

Wastewater Treatment and Reuse for Sustainable Water Resources Management: A Systematic Literature Review

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Abstract: Wastewater treatment involves the extraction of pollutants, removal of coarse particles, and elimination of toxicants. Moreover, wastewater treatment kills pathogens and produces biogas and fresh manure for agricultural production. The connection between waste management and sustainability created the basis for this research. Wastewater treatment is part of the efforts to minimize water waste, minimize pressure on natural sources of water, and create a pathway for clean energy. A systematic literature review was selected for this study to evaluate and synthesize the available evidence in support of wastewater treatment for both economic and environmental sustainability. The articles were evaluated using the PRISMA framework to identify the most appropriate articles for inclusion. A total of 46 articles were selected based on their content validity, relevance to the research question, strength of evidence, year of publication (2000–2023), and relevance to sustainable resource management. The findings indicate that wastewater treatment enables sustainable resource management by improving the supply of clean water, and minimizing pressure on natural resources, energy recovery, and agricultural support. Wastewater treatment provides one of the most sustainable approaches to water conservation, energy production, and agricultural productivity.



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1. Introduction

Background and Scope of Study

The main objective of wastewater treatment is to extract pollutants, remove coarse particles, eliminate toxicants, and kill potential pathogens so that the remaining clean water, known as effluent, can be discharged back into the environment to meet various purposes [1,2]. World Vision estimates that more than 770 million people around the world have no access to clean and safe water for drinking and domestic use [2]. Wastewater treatment is also aimed at making more water available for use and reducing pressure on natural water resources [2,3]. As water scarcity intensifies with increased demand and encroaching drought conditions, wastewater treatment becomes one of the most viable options for enhancing water sustainability [3]. Al-Juaidi et al. [4] believe that the growing human population will continue to exert more pressure on natural resources, including clean water, for domestic and industrial use. Without a sustainable source of water, the world risks facing acute water shortages and diseases associated with polluted water.

Water scarcity is both a natural and man-made problem. More than 700 million people around the world are currently living in countries or regions with a chronic shortage of water [3–5]. The United Nations Water (UN Water) estimates that the number of those who face water scarcity will increase to about 1.8 billion people by 2025 [6,7]. The growing threat of climate change is also pushing more than 50% of the global population to live in areas where they face significant water shortages [5,7,8]. Regions in sub-Saharan Africa are more likely to be affected because they currently account for the largest number of water-stressed

countries in the world [9,10]. The United Nations also estimates that between 70 million and 250 million people will face acute water shortages in Africa [5,9,11]. Taking early measures, including wastewater treatment, may help in reversing the catastrophic effects of living without clean and safe water for drinking, agriculture, or industrial use.

Much of the wastewater comes from homes, industries, and businesses. In homes, water from sinks, showers, bathtubs, dishwashers, toilets, and washing machines is often channeled through collection pipes to sewage treatment plants [10–12]. Industrial processes such as manufacturing and cooling often produce wastewater that may contain chemicals and solid particles [9]. Businesses such as hotels and restaurants also produce significant amounts of wastewater that should be cleaned and made available for the next use. According to Villarín and Merel [2], water treatment is often designed to meet “fit-for-purpose specifications” for the selected next use. The “fit-for-purpose specifications” are the requirements that must be met to protect the public and the environment from the potential hazards associated with wastewater [8,13–15]. Untreated or polluted water may expose consumers to various public health challenges, including cholera outbreaks, dysentery, and typhoid [10,11,16]. When discharged into lakes and oceans, the decaying organic matter and debris in wastewater can use up the dissolved oxygen that fish and other aquatic life need to survive.

Although wastewater treatment has received significant research attention, its connection to sustainable resource management has not been adequately addressed. Most of the current literature has focused on the various techniques of wastewater treatment, touching very little on sustainability [14]. Some of the common wastewater treatment techniques discussed in the previous studies include chemical treatment, physical treatment, the use of biological organisms, and sludge treatment [17]. Previous studies have also explored basic steps in wastewater treatment, including screening and pumping (preliminary treatment), primary treatment, secondary treatment, disinfection, and sludge treatment [12,18–22]. However, the processes in wastewater treatment largely depend on the intended use. According to Libhaber et al. [23], the focus on sustainability ensures that there is sufficient clean water to meet the needs of the current generation without compromising the ability of future generations to obtain the same commodity. Although water remains one of the most abundant natural resources on the planet, accessibility is always limited [16,18,24]. Those who live in arid and semi-arid areas have poor access to clean and sustainable water.

The qualitative hypothesis for this research is that “wastewater treatment leads to sustainable water resource management”. This indicates that wastewater treatment ensures there is sufficient water to meet people’s needs while protecting natural resources from potential depletion. This study examines the extent to which wastewater treatment generates sustainable use and management of water resources. The research intends to test this hypothesis using evidence obtained from various studies. The test will also examine the extent to which wastewater treatment techniques enhance sustainability. The qualitative variables, in this case, include “sustainable outcomes of wastewater treatment” and “wastewater treatment techniques”.

The overarching purpose of this study is to evaluate and synthesize the available evidence in support of wastewater treatment for both economic and environmental sustainability. The paper focuses on the need for wastewater treatment and how it contributes to sustainable water resource management. The paper will also analyze the various wastewater treatment methods and their levels of sustainability. The aim is to identify and recommend an appropriate wastewater treatment approach that can be used in both domestic and industrial environments to ensure no water goes to waste, is polluted, or poorly managed. The study will also educate communities about the benefits of wastewater treatment and options that can be used to enhance the availability of safe and clean water.

2. Wastewater Treatment Background

2.1. Wastewater Treatment and Sustainability

The term “wastewater as a resource” represents a paradigm shift from what was once considered a liability to an essential resource that can be used in addressing the challenges faced in water supply and sanitation [22,25–27]. However, describing wastewater as a resource is just an empty phrase unless technology is added to make the shift a reality [28]. For a long time, wastewater has been considered a liability and a potential source of diseases. People tend to avoid wastewater by creating channels through which the sludge, chemicals, and other solid matter contained in wastewater can be safely disposed of to minimize damage to the human population [29–32]. However, those who live in arid and semi-arid regions have often been forced to find ways in which wastewater can be converted into economic and domestic use [33].

Wastewater treatment is also a major contributor to the circular economy, in which wastewater has always been considered a valuable resource, rather than a liability [34–36]. The circular economy prioritizes the reuse and regeneration of materials and products to minimize pressure on natural resources while supporting environmental sustainability. Wastewater treatment has become an important source of energy, clean water, fertilizers, and nutrients [24,35,37,38]. For instance, it is a crucial source of biogas that can be used for both industrial and domestic purposes. Producing energy from it reduces pressure on natural resources and overreliance on fossil fuels [13,17,39–45]. Most governments around the world have realized ways in which it can be converted into valuable use, rather than disposed of in nearby rivers, lakes, or oceans [15,46,47]. Additionally, the various benefits of it have drawn significant interest from policy makers who are seeking alternative sources of economic growth.

Organizations such as the World Bank have developed various initiatives aimed at raising awareness about the potential of wastewater as a resource. There is a need for global initiatives that also guide the planning and financing of both wastewater treatment and resource recovery [21,48–51]. Policy makers also need to develop various measures for promoting the conversion of wastewater into a valuable resource [52]. According to Maurer et al. [53], there is still limited awareness regarding the benefits of wastewater treatment in various parts of the world. Additionally, the decentralized approach to it has proven more effective than the centralized approach [22,54,55]. The decentralized approach gives individuals an opportunity to participate in the treatment [56]. This may include the creation of domestic reservoirs where wastewater is collected and channeled to the treatment facilities. A significant quantity of this comes from domestic activities, including washing and cooking [57,58]. Individuals also need to understand ways in which rain-water runoffs can be channeled to the treatment facilities.

The significant growth in the global population continues to put massive pressure on the natural sources of clean water. About 36 percent of the global population, especially those in middle-income economies, live in areas that experience water scarcity [35]. Rapid urbanization is also creating various water challenges, including inadequate supply of water, degradation in the quality of clean water, and damage to sanitation infrastructure, especially in the proliferation of informal settlements [49]. Only a small percentage of informal settlements are connected to the urban sewerage system [1,59,60]. According to Delanka-Pedige et al. [33], the connection to the sewerage system is the first initiative toward establishing a sustainable water resource management system. However, the sewerage system needs significant funding and has been a major challenge for middle-income economies, where challenges regarding water scarcity are even more prevalent [43,61–63]. Financial institutions such as the World Bank have been quite instrumental in funding various projects aimed at recovering value from wastewater.

According to Fito and Van Hulle [12], wastewater management is also a driver toward achieving sustainable development goals (SDGs) in various countries. Specifically, SDG 6 is dedicated to ensuring access to safe drinking water and sanitation for all, with a strong focus on sustainable water resource management, wastewater treatment, and ecosystem

preservation. In this sense, for this article, it is relevant that the SDG targets for wastewater treatment include improving water quality, achieving water use efficiency, reducing the number of people exposed to water scarcity, and achieving an integrated water resource management system [44,64,65]. Wastewater treatment can provide clean water for drinking, cooking, washing, and other domestic purposes [33,55,66,67]. Depending on the quality, treated water can also be circled back to the industries to support various needs, including cooling machines [2,22,39]. Treated wastewater can also enhance the supply of clean water, especially in areas facing water scarcity. According to Melo et al. [45], the increased supply reduces the size of the global population that is exposed to the various challenges associated with water scarcity. Wastewater treatment is a significant step towards achieving sustainable development goals and improving people's health across the globe.

The economic value of wastewater is something that has not been adequately explored. Even some of the most developed economies in the world are yet to realize the full economic value of wastewater. Al-Juaidi et al. [4] indicate that challenges such as poor connection to the sewerage system prevent various economies from realizing the full value of wastewater generated from various sources [68–71]. One of the biggest advantages of wastewater is that it can be treated to satisfy various demands, including industrial and agricultural needs. Moreover, the by-products of wastewater such as treated sludge can be converted into fertilizers [13,72,73]. Some of the by-products also provide nutrients to improve plant growth and the overall yield, without resorting to potentially harmful chemicals [74]. For instance, wastewater can be processed to a particular quality needed for irrigation and other agricultural purposes. Further treatment of wastewater can also increase the supply of clean water for drinking. Wastewater treatment ensures that nothing goes to waste from a product that would otherwise be total waste.

