

Water Reuse and Recycling: Investigating the Feasibility and Effectiveness of Water Reuse and Recycling Systems to Provide an Alternative Water Source for Various Applications, Such as Irrigation, Industrial Processes, and Potable Water Supplies

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Abstract:

The present research examines the idea of recycling and reusing water as a sustainable approach to dealing with water scarcity and supplying substitute water sources for varied uses. In order to reduce the strain on freshwater resources, diversify water sources, protect the environment, and save money and energy, the article examines the viability and efficacy of water reuse and recycling systems. The study examines several water recycling and reuse technologies, including industrial water recycling, agricultural irrigation with recycled water, and direct and indirect potable reuse. It also compares and contrasts the various treatment technologies used in the context of water reuse and recycling, providing an overview of the treatment procedures as well as more advanced treatment approaches for particular contaminants. The study also presents case studies of successful water reuse and recycling initiatives, assessing their viability, efficiency, and implementation difficulties. In-depth discussion is given on the significance of factors affecting water quality, such as evaluating standards and regulations, monitoring and controlling contaminants, and determining their effects on the environment and public health. Last but not least, economic factors and cost analysis are looked at, including a cost-benefit analysis and return on investment evaluation of the economic viability of water reuse and recycling systems. In sum, the findings of this study provide new light on the viability of water recycling and reuse as a method for ensuring the long-term security of our water supply.

Keywords —Water Reuse; Recycling; Alternative water resource; water supplies

I. INTRODUCTION

Water is a precious resource that is necessary for maintaining life and a variety of human activities. But as the globe's population continues to grow and climate change effects become more pronounced, water is becoming scarce in many parts of the world [1]. In light of the growing concern about water scarcity, it is crucial that we investigate potential new supplies and develop long-term plans for water management. Reusing and recycling water is one

such tactic, and it entails treating and reusing wastewater for a variety of purposes, such as irrigation, industrial activities, and even potable water sources.

Reusing and recycling water is a potential idea for reducing the strain on freshwater resources and ensuring a steady supply of water for various industries. It is possible to alleviate the effects of water scarcity by increasing the existing water supply and developing alternative sources through

water treatment and reuse. Additionally, putting in place water reuse and recycling systems enables water source diversity, lowering reliance on particular freshwater bodies and protecting against their pollution or depletion [2].

Reusing and recycling water has substantial environmental and financial advantages in addition to addressing concerns about water scarcity. These technologies aid in preventing the contamination of natural water supplies, the destruction of ecosystems, and the release of treated wastewater into waterways. Additionally, processing wastewater for reuse frequently uses less energy than traditional water treatment methods, resulting in energy savings. Additionally, the use of recycled water can lower the price of acquiring freshwater and lessen the need for pricey infrastructure projects like building dams or long-distance water transports [3].

It is crucial to look into and assess numerous implementation-related factors in order to assure the viability and efficacy of water reuse and recycling systems. The goal of this study is to investigate the viability and efficiency of water reuse and recycling systems as a potential new supply of water for a wide range of uses. It will go in-depth on the many technologies for reusing water, including direct and indirect potable reuse, industrial water reuse, and recycled water irrigation for agriculture. The study will concentrate on advanced treatment techniques for particular contaminants as well as the treatment technologies used in water recycling operations. To evaluate the effectiveness and suitability of various treatment technologies for various applications, comparative analysis will be done [4].

In addition, case studies of successful water reuse and recycling initiatives from around the globe will be included in this study. Real-world applications will be used to evaluate the systems' viability, efficiency, and the difficulties associated with putting them into practice. The review of water quality standards and laws, the monitoring and

management of contaminants in recycled water, and the assessment of potential effects on the environment and public health are just a few of the issues that will be taken into account. Additionally, cost-benefit analysis and return on investment estimates will be used to assess the economic sustainability of water reuse and recycling systems.

Overall, the goal of this research is to offer important insights into the viability and efficiency of water reuse and recycling systems as a substitute for freshwater. This research will help advance sustainable water management techniques and tackle the problems associated with water shortage by analyzing many factors associated with their implementation, such as treatment technologies, case studies, water quality considerations, and economic analyses..

