcity occurs when people cannot fulfill their needs because the supply is inadequate or the infrastructure is too inadequate to meet the demands [102]. For most cities, water stress begins with a gradual increase in size and population without providing sufficient resources to meet the growing demands [101]. Poor water infrastructure has also been worsened by the sprawling city population that is growing into areas that may be difficult to reach. Most cities are struggling with a growing informal settlement that is difficult to reach by the water pipes and connect to the main grid [87]. Water stress also occurs due to overconsumption and wasteful use of water for non-essential purposes [99]. Without laying out sufficient plans, it may be very difficult for modern cities to achieve sufficient wastewater reclamation and reuse.

The fast-growing population means that cities must develop larger wastewater treatment facilities to address the growing needs. Research indicates that more than 4.2 billion people around the world are located in areas where they are unable to access natural sources of water, such as lakes, oceans, and seas [89]. It is also worth noting that most of the cities located far away from the large water reservoirs risk facing significant water scarcity as their population rises almost uncontrollably [99]. However, even those cities with adequate access to water sources must also develop sufficient plans to manage those resources effectively [103]. In Santa Barbara (California), for instance, the problem is not about access to water but how to convert the surrounding seawater into valuable products for consumption [98]. The city has developed an elaborate plan to ensure that water obtained from the sea undergoes thorough treatment before being discharged into mainstream circulation.

Apart from the fast-growing population, the increased effort towards wastewater recycling and reuse is the climate emergency [104]. The issue of climate change presents one of the biggest challenges that cities need to overcome [76]. The major climate emergencies include prolonged droughts, flooding, and extreme temperatures [34]. Climate change has significantly increased the frequency with which some of these emergencies occur [56].

For instance, most cities in the American Southwest are already experiencing the effects of prolonged droughts, including water scarcity. Climate emergencies remind cities about the need to prepare for potential water shortages in the future [44,55,91]. The emergencies also indicate the need for cities to develop elaborate wastewater reclamation mechanisms that can stand the test of time [59]. Such investments can be achieved through a gradual process that involves building wastewater treatment plants in phases while focusing on future needs.

4.3. Potential Challenges

The main challenges facing wastewater reclamation and reuse include diseases and pathogens, budgetary constraints, excessive energy consumption, inadequate skills, and difficulties in managing sludge [61]. The study has found that most cities do not have the budgets needed for the development of large wastewater treatment facilities [78]. The cost of building a wastewater treatment plant begins with the selection of suitable land for the project [99–102]. Whether potable or non-potable reuse projects, the city must identify suitable land for the project. Wastewater treatment plants require large sizes of real estate that most cities may not have [101]. Another challenge is that building the treatment plant very far away from the cities may impose additional costs in the infrastructure layout and purchase of land [99]. Most cities prefer building their wastewater treatment plants closer to their residential areas to minimize the cost of infrastructure and real estate.

One of the biggest issues raised against wastewater treatment is the diseases and pathogens that may be caused by the chemicals and impurities. The main concerns include micro-particles, polymer product industrial waste, and organic chemical waste [21]. The micro-particles are suspended solid waste in the wastewater, including paper particles, food particles, industrial waste, and pharmaceutical waste [45]. Organic chemicals include medicines, herbicides, insecticides, petroleum, and detergents. The presence of chemicals and industrial waste inside the wastewater usually generates significant skepticism towards using it as the mainstream source of drinking water [31]. Many people believe that treated water may contain some undetected chemicals that can cause diseases [33]. It may also be challenging for the cities to remove negative perceptions that prevent people from using treated wastewater [98]. Despite the challenges associated with wastewater treatment, cities must put sufficient resources into the projects to enhance the safety of their residents.

The potable reuse projects are more likely to require a heavy investment of about USD 1.5 million or more because of the high-water quality objectives [81]. However, the non-potable reuse projects are less likely to cost about USD 500,000 or more due to the minimal water quality requirements. Since most of the non-potable reuse products end up being used in the farms to boost agricultural production, the overall water quality is likely to be average as long as all the organic chemicals and other suspended materials are removed [84]. Cities can overcome budgetary constraints by obtaining debts from local credit facilities such as banks and government agencies [98]. Moreover, cities can also apply for grants from institutions or government agencies supporting wastewater reclamation and renewable energy generation.