2.2. From Waste to Resource

From “waste to resource” refers to processes that wastewater undergoes to make it fit and valuable for domestic and commercial use. Primarily, wastewater treatment goes through three main stages to convert it into different products for various needs [35,74–76]. As shown in Figure 1 (below), the three steps include primary treatment, secondary treatment, and tertiary treatment. However, preliminary treatment and sludge treatment are added at the beginning and end, respectively [11,25,26,32]. During primary treatment, wastewater is channeled into holding tanks to allow solid particles (sludge) to settle at the bottom while chemicals such as oil float to the top [25]. Primary treatment removes a significant percentage of impurities present in the wastewater. Secondary treatment involves the breakdown of solid waste using aerobic bacteria incorporated into the treatment system [70]. Tertiary treatment involves filtering wastewater to remove nutrients and waste particles that can be harmful to the general ecosystem. The tertiary stage also involves passing wastewater through additional lagoons to remove any remaining impurities or chemicals before the final product is presented for the desired use.

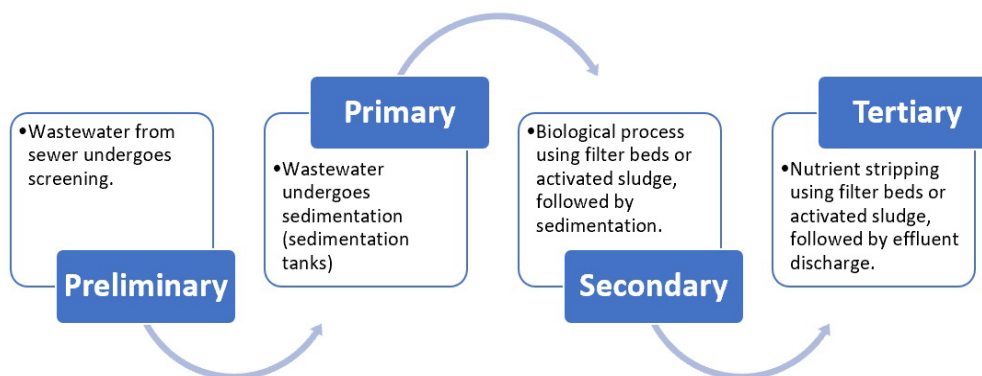


Figure 1. Stages of wastewater treatment, from preliminary to tertiary treatment.

Preliminary treatment is the first step in the wastewater treatment process. The treatment involves the mechanical removal of both coarse and fine solid materials. The wastewater passes through a screening mechanism that traps pieces of wood, rags, plastic particles, and wire, among others [41,55,67,77]. Preliminary treatment removes more than 60 percent of the solid materials from the wastewater. The percentage can also be higher depending on the intended use of the final product. In the case of drinking water, for instance, the preliminary stage may remove more than 80% of the solid materials, leaving very few materials to be removed in the subsequent stages [60,67,68,78,79]. Once the materials are removed, they are either buried or burned. The environmental issues associated with burning have often led to burying as the preferred method for disposing of solid materials [1,3,19]. However, even burying is not environmentally friendly, since it allows chemicals and non-decomposing materials such as plastics to pollute the soil. The quantity of the solid materials extracted from the wastewater usually determines the most appropriate disposal method. Various mechanisms can ensure the safe burning of plastic materials to minimize potential environmental damage [22].

Primary treatment is the second stage of the wastewater treatment process. According to Melo et al. [45], primary treatment allows wastewater or effluent to slowly pass through grit tanks, allowing fine sand particles to settle down. However, it is still possible to have finer sand particles suspended in the wastewater [11,21,34,80]. To remove the finer particles, wastewater is allowed to pass into large primary sedimentation tanks where most of the solid material settles out to form sludge [5]. According to Al-Juaidi et al. [4], primary treatment removes about 60–70 percent of the suspended solid materials. The liquid that remains after primary sedimentation usually contains very fine solids in the form of dissolved matter [12,81–83]. This requires secondary treatment to remove any dissolved particles in the water. The primary sedimentation must remove all the solid materials from water that is needed for various purposes such as drinking and cooking. However, for activities such as irrigation, the wastewater may be ready for use if it does not contain potentially harmful chemicals and solid materials [55,83,84].

Secondary treatment is designed to remove between 70 and 90 percent of the suspended solid materials in the wastewater. Secondary treatment is a biological process that usually involves the use of micro-organisms to decompose the organic compounds [7]. Aerobic bacteria are usually used in this process because of their capacity to provide oxidative energy for dissolution of the organic materials [1,2,5,9,22,85]. The amount of available oxygen usually determines how fast the suspended materials are removed using the microorganisms. Two processes can be used during secondary treatment to remove the dissolved materials in the wastewater [34]. The two processes include filter beds and activated sludge. The filter beds are where the wastewater is sprayed slowly over beds of broken stones or gravel to increase the surface area needed for the speedy oxidation process [33]. The wastewater that collects at the base of the filter beds may contain suspended materials that are removed through secondary sedimentation. The activated sludge also contains micro-organisms that are needed for the oxidation and digestion of all the suspended organic matter in the wastewater.

Tertiary treatment is designed to remove toxic compounds, including phosphorus and nitrogen compounds, that cannot be removed during the primary and secondary treatments. Both the primary and secondary treatments can only remove about 20–40% of the toxic compounds or chemicals in wastewater [5,7,20]. Tertiary treatment involves the use of various tools, including UV lights, filter membranes, and other forms of disinfectants [3,5,7,9,12,86]. The main purpose of the tertiary treatment is to ensure the final product does not contain any toxic compound that can be harmful to human beings or plants, especially if the wastewater is used for irrigation [15]. The various tools used in the tertiary treatment are designed to address specific chemical compounds contained in the wastewater. The final product also undergoes thorough screening to ensure it is free from any chemical or potentially harmful compounds [17]. Various cities around the world rely on treated wastewater to boost the supply of clean and safe water for drinking. Keeping

the final product free from chemicals is one of the topmost considerations before supplying clean water to consumers.

In the quest for improved sustainability and a more environmentally friendly approach, several innovative processes have been developed to recover resources and energy from wastewater. These methods are vital in contributing to the transition towards a circular economy and enhancing the overall sustainability of various industries. Noteworthy among these processes is the Wastewater to Biogas Energy Recovery process in biorefineries [87].

The Wastewater to Biogas Energy Recovery process is specifically designed to treat wastewater while simultaneously recovering biogas energy from it. It proves particularly relevant for biorefineries that convert plants into fuel, as their wastewater contains abundant organic materials that are challenging to treat using conventional systems. Through this process, biogas, a clean-burning renewable fuel, is extracted from the wastewater, significantly enhancing the economic and environmental sustainability of second-generation biorefineries. This approach not only supports the transition to sustainable, plant-based biofuels and bioproducts, but also helps reduce costs and lower greenhouse gas emissions compared to traditional treatment systems [87].

In the realm of wastewater treatment, conventional methods primarily concentrate on eliminating existing pollutants like heavy metals and organic compounds. However, these methods come with significant drawbacks, such as high costs, time consumption, and energy intensity. A novel approach, known as the advanced sustainability approach for resource recovery, views contaminated wastewaters as valuable resources rather than mere wastes. This paradigm shift involves developing new technologies and materials to efficiently manage wastewater while recovering valuable resources [88].

To achieve enhanced performance and reduce secondary contamination, this approach combines different processes using synergistic effects. Technological innovations play a crucial role in significantly improving pollution removal efficiency. For instance, nano-materials have shown promising results in enhancing wastewater remediation efficacy. Moreover, researchers are actively exploring more economical and rational strategies for resource recovery from wastewater [88].

Wastewater has evolved from being considered a waste to becoming a valuable resource. It not only addresses water shortages through water reclamation but also provides a medium for energy and nutrient recovery, offsetting the extraction of precious resources. As we move forward, the focus is on identifying viable resource recovery technologies for domestic and municipal wastewater across various scales of implementation. These scales include small-scale, medium-scale, and large-scale systems. Different approaches, such as non-potable reuse (NPR) projects, have been successfully implemented at all scales, which highlights the ease of implementation and lower water quality requirements compared to conventional methods [88].

From a circular economy perspective, energy recovery from wastewater is considered as an exceptional opportunity that brings environmental, political, economic, and social benefits. This approach emphasizes the transition to a circular economy to address challenges related to wastewater reuse and energy recovery, considering societal, regulatory, and political aspects. The circular economy perspective presents various energy recovery technologies for wastewater treatment plant effluents and evaluates their effectiveness. It also highlights practical strategies for implementing energy recovery from wastewater and provides successful case studies covering different potential scenarios [89,90].

Wastewater treatment involves a range of techniques aimed at eliminating contaminants found in wastewater. In Figure 2 are shown some of the common options for treating wastewater [91–94].

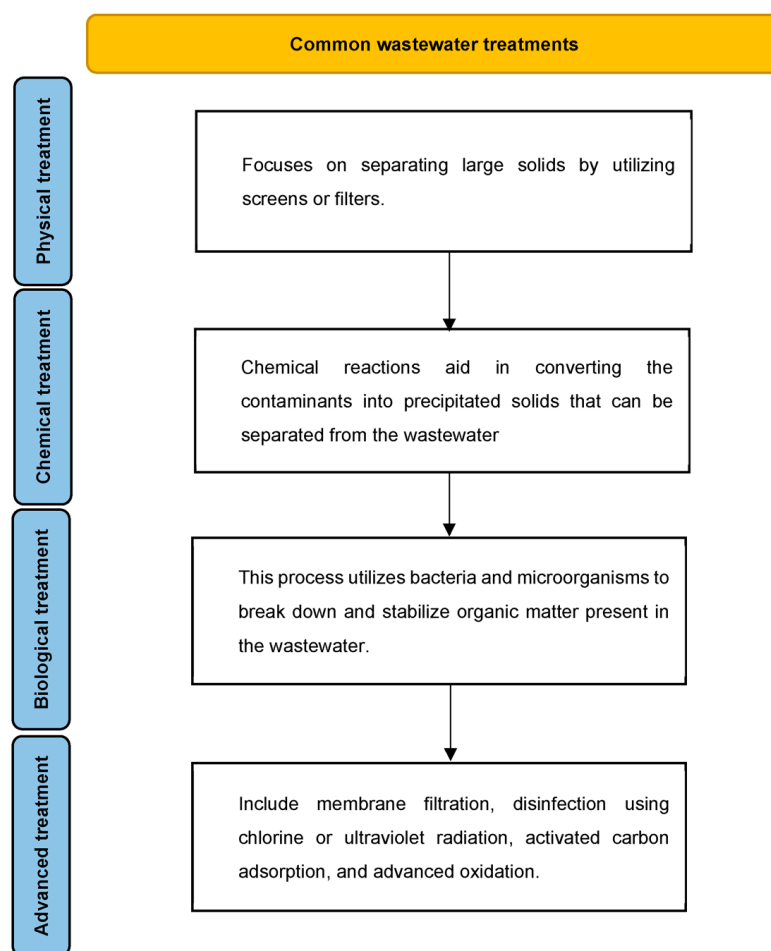


Figure 2. Flowchart to show common wastewater treatments.