II. OVERVIEW OF GLOBAL WATER SCARCITY ISSUES

Lack of access to clean water is a serious issue that millions of people face worldwide [5]. The demand for freshwater resources rises along with population development, urbanization, and industrialisation, putting tremendous strain on the available water supplies. This section gives an overview of the difficulties surrounding worldwide water scarcity and emphasizes the significance of water reuse and recycling as a long-term fix for this serious issue.

When a region's supply of freshwater cannot meet the demand, it is said to be experiencing a water shortage. According to the UN, 4.2 billion people worldwide face water scarcity at least once a month, while approximately 2.2 billion people lack access to safely managed drinking water supplies [6]. These numbers highlight how serious and pervasive the issue is.

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Water shortage is a result of a number of issues, such as population expansion, urbanization, climate change, and ineffective water management techniques. Rapid urbanization and population expansion put a strain on water supplies, particularly where there is already a shortage [8]. The problem is made worse by climate change, which causes erratic rainfall patterns, less snowmelt, and more frequent droughts, all of which lower the amount of water that is available. Additionally, ineffective water management techniques including excessive extraction, pollution, and shoddy infrastructure worsen the scarcity.

Importance of Water Reuse and Recycling as a Solution:

The necessity of developing alternate water sources is made clear by the growing water scarcity situation. Reusing and recycling water are practical ways to reduce the stress on freshwater supplies and guarantee a steady supply of water for varied uses [9].

Reusing water is the process of purifying wastewater so that it can be used for a variety of tasks besides drinking, such as irrigation, business operations, or replenishing groundwater supplies. On the other side, recycling calls for high-quality wastewater treatment for potable use. By lowering the reliance on conventional water sources, both strategies contribute to the conservation of freshwater supplies.

Table 1 Water reuse and recycling several key benefits:

Key Benefits	Description
Augmented water supply	By reusing and recycling water, alternative sources are created, thereby increasing the available water supply for different sectors. This can alleviate pressure on freshwater sources, especially in regions experiencing water scarcity.
Diversification of water sources	Implementing water reuse and recycling systems enables a diversification of water sources, reducing dependency on specific freshwater bodies and mitigating risks associated with their depletion or contamination.
Environmental preservation	Reusing and recycling water minimizes the need for new water extraction, which can have detrimental effects on ecosystems and aquatic

	habitats. It helps protect natural water bodies by reducing the discharge of treated wastewater into rivers, lakes, or oceans.
Energy and cost savings	Treating wastewater for reuse often requires less energy compared to conventional water treatment processes. Additionally, utilizing recycled water can reduce costs associated with freshwater acquisition and decrease the demand for expensive infrastructure projects like dam construction or long-distance water transfers.
Climate resilience	Water reuse and recycling systems enhance resilience to climate change impacts by reducing vulnerability to droughts and ensuring a reliable water supply, even during periods of water scarcity.

In order to address the worldwide water shortage situation, immediate action must be taken. By varying water sources, preserving freshwater resources, and assuring a sustainable water supply for varied purposes, water reuse and recycling offer a practical and effective solution to this problem. By adopting these methods, we can reduce the effects of water scarcity, save the ecosystem, and foster resilience in the face of climate change. To ensure a sustainable and secure water future for all, governments, legislators, and communities must work together to encourage the adoption of water reuse and recycling technology, as well as the relevant policies and public awareness campaigns.

Direct and Indirect Potable Reuse

When wastewater is treated to a high degree and supplied directly as drinking water without an environmental buffer, this process is known as direct potable reuse (DPR). To efficiently remove contaminants using this method, additional treatment techniques are needed. These processes include reverse osmosis, advanced oxidation, or ultraviolet disinfection, followed by conventional treatment (coagulation, filtering, disinfection) [10].

Before being further treated for potable use, wastewater that has been treated to a high degree is introduced into an environmental buffer, such as an aquifer or reservoir. Any leftover contaminants are treated further and naturally attenuated by the environmental buffer. Before being distributed as drinking water, the water is treated using customary

water treatment techniques after the environmental buffer.

There are various advantages to both direct and indirect potable reuse, including:

1. Reduced reliance on traditional freshwater sources and improved water supply reliability, especially in water-stressed regions, are two benefits of implementing potable reuse systems, which recycle water from wastewater treatment facilities.
2. Potable reuse systems guarantee a sustained and robust water supply, even in the face of droughts or other disruptions in the traditional water infrastructure, thereby improving water security.
3. Reusing wastewater for drinkable purposes lessens the amount of treated effluent that is discharged into rivers or oceans, reducing environmental pollution and safeguarding delicate ecosystems.
4. Industrial Water Reuse: Within the same industrial facility, industrial water reuse entails treating and recycling wastewater produced by industrial operations for a variety of non-potable purposes.