Cities are also developing unique solutions to overcome budgetary constraints. In South Africa, Durban is using a public-private partnership (PPP) to develop water treatment facilities [68]. The PPP enables players in the private sector to develop wastewater treatment facilities and recover their funds from the bills paid by the city residents [55]. Once the wastewater treatment facilities are developed, the city administrators can determine the percentage of revenue that goes to the private organizations that constructed the facility on behalf of the city [72]. The PPP is also good for the city because it allows the private sector technology and innovation to improve both public services and operational efficiency [71]. Durban's case also indicates how cities can incentivize the private sector to complete mega projects within schedule and on a budget [88]. Even cities that may not have sufficient resources for building better wastewater treatment facilities can partner with the private sector to deliver outstanding projects for the residents.

The practical utilization of reclaimed water extends beyond technological innovations. This encompasses health, socio-economic, and legal dimensions, in addition to the incorporation of emerging technologies over nearly a century of wastewater reuse. The economic aspects of wastewater treatment can be challenging, and they vary across different countries and regions, impacting factors such as costs, benefits, and sustainability. It should consider the capacity for adequately operating and maintaining the systems and the financial capacity limits/governs the selection [51]. The rapid pace of urbanization and economic growth is exerting significant pressure on sanitation in many developing countries. This is evidenced by the lack of adequate planning for efficient sanitation infrastructure, leading to critical challenges. Countries such as Brazil, Mexico, China, South Africa, Algeria, India, Thailand, Egypt, and Turkey are experiencing these issues. To address these challenges, developed countries can find value in encouraging studies conducted within the poorest nations. Similarly, poorer countries can draw inspiration from ideas and practices adopted by developed nations, including those from the United States and Europe [105].

Apart from budgetary constraints, another challenge that may prevent cities from building wastewater treatment facilities is excessive energy consumption. Wastewater treatment facilities consume a significant amount of energy that may be a challenge to many cities [90]. Excessive energy consumption specifically affects large-scale potable water reuse projects where the wastewater has to undergo numerous processes to remove suspended materials and organic chemicals from the water [99]. Although wastewater treatment facilities can generate most of their internal energy to support their processes, this is something that is still poorly developed in most of the current facilities [11,15,19]. Most of the current wastewater facilities can only produce enough energy to power only a quarter of their operations for a few hours [14,18,19]. If cities want to roll out large-scale wastewater treatment, they may have to invest in large power plants at a high cost to the taxpayers [23]. Moreover, there are growing concerns about the polluting effects such projects may have on the environment.

The skills and level of training needed for the production of clean and safe water from reclaimed wastewater are still lacking in most cities. The dangers associated with wastewater reclamation make it a sensitive project that must be subjected to a high level of expertise [90]. Apart from the high cost of labor and materials needed for training, most cities do not have sufficient skilled workforce to work in large-scale water treatment plants [31]. Without skills, it may be difficult for the cities to provide sufficient clean and safe water through reclamation. It may also be difficult to create a mentorship program that trains future skilled laborers to provide a sustainable supply of experts [35]. The public-private partnership (PPP) is providing a potential solution to this challenge by allowing the private sector to provide the required labor at their cost [39]. The PPP enables cities to access highly skilled labor and technologies that may be too expensive for limited budgets.

Another significant challenge that cities may face is the difficulties in sludge management [41]. Factors that make sludge difficult to handle include high water content, chemicals, poor dewaterability, and strict regulation in the reuse or disposal of sludge [43]. The sludge contains a high water content that has to be drained to separate solid suspensions and allow the remaining water to undergo further treatment process. The suspended solid waste may contain chemicals and should be disposed of in ways that do not expose other components of the environment to danger [55]. Apart from the high water content, sludge requires sophisticated technology to remove other components, including chemicals [9]. Poor dewaterability means that it takes longer for the water to be separated from the suspended solid particles [27]. Allowing the solid waste to settle down through sedimentation is not sufficient in the management of sludge.

Sludge management challenges may also occur due to the high chemical content in it. Some of these chemicals include carbon, phosphorous, and nitrogen compounds. There are also organic chemicals that may be suspended in the water [54]. These chemicals have to be removed to prepare clean and safe water for domestic use. Sludge management regulations also require cities to invest sufficient resources in technology to help identify all the potential chemicals present in the sludge and remove them [26]. Cities may also face challenges in dealing with chemicals that are either too difficult to detect or remove. The above chemicals may also be harmful if disposed into nearby rivers, farms, or landfills [31]. The sludge regulations recommend the removal 1of all potentially harmful chemicals before using the sludge as fertilizers in farms [38]. Conversion of sludge into fertilizer not only promotes crop growth but minimizes the harmful effects of chemical fertilizers on farms.