It is important to note that the choice of wastewater treatment options may vary depending on the specific characteristics and context of the wastewater being treated. Selection of the most suitable treatment approach is based on technical, economic, social, and environmental criteria, which should be considered in each individual case.

2.3. Contributions to Environmental Sustainability

The primary contribution that wastewater treatment makes to sustainable resource management is the reduction in waste. According to Gernaey et al. [69], waste is a major threat to sustainability because it leads to the depletion of natural resources. Although there is sufficient water to meet the needs of everyone around the world, a lot of it goes to waste [95]. Additionally, most of the water is inaccessible to a significant percentage of the global population. Nearly 36 percent of the global population lives in areas where they face significant water scarcity [6,10,17]. Therefore, letting a significant amount of wastewater go to waste can be harmful to people who face water scarcity. Even those who live in areas with an adequate supply of water may face scarcity if continuous waste amounts to the depletion of natural resources [41,45,57,61,96]. Wastewater treatment turns potential waste into a valuable product that can be used for both domestic and industrial use. Moreover, wastewater treatment protects natural sources of water from potential depletion.

According to Kamali et al. [17], the role of sustainability is to ensure that natural resources are always available to meet the needs of both current and future generations. One of the biggest threats that the world is facing is the potential depletion of natural resources due to growing populations and demands [71,78,82,97]. For instance, most forests that were once covered with green vegetation have been turned into farmlands, industrial parks, and cities where people live. Once green places have been turned into concrete to

meet the needs of people [40]. Trees and forests are major components of the water cycle. Water that evaporates from the seas and trees is eventually converted into clouds and rain through a process known as condensation [30]. Deforestation presents a significant threat to water sustainability by cutting off a significant supply of vapors needed for rain formation [23,45,50,98]. Wastewater treatment addresses this challenge by ensuring there is a significant amount of water for both industrial and human consumption. Additionally, it is important because it considers SDG 6, which aims to ensure the availability and sustainable management of water and sanitation for all [44,64,65].

Wastewater treatment is also a source of green energy in the form of biogas. According to Melo et al. [46], climate change can be avoided or minimized if the global population turns to green sources of energy and cuts down their reliance on fossil fuels. Wastewater treatment has demonstrated a significant capacity to produce clean energy that can be used in powering the entire treatment facility or for domestic purposes [76,79,82]. During secondary treatment, the use of microorganisms or bacteria to absorb the suspended solid materials usually produces large quantities of biomass. At temperatures of about 35 degrees Celsius, biodigesters used in the decomposition of organic matter can produce large quantities of biogas [13,99,100]. A combustible gas known as methane forms the largest part of biogas. According to Al-Juaidi et al. [4], methane can be used to generate the required energy for powering the entire wastewater treatment facility. The methane obtained from the biodigesters can also be processed, packaged into gas cylinders, and sold to potential consumers to be used at home or in industrial processes [11,17,19,101]. This will reduce the dependence on fossil fuels and protect the environment from its consequences.

Scientific studies indicate a continuous decline in the sources of clean water around the world. Factors such as climate change, drought effects, increased urbanization, farming, and the growing population are putting excessive pressure on the few sources of clean water that are still available on the planet [33,39,41]. Scientists believe that much of the current water sources will be lost over the next 10 years if nothing is done to prevent the current onslaught [60,63,78,99]. The projected population increase over the next 10 years has also generated significant concerns about the demand and supply of clean and safe water. Wastewater treatment has become an important source of clean water [35,37,45,71]. Wastewater treatment is ensuring there is a balance between supply and demand. Since the current demand exceeds the supply, there is a need for additional sources of water to minimize scarcity in the cities, especially informal settlements, which are more vulnerable to water scarcity [11,18,49,102,103]. Wastewater treatment also protects the water cycle by maintaining biodiversity.

Although fossil fuels account for most of the current fertilizer supply, wastewater treatment is promising a more effective organic fertilizer that is less harmful to the environment [80,104–106]. The fertilizer obtained from fossil fuels has various associated concerns, including algae blooms and soil acidity [50]. The use of chemical fertilizers has also been associated with various concerns, including health concerns. Replacing chemical fertilizers with organic fertilizers will protect the environment and consumers from the potential dangers associated with the chemicals [42,107,108]. The organic fertilizers are obtained from the organic matter that is present in wastewater. One of the major benefits associated with organic fertilizers is the rich nutrients that not only support growth but also provide nutritional benefits to consumers [61,75,79,109]. The use of organic fertilizers also enhances soil sustainability by minimizing the chances of acidification.

3. Methods

In this study, a systematic review of the literature was chosen to determine if the practice being studied is based on sufficient evidence. The PRISMA checklist document is provided in the Supplementary Materials (See Table S1). According to Muga and Mihelcic [25], a systematic review of the literature is always the best option when researchers want to determine if a given practice is supported by sufficient evidence. In this case, the methodology helped to determine if wastewater treatment supports sustainable water

resource management as indicated in the hypothesis [34]. Evidence obtained from a systematic review of the literature helps in providing concrete answers to specific research questions [29,57,99]. For instance, a practice is only valid or scientifically relevant if there is sufficient evidence to support it. Any practice that is not supported by evidence can be harmful or a potential waste of resources. Most systematic reviews are based on primary studies that were conducted using various research designs, including experiments, randomized controlled trials, and quasi-experiments [27]. The systematic reviews help in identifying gaps in the evidence and proposing future studies.

Apart from answering specific questions, a systematic review of the literature was also selected for this study because it is detailed and comprehensive. The first step involves the formulation of the research question to guide the research. In most cases, the CIMO (Context, Intervention, Mechanisms, and Outcomes) approach helps in formulating specific questions, focusing on the problem, intervention, comparison, and outcomes [110]. In the case of wastewater treatment, a comparison can be drawn to letting wastewater go rather than subjecting it to treatment. The research question may differ based on the type of study and the required outcomes. Most systematic reviews are used in medical research where they assist in answering specific clinical questions [111]. From the research question, the researchers can identify the keywords and use them to search for the previous studies. Strict eligibility criteria must be developed to ensure that only relevant articles are selected to answer the research question [110,111]. The criteria help in eliminating articles that are not related to the research question or are too old to be included in the study. For instance, the studies conducted in the 1970s or 90s were not used in the study because they are too old and do not reflect the latest findings on a topic.

Systematic reviews are also effective in producing accurate and reliable results. The results obtained from a systematic review can be analyzed using a narrative approach or quantitative approaches such as correlation measurements, meta-analysis, and other numeric estimates [110]. In both correlations and meta-analysis, there is a confidence level that helps in determining the overall accuracy and reliability of the results. For instance, in correlations, a confidence interval determines the degree of certainty to which the given results fall within the range of the confidence level. A 95% confidence interval indicates that the results have a high degree of certainty, indicating a strong or negative correlation between two variables [110]. In this study, a narrative approach was used to analyze the results obtained from the previous studies. Both the narrative and quantitative approaches are acceptable routes for analyzing and drawing logical conclusions from the available data.

A systematic review of the literature was also deemed fit for this study because they are exhaustive, comprehensive, and reproducible. Systematic reviews are exhaustive because every detail of the evidence is used in synthesizing the outcomes. The use of primary sources also improves the quality of evidence, especially if the researchers used experiments, observation, randomized controlled trials, or case studies [111]. For instance, some scientists examined the application of wastewater treatment in countries such as China and how it leads to sustainability. The outcomes of systematic reviews are also reproducible to enhance the overall degree of accuracy. Most of the methods used in systematic reviews have been tested in various studies to determine their accuracy and ease of reproduction [110]. It is also easier for the academics to trace their steps and identify areas where there were omissions. Moreover, the study aimed at making sufficient evidence available to support the use of wastewater treatment to achieve sustainable resource management [111]. Gaps identified in this study will also assist in developing and conducting future studies to provide answers to questions that were not adequately addressed in the previous studies.

3.1. Question Formulation

Research question formulation is a delicate process that plays a key role in determining the overall outcomes. The formulated question produces key words, qualitative variables, and directions that researchers should take to provide accurate answers. Various

methods or logic can be used to develop specific and accurate questions. One of the most reliable logics is CIMO. The CIMO logic is more applicable in non-medical research where there is a limited requirement to compare interventions [107]. Moreover, the CIMO approach is more simplified and easier to apply even in studies involving big data analysis.

In this study, the research question was formulated using the CIMO approach. The context (wastewater treatment), intervention (implementation or integration), mechanisms (sustainable resource management), and outcomes (efficiency). The final question read as follows: “Does wastewater treatment lead to sustainable water resource management?” The question examines the role of wastewater treatment in contributing to sustainable resource management. The question also examines the various benefits that society is likely to gain from wastewater treatment. The question also touches on responsible consumption and production to ensure there is a sufficient quantity of clean water for drinking to meet the needs of the global population.

3.2. Source Identification

The two methods used in the second step, after formulating questions, included searching using “the Web” and “Boolean Operators”. The web search involved the use of keywords to identify and retrieve articles that are related to the research question and qualitative variables. The keywords included wastewater treatment, sustainability, and water management. They were used in combination to enhance the accuracy of the outcomes. For instance, “wastewater treatment” and “sustainable management” were used in combination to obtain articles that examined the relationship between wastewater treatment and its role in sustainable water management. The purpose of using the keywords was to enhance the accuracy of the articles.