This strategy reduces the negative environmental effects of industrial activity while preserving freshwater resources [11-12]. Industrial water reuse systems frequently contain pre-treatment steps to get rid of impurities and modify water quality to satisfy particular process needs. The following advantages of industrial water reuse:

1. Reducing the need for new supplies of potable water is one of the most tangible benefits of recycling and reusing wastewater in industrial operations.
2. The implementation of water reuse systems in industrial facilities can reduce the costs associated with acquiring freshwater, treating wastewater, and discharging it.
3. Reducing the amount of wastewater released into the environment through industrial water reuse is important for

environmental sustainability since it helps to conserve both water supplies and natural ecosystems.

Agricultural Irrigation with Recycled Water:

Using treated wastewater to irrigate crops is referred to as agricultural irrigation with recycled water [13]. By providing a sustainable and different water supply for crop irrigation, this approach helps to conserve freshwater resources and lessen dependency on potable water sources. The wastewater goes through the proper treatment procedures before being used for agriculture in order to eliminate impurities and make sure irrigation water quality criteria are met. Recycled water irrigation for agriculture has the following advantages:

1. By using recycled water for irrigation, farmers are able to decrease their consumption of potable water from freshwater sources, freeing up more of this precious resource for other purposes.
2. Enhanced soil fertility and crop development with fewer applications of fertilizer are possible because to the nutrient enrichment afforded by recycled water's naturally occurring nitrogen and phosphorus.
3. By eliminating the need to buy costly freshwater and decreasing the energy costs associated with pumping water, using recycled water for irrigation can result in significant cost savings for farmers.

Diversifying water sources, conserving freshwater resources, minimizing environmental impacts, and promoting sustainability are just a few advantages of implementing various types of water reuse and recycling systems, including direct and indirect potable reuse, industrial water reuse, and agricultural irrigation with recycled water [14-15]. These systems are essential for resolving water scarcity, improving water security, and making sure that water resources are managed sustainably. To maximize the potential of water reuse and recycling practices, governments, businesses, and the agricultural sector should work together to

implement and promote the adoption of these systems, taking into account the unique regional needs as well as the appropriate treatment procedures, regulations, and public acceptance.

III. TREATMENT TECHNOLOGIES FOR WATER REUSE AND RECYCLING

Water recycling is the process of purifying wastewater through a series of treatment steps to eliminate pollutants and toxins before using the useable water for various non-potable or potable uses. Many different types of treatment methods are used in water recycling systems, but the following are the most frequent [16].

Screening and Preliminary Treatment

Screening: In this process, large solids, debris, and coarse materials are removed using screens or grates to prevent clogging and damage to downstream equipment.

Grit Removal: Grit chambers are used to settle and remove heavy inorganic particles such as sand, gravel, and silt.

Primary Treatment

- **Sedimentation:** Wastewater flows into large settling tanks, allowing suspended solids and heavy particles to settle at the bottom. The settled material, known as primary sludge, is then removed.
- **Floation:** Dissolved air floation (DAF) is employed to remove fats, oils, and greases (FOG) by introducing air bubbles that attach to the FOG particles, causing them to float to the surface for removal.

Secondary Treatment

- **Biological Treatment:** This process utilizes microorganisms to break down and remove organic matter and nutrients present in wastewater. The most commonly used method is activated sludge, where wastewater is mixed with a culture of microorganisms in an aeration tank. Equations such as the Monod equation ($\mu = \mu_{max} * S / (K_s + S)$) can be employed to

model microbial growth rates in the activated sludge process.

- **Aeration:** Oxygen is supplied to the aeration tank to support the growth and metabolism of the microorganisms, facilitating the breakdown of organic compounds.

Tertiary Treatment

- **Filtration:** Filtration methods, such as sand filters, membrane filtration (microfiltration, ultrafiltration, nanofiltration, or reverse osmosis), or granular activated carbon filters, are employed to remove remaining fine particles, suspended solids, and residual organic and inorganic contaminants. Equations like the osmotic pressure equation ($\pi = iCRT$) can be used to calculate osmotic pressure across a membrane.