4.4. Future Strategies and Innovations

Regarding the land challenge, there are emerging ways that can be used to expand the wastewater treatment plants without asking for additional land. The land question is one of the major challenges facing wastewater treatment plants [11]. Most cities do not have sufficient land that can be used for building large-scale wastewater treatment facilities [94]. However, there are recent technologies that provide new ways of expanding wastewater treatment facilities to meet future needs, even without additional real estate. For instance, OxyMem offers a new method of plant expansion known as "drop-in" [95]. This alternative method involves digging additional inches into the soil to expand the filtration capacity and take in more wastewater [95]. The new method can also be used to improve production capacity without hiring additional staff, reducing the overall cost of operations.

The time taken to upgrade the wastewater treatment facilities is another challenge that can be addressed using technology. Wastewater treatment facility upgrades can take many years and require additional investments, including the acquisition of land [97]. From needs assessment to land acquisition, it can take cities many years to drain all the tanks and conduct the required upgrade [95]. However, technology enables cities to upgrade their wastewater systems within a short duration. Technologies such as OxyMem MABR drop-in can facilitate upgrades without draining tanks or building new structures [95]. Technology also reduces the need for upgrading capital and improves risk assessment to ensure problems are identified and solved on time [95]. The use of technology may also assist cities in improving their relationships with the surrounding communities by preventing eviction notices.

The energy issue is also a significant challenge that cities must address to improve their wastewater treatment capacity. Expanding wastewater treatment implies that cities must add more equipment and power supply to enhance efficiency in operations [95]. However, adding equipment and power also increases the carbon emissions associated with wastewater treatment [96]. In an era where carbon emissions are becoming a major concern, cities must develop new ways of expanding their wastewater treatment plants without exerting more pressure on the available resources [95]. The bubble-less transfer of oxygen technology is designed for the anaerobic decomposition of sludge without consuming a significant amount of energy [95]. Since the bubble-less transfer of oxygen works similarly to normal respiration, it provides simultaneous nitrification and denitrification for the removal of nitrogen.

The solution to wastewater treatment challenges lies in the willingness to adopt innovative technologies that provide breakthrough approaches to expanding operations and reducing carbon emissions [95]. Wastewater treatment facilities are designed to serve both the current and future generations [78]. However, most of the facilities still use traditional methods of expansion to optimize their operations [83]. To avoid the bottlenecks associated with traditional expansion strategies, cities need to adopt innovative technologies that may be costly at the initial purchase but eventually lower the cost of operations [97]. Technology is also required for the efficient management of the supply system to ensure every cubic meter that is pumped to the residents is fully accounted for.

5. Conclusions

This study examined the effectiveness of expanding water reuse as a solution to water supply for future cities. The question asked was, "How effective is expanding water reuse as a solution to water supply for future cities?" The findings indicate that expanding wastewater reuse increases water supply by providing alternative sources of water for industrial and domestic use. The potable reuse projects are designed to provide water for domestic use, while non-potable reuse projects are designed to provide water for other needs such as industrial and agricultural production. Wastewater reuse limits pressure on natural resources and promotes sustainable approaches to providing sufficient water for future populations. However, the study has found that investments in wastewater treatment are still significantly low due to budget constraints. Some cities around the world are relying on public-private partnerships to construct and operate wastewater treatment facilities with minimal resources.

The study has found that the main drivers of wastewater reuse include water stress, climate emergencies, and fast-growing populations. Climate emergencies such as prolonged droughts are pushing many cities around the world to the edge of day zero. Water stress is mainly associated with the overconsumption of water and intense competition between different sectors. The fast-growing populations are likely to put more pressure on the available water sources, leading to potential depletion. The study has also found that major innovations such as potable reuse and decentralized systems may help cities improve water supply for their future populations. However, there are still significant challenges that cities need to address to improve their capacity to reclaim valuable resources from wastewater. The challenges include diseases and pathogens, excessive energy consumption, budgetary constraints, inadequate skills, and difficulties managing sludge. By adopting innovative technologies, cities are more likely to improve their wastewater reclamation capacities at minimal costs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15173064/s1, Table S1: PRISMA 2020 checklist [106].

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