The Boolean operators approach was also used to combine search terms in ways that broaden and limit the search results. For instance, if the keywords “wastewater treatment” are used in the search for articles, it broadens the search by returning nearly all the articles regarding wastewater treatment. However, the use of combined keywords such as “wastewater treatment and sustainability” limits the search results by returning mostly articles focusing on sustainability. Boolean operators are more effective when the re-searchers need to broaden the search while limiting the results to specific terms or years of publication. Boolean operators can also be used to limit the databases or journals where the results should come from. In the case of wastewater treatment and sustainability, the databases included Resources, Conservation and Recycling, Sustainability, Nature, Waste Management, and Journal of Industrial Ecology. The Boolean operators played a significant role in limiting the search results to the specific inclusion and exclusion criteria.

The Boolean Operators were also useful in receiving more articles using a method known as snowballing sampling. Snowballing sampling is used when the identified results do not provide direct answers to the research questions [108]. In snowballing sampling, the researcher relies on the reference list of the identified articles to obtain more specific articles that can provide more direct answers to the research question [108]. However, snowball sampling presents additional tasks and may be difficult in a case where the researcher has to deal with several articles. The snowball sampling includes additional evaluation of the articles and may not meet certain inclusion criteria such as year of publication. This helped in expanding the number of articles used in the research and adding strength to the evidence.

Six factors were considered when identifying and selecting the most appropriate articles for further analysis, as shown in Figure 3.

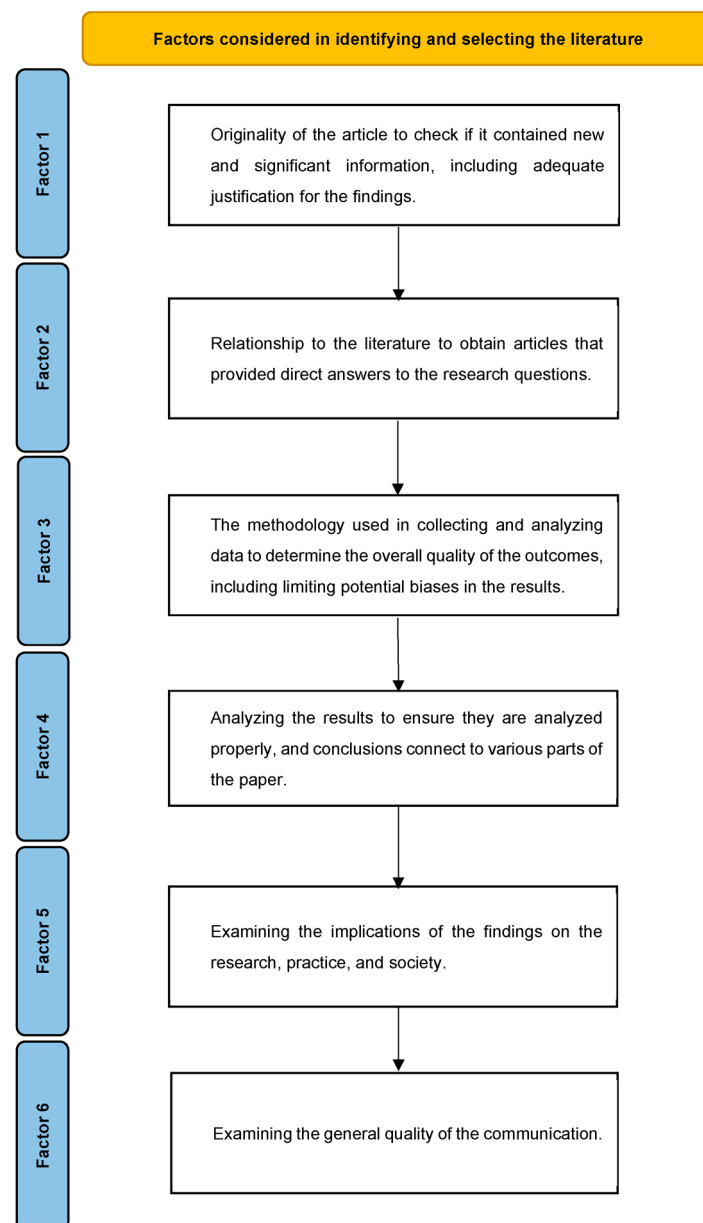


Figure 3. Flowchart to identify and select literature.

In the first factor, the researcher asked if the article contained new and significant information, including adequate justification for the findings. Originality was an important factor to consider, because the primary role of research is to present new information and contribute to the growth of information literacy. Articles that presented new information on the topic were more likely to be selected by the researcher than articles that were simply regurgitating what other researchers found in their primary studies. The researcher also gave significant priority to the original data that were obtained using primary research methods. Original articles also boost the overall strength of the evidence since they provide new information that is missing in other publications.

In the second factor, originality and relevance to the research question were very crucial. The papers had to demonstrate an adequate understanding of the literature and support their arguments with a wide variety of articles and concepts. It was also important to examine if any significant work was ignored. This would assist in identifying research gaps and areas that future researchers should focus on. A thorough evaluation of each article was required to ensure all the relevant information was included by the researchers.

At some points, screening the articles using the abstract was not enough to establish the position of the researchers. It also took a significant duration to screen all the selected articles and put the obtained information into the right context.

In the third factor, according to Fito and Van Hulle [12], the methods used in research determined the overall quality of the outcomes, including limiting potential biases in the results. For this reason, the reliability and validity of the results are fully dependent on the methods used in both data collection and analysis. The validity ensures that the results obtained are accurate and verifiable, while the reliability ensures that the same results would be obtained if a similar methodology is used in collecting data. Crucial factors to consider included the research design, sampling procedures, data collection instruments, and methods used in analyzing the outcomes. It was also crucial for the researcher to determine if the equivalent work on which the paper is based is well-designed and backed with sufficient evidence.

In the fourth factor, the findings provided details about the outcomes of the research and whether they adequately address the research questions and hypotheses. Analysis of the results began with a closer examination of the abstract. The review focused on the results that were found in relation to the research questions, methods used in collecting data, and analysis of the results. The researcher also examined if the results were properly interpreted to explain their implications on the issue under investigation. Papers that qualified for review fully satisfied both the analysis and conclusion criteria. They were also based on the recent findings, within the last five years, to reflect current trends in the market.

In the fifth factor, the first question was to determine whether the results met the intended objectives of the study. This was crucial, since the results that fall below the objectives allow gaps that should be explained by the researcher. Papers that qualified for review met all the objectives that the researchers sought to achieve. The second issue was whether the results aligned with the modern practice requirements. In the case of wastewater treatment, the researcher was looking for those who connected their findings to sustainability. The researcher also examined how the findings connect to the needs of society. In this case, the paper examined how the findings provide solutions to water scarcity around the world. It was also crucial to examine how the researchers connected their findings to the current and future challenges regarding clean water and sanitation.

In the sixth factor, elements to consider included whether the papers clearly expressed their case, measured against the language of the expected knowledge or the journal standards. Papers that qualified for review clearly expressed themselves and met the language expectations, including the use of terminologies associated with the research problem. The selected papers also avoided the use of jargon that may confuse readers and limit their capacity to internalize the contents of the paper. They also avoided the use of acronyms without explaining what the individual letters represented. Those which were selected met all the standards of the peer-reviewed journals and were selected based on their relevance to the research questions and hypotheses.

3.3. Selecting and Evaluating Sources

The article selection occurred in two main phases, beginning with the abstract screening. An organized abstract contains three main sections, including background, methods, and results or findings. Screening through the abstract provides information about the purpose of the study, background information, methods used in collecting and analyzing data, and the findings. The second phase examined if the articles met the inclusion criteria. The basic inclusion criteria included the year of publication (2000–2023), wastewater treatment, sustainable water management, journal, book, and authoritative website. The inclusion criteria also included an examination of whether the articles were biased regarding funding or affiliation. Funding bias affects the quality of the outcomes because it prevents the researcher from disclosing information that can be potentially damaging to the organization

or individual funding the research. The articles that were used in this study met all the inclusion criteria and were deemed appropriate and relevant to the research topic.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model was used in the study to synthesize and select the most appropriate results [110]. The total number of articles obtained from manual research was 350. However, not all these articles were eligible for the study. Most of them did not meet the year of publication requirements which limited the articles to a period between 2000 and 2023. More than 250 articles were rejected for being duplicates, ineligible, or removed for other reasons such as the year of publication. The remaining 100 articles were further subjected to further evaluation to identify the ones with specific answers to the research question. A total of 46 articles met the final criteria and were selected based on their relevancy and accuracy in answering the research question. The remaining 68 articles are included in the references list to add more perspective to the arguments made in this paper.

3.4. Data Analysis

The retrieved articles ($n = 46$) were classified into various critical dimensions for analysis, as shown in Figure 4. The main classifications included title, document type, authors, and main findings. The analysis involved examining each of the findings to determine how they relate to sustainable resource management. The study aimed at determining if wastewater treatment correlates with or supports sustainable resource management. Each of the findings was carefully examined to determine the correlation between wastewater treatment and sustainability. The comparisons also included similarities and differences among the findings.

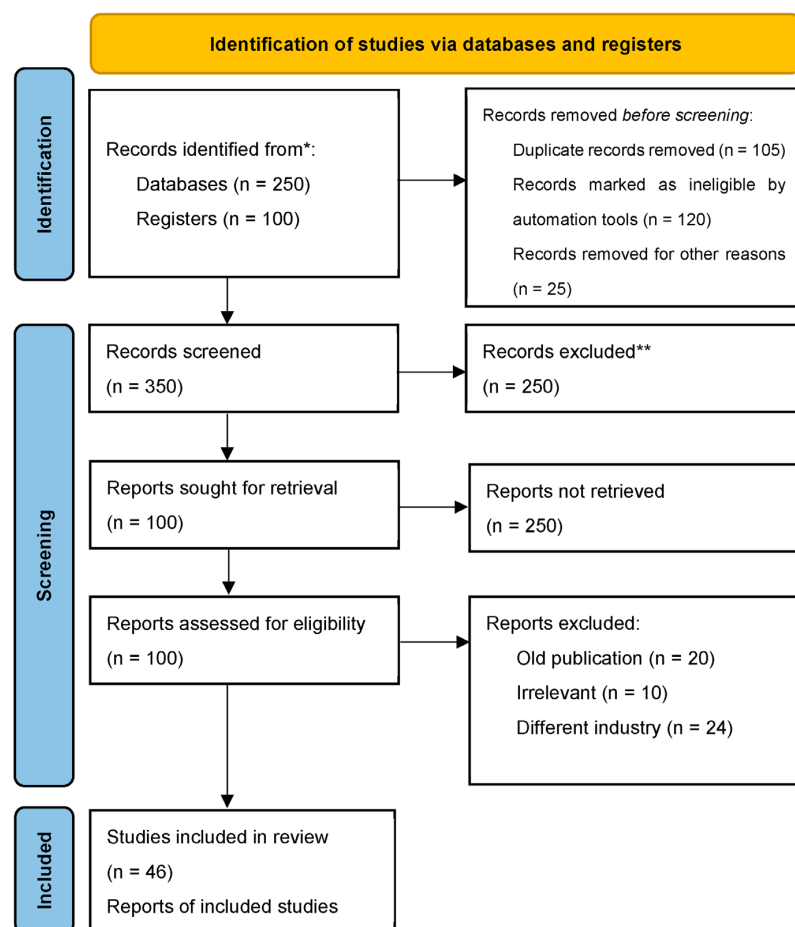


Figure 4. PRISMA flowchart.

4. Results

The application of PRISMA helped in narrowing the results to identify the most accurate articles that provided answers to the research question. The research also evaluated evidence to enhance validity and reliability. The results were also ranked based on strength, content validity, bias, and application to wastewater treatment and sustainable resource management. A summary of the findings is shown in Table 1.

Table 1. Selected Articles.

Title	Type of Document	Authors and Date	Findings
Sustainable water management for the city: technologies for improving domestic water supply.	Journal Article	Suzenet et al., 2002 [41]	Found that sustainable water management may not be achievable without the application of technology. The researchers explain how technology helps in eliminating toxic substances from wastewater and generating clean energy sources such as biomethane.
Wastewater reuses potential analysis: implications for China's water resources management.	Journal Article	Chu et al., 2004 [10]	Found that the economic and social potential of wastewater treatment has not been fully explored. However, current research indicates that wastewater treatment reduces dependence on natural water sources and enhances sustainability.
Experimental methods in wastewater treatment.	Book	Gernaey et al., 2004 [69]	Found that wastewater treatment and reuse is a sustainable source of water for agriculture and domestic use. Wastewater reclamation minimizes pressure on natural water sources.
Municipal wastewater reclamation: where do we stand? An overview of treatment technology and management practice.	Journal Article	Bixio et al., 2005 [43]	The findings indicate that most of the municipal wastewater treatment facilities are not operating at their full capacity. The research recommends the use of technology to enhance productivity.
Perspectives on sustainable wastewater treatment technologies and reuse options in the urban areas of the Mediterranean region.	Journal Article	Bdour, 2007 [42]	The researcher found significant support for wastewater treatment among the people who participated in the survey. Wastewater treatment was perceived as a sustainable solution to the threats of water scarcity.
Evaluating greywater reuse potential for sustainable water resources management in Oman.	Journal Article	Jamrah et al., 2008 [15]	Found that wastewater treatment and reuse protect the environment from human and natural forces and provide sufficient clean water for domestic and industrial use. The researchers support wastewater treatment as a major component of sustainable resource management.
Sustainability of wastewater treatment technologies.	Journal Article	Muga and Mihelcic, 2008 [25]	Found various technologies, including SBR and nanotechnologies, that have become very effective in wastewater treatment and reuse. Technology automates processes, minimizes energy waste, and enhances overall efficiency.

Table 1. Cont.

Title	Type of Document	Authors and Date	Findings
The role of satellite and decentralized strategies in water resources management.	Journal Article	Gikas and Tchobanoglous, 2009 [13]	The findings indicate that decentralized strategies are more effective because they give people an opportunity to implement wastewater practices in their homes, rather than depending solely on municipal wastewater treatment facilities.
Reuse potential of municipal wastewater treatment facility effluents for sustainable water resource management in Ulsan, Korea.	Journal Article	Kim et al., 2010 [21]	The researchers studied the reuse potential of wastewater treatment in Ulsan, Korea. The findings indicate that wastewater treatment is a major contributor to sustainable resource management.
Sustainable Treatment and Reuse of Municipal Wastewater: For decision-makers and practicing engineers.	Book	Libhaber and Orozco-Jaramillo, 2012 [23]	The findings indicate that wastewater treatment and reuse enable municipal administrations to provide sufficient clean water for their residents. Wastewater treatment also provides a clean source of energy to power the facilities and reduce the cost of operations.
Wastewater treatment and reuse: sustainability options.	Journal Article	Jhansi and Mishra, 2013 [16]	Found various sustainable options associated with wastewater treatment, including increased clean water supply, energy recovery, and healthy communities. The researchers support wastewater treatment as a strategic option for improving water supply in the cities.
Nanotechnology for a safe and sustainable water supply: enabling integrated water treatment and reuse.	Journal Article	Qu et al., 2013 [46]	Recommends the use of nanotechnology in replacing or facilitating aeration processes during the secondary treatment of wastewater. The use of technology also enhances efficiency and minimizes demand for large facilities.
Hydrologic-economic model for sustainable water resources management in a coastal aquifer.	Journal Article	Al-Juaidi et al., 2014 [4]	Found that wastewater treatment contributes to the sustainable hydrological cycle by protecting natural sources of water from depletion, protecting forests, creating additional water bodies, and providing a clean source of energy.
Environmental and cost life cycle assessment of different alternatives for the improvement of wastewater treatment plants in developing countries.	Journal Article	Awad et al., 2019 [6]	Findings indicate that the use of technology is the most cost-effective alternative for improving wastewater treatment. The researchers also support the use of technology to optimize operations and enhance accountability.
Wastewater treatment and water reuse in Spain. Current situation and perspectives.	Journal Article	Jodar-Abellan et al., 2019 [39]	The findings indicate that Spain is among the European countries where there is a growing application of wastewater treatment to address shortages and provide sustainable sources of clean and safe water for use in both industries and homes.

Table 1. Cont.

Title	Type of Document	Authors and Date	Findings
Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: Current status and future outlook.	Journal Article	Kamali et al., 2019 [17]	Supports the use of nanotechnology to speed up biodigester reactions and conversion of wastewater into useful products, including biomethane, fertilizers, and clean water. Nanotechnology also provides real-time monitoring and supports timely interventions using accurate data.
Environmental and economic performance evaluation of municipal wastewater treatment plants in India: a life cycle approach.	Journal Article	Kamble et al., 2019 [18]	The findings indicate that the environmental benefits of wastewater treatment included reduced wastewater pollution and minimal pressure on natural resources. The economic benefits include clean energy recovery, water for irrigation, and fertilizers for higher crop yield.
On the economic analysis of wastewater treatment and reuse for designing strategies for water sustainability: Lessons from the Mexico Valley Basin.	Journal Article	López-Morales and Rodríguez-Tapia, 2019 [24]	Found that wastewater treatment and reuse provide a sustainable supply of clean water to the residents of the Mexico Valley Basin. Wastewater treatment also provides fertilizers used in farms to enhance productivity.
Review on biological wastewater treatment and resources recovery: attached and suspended growth systems.	Journal Article	Machineni, 2019 [36]	The findings indicate major contributions that wastewater treatment makes towards environmental sustainability, including the enhanced provision of clean water and turning waste into energy.
Trends and resource recovery in biological wastewater treatment system.	Journal Article	Meena et al., 2019 [35]	Examined the emerging trends in resource recovery in the biological wastewater treatment system. The findings indicate energy recovery and organic fertilizers as the main trends in resource recovery.
Adequacy analysis of drinking water treatment technologies in regard to the parameter turbidity, considering the quality of natural waters treated by large-scale WTPs in Brazil.	Journal Article	Melo et al., 2019 [45]	Examined if wastewater treatment can provide clean and safe water for drinking at home. The findings indicate that wastewater treatment can create clean and safe water once all the toxic compounds are properly removed.
Vermifiltration as a sustainable natural treatment technology for the treatment and reuse of wastewater: a review.	Journal Article	Singh et al., 2019 [30]	Found that vermifiltration, involving the use of biofilters such as earthworms, speed-up the decomposition process and produce fresh manure for agricultural activities. The authors describe the use of vermifiltration as a sustainable process.
Green and sustainable pathways for wastewater purification.	Journal Article	Yadav et al., 2019 [29]	The findings indicate that wastewater treatment can be achieved using sustainable strategies, including the use of ultrafiltration, vermifiltration, and finding sustainable sources of energy. The authors argue that the purification of wastewater can be achieved without exerting additional pressure on natural resources.

Table 1. Cont.

Title	Type of Document	Authors and Date	Findings
Integrating the three E's in wastewater treatment: efficient design, economic viability, and environmental sustainability.	Journal Article	Yenkie, 2019 [31]	The findings indicate that wastewater management contributes towards sustainable resource management by fulfilling what the author describes as the three E's: efficient design of the facilities, economic viability, and environmental stability.
Suitability of SBR for wastewater treatment and reuse: Pilot-Scale reactor operated in different anoxic conditions.	Journal Article	Alagha et al., 2020 [1]	The research found a correlation between Sequencing Batch Reactor (SBR) and operational efficiency in wastewater treatment. The researchers recommend the use of SBR in the treatment stages to improve productivity.
Public perceptions of reusing treated wastewater for urban and industrial applications: challenges and opportunities.	Journal Article	Baawain et al., 2020 [34]	Found that there is a growing awareness of the benefits of wastewater treatment in society. This enables decentralized wastewater treatment and helps the government to achieve the desired goals.
A transition from conventional irrigation to fertigation with reclaimed wastewater: Prospects and challenges.	Journal Article	Chojnacka et al., 2020 [11]	Supports the use of wastewater treatment to provide sufficient water for irrigation. The nutrients contained in wastewater make it ideal for irrigation and detoxification.
Water reuse for sustainable microalgae cultivation: current knowledge and future directions.	Journal Article	Lu et al., 2020 [32]	Found that wastewater treatment contributes to the sustainable management of water, a scarce resource in many places of the world. The cultivation of microalgae is effective in speeding up the bio-digestion process.
Methodological frameworks to assess sustainable water resources management in industry: A review.	Journal Article	Navarro-Ramírez et al., 2020 [27]	The findings indicate various sustainable frameworks of wastewater treatment, including optimized aeration, vermifiltration, UV light disinfection, and reverse osmosis.
Contributions of recycled wastewater to clean water and sanitation Sustainable Development Goals.	Journal Article	Tortajada, 2020 [3]	Supports recycling of wastewater as a sustainable source of clean water for both domestic and industrial use. Supports recycling as one of the strategies for meeting the SDGs.
Paradigm shifts and current challenges in wastewater management.	Journal Article	Villarín and Merel, 2020 [2]	The paper describes “wastewater as a resource” as a new paradigm shift in water management. The researchers also highlight ways in which challenges such as energy consumption and inadequate staffing can prevent the realization of the paradigm shift.
Wastewater treatment and resource recovery technologies in the brewery industry: Current trends and emerging practices.	Journal Article	Ashraf et al., 2021 [38]	Found that wastewater treatment provides a sustainable solution to the brewery industry where a significant amount of water used in cooling goes to waste.

Table 1. Cont.

Title	Type of Document	Authors and Date	Findings
Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: A case study in southern Italy.	Journal Article	Canaj et al., 2021 [8]	Found that wastewater treatment provides sufficient water for irrigation among farmers in southern Italy. The rich nutrients from wastewater treatment also make the practice more effective than chemical fertilizers.
Fit-for-purpose urban wastewater reuse: Analysis of issues and available technologies for sustainable multiple barrier approaches.	Journal Article	Capodaglio, 2021 [9]	The findings indicate that fit-for-purpose wastewater reuse provides sufficient water for urban dwellers and protects them against diseases associated with contaminated water. The term fit-for-purpose indicates that wastewater is treated to meet specific needs.
Solar disinfection (SODIS) technologies as an alternative for large-scale public drinking water supply: Advances and challenges.	Journal Article	Cháuque and Rott, 2021 [40]	Wastewater treatment relies on various technologies, including solar disinfection (SODIS). The use of solar disinfection may help in removing toxic substances and providing sufficient clean water for drinking.
Wastewater infrastructure for sustainable cities: assessment based on UN sustainable development goals (SDGs)	Journal Article	Delanka-Pedige et al., 2021 [33]	Examined how wastewater treatment and reuse increase chances of achieving the United Nations' sustainable development goals (SDGs). The findings indicate that wastewater treatment is needed for the creation of sustainable cities and communities, responsible consumption, and waste disposal.
Industrial wastewater treatment: Current trends, bottlenecks, and best practices.	Journal Article	Dutta et al., 2021 [5]	Found that the use of technology is one of the latest trends in industrial wastewater treatment and is designed to boost productivity, enhance efficiency, monitor operations, and bridge the gaps created by inadequate staffing. The researchers also explained challenges, including poor staffing as a major challenge affecting industrial wastewater treatment facilities.
Wastewater reclamation and reuse potentials in agriculture: towards environmental sustainability.	Journal Article	Fito and Van Hulle, 2021 [12]	Found that wastewater reclamation is a major contributor to environmental sustainability because it limits pressure on natural resources, improves clean water supply, generates clean energy, and provides organic fertilizers that can improve agricultural productivity.
Wastewater treatment and reuse: a review of its applications and health implications.	Journal Article	Kesari et al., 2021 [19]	Found that wastewater treatment and reuse improve the supply of clean water for domestic use. The researchers also found that wastewater treatment reduces health concerns associated with water scarcity or drinking contaminated water.
Wastewater treatment and reuse situations and influential factors in major Asian countries.	Journal Article	Liao et al., 2021 [22]	Found a growing application of wastewater treatment in many Asian countries to address challenges such as water shortages. Wastewater treatment contributes towards sustainable resource management.

Table 1. Cont.

Title	Type of Document	Authors and Date	Findings
Zero Fenton sludge discharge: a review on reuse approach during wastewater treatment by the advanced oxidation process.	Journal Article	Mahtab et al., 2021 [37]	Found that the advanced oxidation process enables wastewater treatment facilities to breakdown organic matter to extract clean water that can be used for both domestic and industrial use.
Sustainable treatment of paint industry wastewater: Current techniques and challenges.	Journal Article	Nair et al., 2021 [26]	Found that industries are among the major sources of wastewater in the world. Wastewater treatment enables industries to minimize waste, reduce the cost of production, and protect natural sources of water from potential depletion.
Sustainable implementation of innovative technologies for water purification.	Journal Article	Van der Bruggen, 2021 [44]	Findings indicate that innovative technologies are a future approach to effective wastewater treatment. Technology may help in replacing bacteria, increasing productivity, and monitoring operations to prevent potential damages.
Recovery, regeneration and sustainable management of spent adsorbents from wastewater treatment streams: A review.	Journal Article	Baskar et al., 2022 [7]	The findings indicate that spent absorbents from the wastewater treatment streams can become an environmental menace if not disposed of properly.
Membrane technology for sustainable water resources management: Challenges and future projections.	Journal Article	Issaoui et al., 2022 [14]	Examined the use of membrane technology in wastewater treatment. Findings indicate that the use of technology improves aeration and overall efficiency in the treatment process.
Environmental technology and wastewater treatment: Strategies to achieve environmental sustainability.	Journal Article	Khan et al., 2022 [20]	Examined the environmental impacts of wastewater treatment. The researchers found that wastewater treatment minimizes pressure on the forests and other natural sources of water, making them available for the current and future generations.

5. Discussion

This research asks, “Does wastewater treatment lead to sustainable water resource management?” Considering the hypothesis of this research, the findings indicate that wastewater treatment contributes toward economic and environmental sustainability in four ways: converting waste to clean water (Section 5.1), converting waste to energy (Section 5.3), reducing the environmental effects of wastewater (Section 5.4), and builds sustainable cities and communities (Section 5.5). The evidence provided in the table also indicates the relationship between “sustainable outcomes of wastewater treatment” (qualitative variable) and “wastewater treatment techniques” (qualitative variable). A detailed discussion of the findings is provided below.

5.1. Converting Waste to Clean Water and Sanitation

The rigorous process of wastewater treatment ensures that the final product is clean and safe water that can be used at home for various purposes, including drinking, cooking, and sanitation [30]. In the circular economy, the wastewater that is generated from home can also be channeled back to treatment facilities for various purposes such as irrigation [33,49,51]. In places such as urban areas where there is prevalent water scarcity, wastewater treatment provides an alternative source of clean and safe water for domestic

use [22,33,57,69]. Most of the informal settlements where water scarcity is a major problem can rely on wastewater treatment to boost the supply of clean and safe water. According to Nair Manu and Azhoni [26], wastewater treatment is likely to improve the supply of clean water around the world and offset the demand that has become very difficult to fulfill.

The provision of clean water for domestic and commercial use contributes towards sustainability by protecting natural water sources from potential depletion. Gernaey et al. [69] describe sustainability as the use of resources in ways that ensures that they are always available for the coming generations. Although water is one of the most abundant commodities on the planet, accessibility remains a significant challenge [27,95,98]. The chances of depleting the natural resources in places that experience arid and semi-arid climates are quite high [78,81,99,102]. Approximately 771 million people, which is around 1 in 10 individuals worldwide, still lack access to clean water. This lack of access to safe drinking water has severe consequences, leading to 1.2 million deaths annually caused by unsafe water sources, with 6% of deaths in low-income countries attributed to these sources [112].

Jamrah et al. [15] estimate that most places that experience water scarcity are likely to face even bigger challenges over the next ten years as the problem intensifies. Unless something is done to reverse the current challenges, a huge section of the global population is likely to face significant water shortages and potential consequences, including diseases [33]. Instead of letting large amounts of water go to waste, the treatment process turns potential waste into valuable products that can protect the world from potential dangers associated with water shortage.

Apart from reducing pressure on the natural sources of water, wastewater treatment reduces waste, which is necessary for sustainability. Sustainable strategies depend on the capacity to reduce waste while controlling consumption and production [60,75,79,82]. Most organizations rely on the Six Sigma approach to enhance economic sustainability by reducing waste while expanding productivity [35,47,51]. In the case of sustainable re-source management, wastewater treatment plays a significant role in reducing waste and boosting the supply of water as a crucial commodity. Singh et al. [30] describe waste as one of the biggest challenges limiting the earth's capacity to maintain its resources. The growing human population and increased demand for essential resources indicate that various sources of water could be depleted even before the end of the current century [99,103,107]. By reducing waste, the treatment process ensures that the natural resources remain active to serve the current and future generations.

Wastewater treatment also promotes good behavior in society. According to Navarro-Ramírez et al. [27], studies have shown the centralized approach to sustainability is not working because most of the government efforts end up being opposed or are too little to address a major problem [22,36,44,48]. Indeed, governments cannot keep up with the pace at which people consume water and other essential commodities. Attempts to initiate measures such as increasing taxation to reduce overconsumption have not generated the desired outcomes. The decentralized approach ensures that people can take the initiatives to minimize waste [51,54,64]. However, this cannot only be effective if people are informed about the benefits of wastewater treatment and how they can minimize waste at home. Raising awareness about water conservation may assist many governments to enhance water conservation and minimize waste [77,97,101]. Additionally, raising awareness is likely to convince more people to join the national or urban sewerage system to have their homes connected to water treatment facilities.

5.2. Role of Technology in Wastewater Treatment and Sustainability

Wastewater treatment can be challenging without using various technologies to achieve the desired goals. Wastewater treatment occurs through a series of steps, including coagulation, flocculation, sedimentation, filtration, and disinfection [21,45]. Technology is usually involved in every step of the wastewater treatment process. Some of the latest technologies include an activated sludge model, bio-oxidation process, advanced oxidation system, aerated lagoons, aerobic granular reactors, and aerobic granulation [78,83,102]. The

main purpose of technology is to perform significant tasks or facilitate systems throughout the treatment process. For instance, the aerated lagoons provide a platform for oxidizing the wastewater so that micro-organisms such as bacteria can decompose the suspended organic compounds and make the water safe for the intended use [27]. The aerobic granular reactors also create suitable conditions to favor the decomposition of the organic matter suspended in the wastewater [41,57,83,99]. The technology ensures that wastewater treatment occurs more efficiently and cost-effectively.

Technology is also suitable in the analysis of processes to identify areas of weaknesses and minimize potential disasters. The wastewater treatment system is designed in a way that makes it vulnerable to potential disasters such as fire or spillage into nearby farms or homes [44,49,51]. The oxidation process and decomposition of the suspended organic matter produce various gases, including methane [60,71]. One of the dangers of methane is that it is highly combustible and can cause massive explosions if exposed to fire [77]. Technology helps in analyzing the entire wastewater treatment system to identify specific areas of weaknesses and recommend suitable solutions [98]. Data analysis is part of the risk assessment which occurs daily or weekly, depending on the management's policy. The technology prevents damage and ensures that wastewater treatment goes in accordance with the plan. Investments in the latest technology such as artificial intelligence are also crucial in automating the processes, reducing waste, and enhancing the overall operational efficiency [78,99,102]. Artificial intelligence is more effective in reading the machines and providing real-time monitoring and maintenance.

Wastewater treatment enables people to discover various technologies that can be used in achieving sustainable development goals. Technology enhances sustainability by giving policymakers the tools they need to make informed and timely decisions [44,49,55,61]. For instance, data analysis enables policy makers to identify potential risks that can damage the sewerage treatment system. The automated processes also enhance operational efficiency and reduce potential waste of resources [67]. The use of technology helps in saving resources and minimizing pressure on the environment [71]. For instance, wastewater treatment is usually powered by the biogas that is produced during the de-composition of the organic matter. Technology is needed to help in the production of clean energy and reduce dependence on the fossil fuels such as diesel used in running power generators [98,103,109]. Technology also generates value by reducing expenditures on fuel, lowering the overall cost of running wastewater treatment facilities.

Sustainable resource management is not just about policies, but also the use of technology to support decision making. According to Gernaey et al. [69], sustainable resource management involves monitoring natural resources and taking immediate measures to eliminate potential threats. Technology helps in collecting essential data that enables policy makers to monitor the threats facing forests and other water catchment areas [95,98,106]. For instance, technology can be used in collecting data regarding land and water-use in a given area. In a country such as China, technology has been used for many years in collecting data regarding the amount of water needed by the farmers to support rice and other types of farming [55,57,69]. The accurate data enables policy makers to allocate sufficient resources to specific activities aimed at addressing the key challenges facing natural resources [67]. Data can also help in predicting future trends and developing sufficient steps to protect natural resources from potential harm. Technology has made sustainable resource management more effective by providing information and guiding practices that are beneficial to the environment.

5.3. Converting Waste to Energy

Waste to energy (WTE) is a term that refers to processes that convert waste into a clean source of energy for cooking, heating, lighting, and powering vehicles. For a long time, sources of energy have been a significant source of concern among policy makers [55]. The use of fossil fuels continues to raise concerns over their overall cost to the environment. The need for a clean source of energy with minimal impact on the

environment has been a major priority among policy makers [32,79]. Wastewater treatment provides an alternative source of clean energy that can be used for powering homes and commercial facilities. The biogas obtained from the decomposition of organic matter during wastewater treatment is also capable of powering vehicles and replacing gasoline, diesel, and petrol [39,79,108]. However, the cost of developing sufficient biogas to replace fossil fuels remains a significant challenge. Additionally, most wastewater treatment facilities have not established sufficient capacity to treat or convert waste into energy [11,19,97,104]. For instance, only 40–50 percent of the current wastewater treatment facilities can convert waste into energy for both domestic and commercial use. The average energy produced from converting wastewater to energy can vary depending on multiple factors. These factors include the specific technology and process used for conversion, the composition of the wastewater, and the scale of the conversion facility.

Since energy is one of the greatest sources of air pollution, wastewater treatment has demonstrated a significant capacity to provide a sustainable solution to the problem [46]. Most wastewater treatment plants have on-site anaerobic digesters that can produce biomethane, an important source of clean energy. By estimates, about 1260 wastewater treatment plants can produce a total of 5 million gallons of biomethane [11,77,97]. If the biomethane is channeled into the gas grid, it can power homes and industries, reducing carbon emissions by about 2.3 million metric tons daily [56,68,78]. This is equal to the annual emissions of about 430,000 fossil-fueled passenger vehicles. Wastewater treatment is capable of reducing the overall dependency on fossil fuels as the primary source of energy [98,105]. However, this would require significant investment from various governments around the world to achieve the desired milestone. The current cost of converting waste to energy remains a challenge that would require a collective effort from many governments around the world.

Converting waste to energy is also likely to reduce the current cost of fossil fuels around the world. The high prices of oil and gas continue to affect many families around the globe. According to Nair Manu and Azhoni [26], oil prices have increased by significant margins since the pandemic, making essential commodities difficult to acquire for many families. Moreover, the main challenge with fossil fuels is that not enough alternatives have been produced to rival the mainstream supply of oil and gas [9,11,98]. Wastewater treatment may solve the problem by providing an alternative source of energy that people can use at home and in their industries [75,83]. This will reduce demand for fossil fuels and lower prices to levels that people can afford. Since the production of biomethane is likely to be less costly once the facilities are constructed, it will enable many people to afford clean energy [86,103,107]. Lowering the prices of oil and gas will also reduce the cost of production in the industries, and eventually contribute towards lowering the current level of inflation that continues to affect many economies around the world.

Wastewater treatment also creates opportunities for innovations around energy production. As the world grows wearier about the effects of climate change, scientists have been working towards developing more innovative approaches to energy production [105]. The production of electricity, for instance, remains a significant challenge to those who are concerned about the effects of climate change and environmental degradation [56,66]. While electricity is a clean source of energy, its production has never been clean or sustainable. Most of the electricity used around the world is produced using fossil fuels such as coal and diesel. Current innovations have focused on converting solar and wind into sustainable sources of electricity [34]. However, wastewater treatment provides opportunities for scientists to explore other sources of clean energy to support solar and wind. Innovations around biomethane would assist in making the gas more stable and efficient for large-scale applications [11,18,29]. The current innovations will also motivate future researchers to create better sources of clean energy from wastewater.

Sustainable resource management demands that nothing that contains potential value should go to waste. However, it may be difficult to understand the value of wastewater until the treatment and by-products are made available [105]. Rather than al-

wastewater to go into total waste, it is more economically and environmentally viable to extract the potential value that it contains [79]. Waste management is an important part of sustainability because it limits pressure on natural resources and prevents potential depletion. The current natural resources have been subjected to significant pressure and require innovative solutions such as alternative sources of energy [61,78,101]. The reduction in waste also saves the environment from the environmental damage associated with wastewater. Examples include nutrient pollution, oxygen depletion, toxicity impacts, and floating debris [44,97,99]. Wastewater pollution is something that has not been adequately addressed in previous studies. Turning wastewater into useful products such as energy is an innovative approach to sustainable resource management.

5.4. Reducing the Environmental Effects of Wastewater

Although the environmental consequences of wastewater have not been adequately addressed in previous research, there is a need to raise awareness about the problem so that more people can understand why wastewater treatment is necessary [98]. One of the biggest challenges associated with wastewater pollution is known as nutrient pollution. According to Singh et al. [30], nutrient pollution occurs when excessive nutrients in the wastewater are washed down into the rivers, lakes, or oceans where they cause massive destruction. The massive effluents that are washed down into the oceans mostly contain phosphorus and nitrogen [76,79,81]. Once these nutrients touch the bottom of the lake or river, they cause a phenomenon known as algae bloom. Algae take up all the oxygen that supports aquatic life, including fish and plankton. The depletion of oxygen is also harmful even to animals such as alligators and turtles that spend most of their lives in water [3,7,9]. Wastewater treatment ensures that these nutrients are converted into organic fertilizers, rather than allowing them to cause nutrient pollution.

The presence of many toxic substances in wastewater effluents is another significant concern associated with wastewater. The toxic substances are often fine particles that may be difficult to see unless the wastewater is subjected to chemical analysis [19,21,67]. During the second phase of wastewater treatment, the effluent undergoes screening to determine the toxic substances or chemicals dissolved in the water [9]. The removal of toxic substances such as ammonia may require more advanced technologies to prevent returning such substances into circulation [7,12,18,69]. Treatment not only saves waterbodies from toxicity but also protects the soil from potential danger. There are also uncertainties regarding the actual impact of toxic substances on living organisms [68]. Very little is known about the actual consequences of toxic chemicals on human life. Wastewater treatment limits the chances of being exposed to toxic substances that can be harmful to both humans and aquatic life.

Another environmental concern associated with wastewater is floating debris. Most of the floating debris consists of plastic waste and other materials that have been swept down into rivers or lakes [39]. The floating debris affects aquatic life by preventing sunlight that enables plankton to grow. The limited sunshine penetration may also create significant changes in the water temperatures, sometimes forcing aquatic life to re-adjust to the new conditions [44,56,65,71]. The floating debris also affects the movements of fish and generates massive death, making the water even more toxic. If not removed, the floating debris can also affect the recreational use of the rivers and lakes [100]. The surrounding waterbodies are essential both for drinking and recreational purposes. Activities such as swimming and boat riding provide opportunities for the community to come together and explore their talents [108]. However, the floating debris affects the general water surface and prevents both the recreational use and the overall social value of the nearby rivers and lakes.

Wastewater treatment also protects people from drinking contaminated water. Drinking contaminated water can expose humans to various bacteria, viruses, and other dangerous micro-organisms such as giardia and cryptosporidium [98]. Most of these bacteria or viruses are in microscopic forms, making them difficult to see without the help of devices such as microscopes [44,69,97]. While water may appear clean on the surface after

the sedimentation, it may contain harmful micro-organisms that are associated with various gastrointestinal diseases, including typhoid, dysentery, and cholera [21]. Wastewater treatment prevents the discharge of potentially harmful effluent into nearby waterbodies. Some of the irresponsible practices that have been noted in the past include discharging industrial effluents into the nearby creeks and rivers [79]. Even some of the most renowned companies such as Monsanto have a disturbing history of discharging industrial effluents into the nearby creeks and rivers [45,78,98]. Wastewater treatment protects human beings from potential catastrophes associated with domestic or industrial effluents.

5.5. Sustainable Cities and Communities

Wastewater treatment creates sustainable cities by ensuring there is sufficient water supply to meet the ever-increasing urban needs. Wastewater treatment is designed to maximize the supply of water, especially to deprived areas such as informal settlements [84,98,106]. Currently, more than half of all accessible water runoff is used by human activities. Industrial purposes account for approximately 90% of total water use, while domestic purposes constitute less than 10%. Although households are the smallest consumers of water, they possess significant potential to impact water conservation. By implementing water-saving habits and strategies within their homes, households can contribute to reducing water consumption and promoting conservation efforts beyond their own premises. Household water usage is projected to be the fastest-growing sector, expected to increase by over 80% in the next 25 years. This sector serves as a testing ground for developing strategies and promoting social behavior changes aimed at reducing water consumption in agriculture and industry [113]. Many cities around the world have created wastewater treatment plants to boost their water supply while maintaining high standards of hygiene in the cities [23,49,51]. Even in sub-Saharan Africa where water scarcity is prevalent, wastewater treatment is providing sustainable water supply to both urban and suburban populations. According to Navarro-Ramírez et al. [27], the growing urban population has pushed many families into informal settlements where the supply of water remains problematic. The growing urban population also means that more water is needed for both domestic and industrial use. Wastewater treatment provides a stable supply of water without exposing natural sources to potential depletion [98,109]. For a sustainable city, clean and safe water is needed for maintaining high standards of hygiene and protecting people from potential diseases.

According to Nair et al. [38], low-cost and decentralized wastewater treatment plants are addressing the prolonged imbalances between demand and supply of water in various communities. The decentralized wastewater treatment plants are aimed at providing sustainable solutions, especially in communities where there is a significant risk of water scarcity [67]. The decentralized system is also cost-effective because it does not have to connect hundreds of homes to a single wastewater treatment plant. Instead, a community can develop several small wastewater treatment plants to enhance access to sustainable solutions [69,78]. Moreover, the decentralized system educates communities about the value of wastewater treatment and how they can treat it even in their homes [29,39,48,59]. The increased awareness enables people to set up wastewater treatment facilities even in their homes. Other benefits such as the generation of energy help various communities around the world to boost their energy supply and minimize dependence on the national grid system [79,95,99]. Wastewater treatment plants ensure that communities have sufficient access to clean water and sanitation.

5.6. Challenges in Wastewater Treatment

One of the biggest challenges in wastewater treatment is the huge cost of setting up the treatment facilities. According to Manning et al. [81], the average cost of setting up a functional wastewater treatment plant ranges between GBP700,000 and GBP2.5 million, depending on the facilities required by a city [81,102,105]. The huge cost of wastewater treatment makes it unavailable to low-income communities despite its advantages in en-

hancing sustainability [31,39,41]. The high cost of installation also prevents many cities in low-income regions to build good facilities for both wastewater treatment and energy generation. The high cost of implementation is also discouraging many potential communities from creating small wastewater treatment facilities [50,60,75]. Most governments in low-income economies rely on donations and grants to implement such projects, since the cost may be too heavy for the taxpayers [40,50,71,97,104]. Despite the cost being too high for some administrations, wastewater treatment is a necessity that cannot be ignored. Cities and communities have to source funds and use them to create treatment plants to improve both water supply and general hygiene.

Another significant operational challenge facing treatment facilities is the huge cost of energy. Wastewater treatment plants consume about 2–3% of the electrical energy in most developed economies [100]. Wastewater treatment plants are among the largest consumers of electrical energy in the world. While the solution to this challenge is the production of biomethane to complement electrical sources of energy, most wastewater treatment plants have inadequate capacity to produce sufficient electrical energy [109]. Currently, the electrical energy generated by wastewater treatment plants can power between 50% and 60% of the facilities [49,109]. This leaves about 40% of the facility that has to be powered by alternative sources. The huge cost of electricity is a recurrent cost and has to be met by the administrators regularly. However, this challenge can also be solved by turning the sludge obtained from the wastewater into valuable products such as fertilizer for commercial use [106]. The income generated from the various activities within the treatment plants can assist in meeting some of the recurrent costs and ensuring that the plants remain operational.

Most of the wastewater treatment plants around the world face staff shortages. Staffing is a major challenge that can paralyze the operations of the plant. Individuals who work at wastewater treatment facilities are highly trained and certified by the relevant agencies to provide the required services [98]. However, the cost of hiring the most qualified staff to provide the desired services remains a significant challenge. Some of the facilities address this challenge by training their internal staff to provide the services they need [19,24,95]. This can be achieved by recruiting those who have little information about wastewater treatment and training them until they become fully fledged experts who can provide the required services [49,54,56]. Training also creates a loyalty program that encourages the employees to stay longer in the facility. Staying longer is also beneficial to the facility because the highly experienced staff can pass their knowledge to the recruits through mentorship programs [78,97,99]. Creating a loyal staff enables the company to minimize the cost of operations and enhance overall efficiency.

Another significant environmental challenge facing wastewater treatment plants is the disposal of excess sludge. Both the primary and secondary treatment processes create large quantities of sludge that must be removed to create room for the treatment of more wastewater [81,95,100]. While the sludge contains significant nutrients, it may also contain chemical compounds that can be harmful to the soil. The disposal of excess sludge is a challenge that must be considered when establishing a wastewater treatment facility [96]. The solid material that remains after wastewater treatment can be a great source of fertilizer since it contains sufficient nutrients. In some treatment plants, some of these solid materials are processed to determine if they contain harmful chemicals and channeled to the farms to increase crop yield [35]. However, in a case where the quantity of the sludge overwhelms the amount that can be processed for fertilizer, it becomes a major challenge to the organization [53,67,70]. One of the solutions to this challenge is burying the excess sludge. However, the treatment facility may require a large piece of land to safely dispose of excess sludge.

The activated sludge may also face many challenges, including the fact that the size of land needed for sludge production may not be available for many municipal administrations. The primary and secondary treatment processes require a significant amount of land to install various tanks to act as aeration basins [23,67]. However, the large

area of the land is not always available, innovative solutions must be developed to ensure even small pieces of land can provide sufficient ground for sludge production [23]. One of the innovative solutions is the use of advanced technology known as a membrane aerated biofilm reactor (MABR) to increase biomass concentration. According to Manning et al. [81], a higher concentration of biomass per unit volume is a crucial solution to the problem. The maximization of biomass per unit volume is one of the leading strategies for reducing the footprint so that municipalities can still achieve the desired goals using the available piece of land [45,97]. Moreover, sustainable resource management relies on innovative solutions to reduce pressure on natural resources.

Other challenges that municipalities may face include meeting the required standards set by the various agencies, including the National Green Tribunal (NGT), fragmentation of information, and the need for real-time monitoring [38]. The wastewater treatment standards are the limits of the chemical that must be met for the treated water to be declared as safe for the intended use [49,64]. The fragmentation of information occurs when the information does not reach the intended target. For instance, if the information meant for a given station manager does not reach the required recipient, it may lead to a breakdown in communication which is potentially harmful to the communication system [27]. The wastewater treatment facility also requires real-time monitoring to prevent potential accidents while delivering the desired outcomes [31,47,49,51–53]. Without sufficient staffing, it may be difficult for the wastewater treatment facility to provide real-time monitoring. The use of technology to automate processes is one of the leading strategies used by wastewater treatment plants to provide full-time monitoring and timely interventions.

6. Conclusions

The main objective of this study was to examine whether the available evidence supports the use of wastewater treatment for both environmental and economic sustainability. The results indicate that wastewater treatment contributes toward economic and environmental sustainability in four ways: converting waste to clean water, converting waste to energy, reducing the environmental effects of wastewater, and building sustainable cities and communities. The evidence also indicates the relationship between “sustainable outcomes of wastewater treatment” (qualitative variable) and “wastewater treatment techniques” (qualitative variable). Wastewater treatment extracts pollutants, neutralizes coarse particles, eliminates toxicants, and kills pathogens to provide clean water for drinking and other uses. Wastewater treatment eliminates waste by ensuring that dirty water that would go to waste is converted into valuable products, including energy, clean water, and fertilizers. Wastewater treatment also provides sufficient nutrients that can increase crop yield if used for agricultural purposes. The study has found that wastewater treatment prevents exposure to potentially harmful chemicals that can cause serious diseases. The recovery of energy from wastewater has been described as one of the most sustainable ways of achieving a sustainable energy supply. However, the study has also found various challenges that municipalities may face when implementing wastewater treatment facilities. Some of the challenges include inadequate staffing, excessive energy use, sludge protection, and the need for large pieces of land for the facilities.

The paper argues that sustainable resource management can be achieved by reducing the waste of water, increasing the supply of clean water, converting waste to energy, developing sustainable cities and communities, and responsible consumption and production. It is essential to acknowledge that these elements are interconnected and contribute to the overarching SDG 6. By effectively managing water resources, promoting water conservation, and implementing sustainable waste-to-energy solutions, it is possible to progress towards achieving universal and fair access to clean water and sanitation for all. The first approach to sustainable resource management is reducing the waste of water. This study has found that water is the most available commodity on the planet but most of it is inaccessible to nearly 36% of the global population. The research has also found that most of the water used at home and in industries usually goes to waste. Building

wastewater treatment facilities is the first step towards minimizing waste and ensuring what would have been lost goes back to circulation. Wastewater treatment facilities can produce a sufficient amount of water to support cities and suburban populations that are facing risks of water scarcity. Additionally, wastewater treatment reduces the potentially harmful environmental effects of discharging effluents into rivers, lakes, or oceans. Even landfills do not provide safe havens for discharging wastewater or sludge.

Increasing the supply of clean water would minimize scarcity and reduce pressure on natural resources. Sustainable resource management demands that supply should always exceed demand to minimize the potential depletion of natural resources. Wastewater treatment enhances the supply of clean water for both home and commercial use. Nonetheless, the process of obtaining clean water from wastewater can be costly and involves the use of technologies to minimize exposure to micro-organisms that can be harmful to health. The minimal pressure on natural resources ensures that there is sufficient water available to meet the needs of current and future generations. This will also protect millions of people around the world from being exposed to various dangers associated with drinking contaminated water. An adequate supply of clean water is also needed for maintaining high standards of hygiene in urban areas, especially in informal settlements where congestion creates opportunities for the spread of diseases associated with poor sanitation.

However, there are challenges that the municipalities should address to enhance adequate wastewater treatment. For instance, wastewater facilities should convert most of the solid organic materials into biomethane for powering the facilities and reducing dependence on external sources of energy. This will help in increasing the current conversion and consumption rate to more than 50% of the facility. Most wastewater treatment facilities can power about 50% of their plants using internally generated energy. Nevertheless, there is a need for these facilities to reach 100% to minimize any need for electricity as the primary source of energy. The use of technology should be a top priority for wastewater treatment. Investments in advanced technologies will improve data collection, real-time monitoring of the facility, and making timely interventions. Data management is also a crucial aspect of sustainable resource management since it provides accurate information to support decisions.

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