Advanced Treatment Methods for Specific Contaminants

Water recycling systems often incorporate advanced treatment methods to target specific contaminants that may not be effectively removed by conventional treatment processes. Some examples include:

Advanced Oxidation Processes (AOPs)

Processes such as ozonation, UV/H₂O₂, or photocatalysis using semiconductor materials (e.g., TiO₂) generate highly reactive hydroxyl radicals (OH•) to degrade persistent organic compounds. Equations describing the reactions and kinetics of these processes, such as the Langmuir-Hinshelwood equation, can be used to model the degradation rates.

Membrane Technologies

Reverse Osmosis (RO): RO employs a semipermeable membrane that selectively allows water molecules to pass through while rejecting dissolved salts and other contaminants. The rejection of solutes can be calculated using the solute rejection equation ($R = (1 - C_p / C_f) * 100\%$).

Nanofiltration (NF): NF membranes have a larger pore size than RO membranes, allowing for the removal of divalent ions, organic matter, and certain micropollutants while allowing some monovalent ions to pass through.

Comparison of Treatment Technologies for Different Applications

The choice of treatment technology for water reuse and recycling depends on the intended application and the required water quality [17-18]. Here is a comparison of treatment technologies for different applications:

Non-Potable Water Reuse

Conventional Filtration: Suitable for applications such as irrigation, industrial processes, and toilet flushing, where the water quality requirements are relatively less stringent.

Advanced Treatment: Advanced oxidation processes, activated carbon filtration, and UV disinfection may be incorporated to achieve higher-quality water for specific non-potable reuse applications.

Indirect Potable Reuse:

Advanced Treatment: Advanced treatment processes, including microfiltration, reverse osmosis, and UV disinfection, are used to produce high-quality water that meets stringent drinking water standards.

Direct Potable Reuse:

Advanced Treatment: Direct potable reuse requires additional treatment steps beyond indirect potable reuse, such as advanced oxidation processes

(AOPs), granular activated carbon (GAC) filtration, and advanced monitoring systems to ensure the safety of the treated water.

IV. CASE STUDIES OF SUCCESSFUL WATER RESCUE AND RECYCLING PROJECTS

Four examples of effective water reuse and recycling initiatives are summarized in the table below 2. Each case study is based on a real-world situation from a particular area, illustrating the wide range of possible applications and methods of therapy.

An example of the need of addressing public acceptance concerns in order to maintain a reliable water supply is the Orange County Groundwater Replenishment System in California, USA. The NEWater project in Singapore is proof that it is possible to diversify water sources and achieve water sustainability using cutting-edge treatment methods. Direct potable reuse is demonstrated and regulatory difficulties are addressed at the Windhoek Goreangab Reclamation Plant in Namibia. Aquifer recharge is shown to be effective at the Porirua City Aquifer Storage and Recovery Scheme in New Zealand, however it remains difficult to manage water quality [19].

The importance of these projects in reducing water shortages, expanding access to clean water, and maintaining responsible water management is highlighted by the case studies. Communities all across the world can learn from them as they serve as examples of the feasibility, effectiveness, and difficulty of adopting water reuse and recycling systems.

Table 2 Case studies of different locations

Case Study	Location	Treatment Processes	Application	Feasibility and Effectiveness	Challenges
Orange County Groundwater Replenishment System	California, USA	Microfiltration, Reverse Osmosis, UV Disinfection	Groundwater replenishment	Successful in providing a sustainable water source and reducing reliance on imported water.	Overcoming public acceptance and initial skepticism regarding the safety of recycled water for potable use.

Singapore NEWater	Singapore	Microfiltration, Reverse Osmosis, UV Disinfection	Industrial use, others	Highly successful in diversifying water sources and achieving water sustainability.	Addressing public perception and acceptance challenges.
Windhoek Goreangab Reclamation Plant	Namibia	Activated Carbon Filtration, Chlorination, Advanced Disinfection	Direct potable reuse	Instrumental in addressing water scarcity and recognized for technical innovation.	Securing public acceptance and addressing regulatory concerns surrounding direct potable reuse.
Porirua City Aquifer Storage and Recovery Scheme	New Zealand	Filtration, UV Disinfection, Chlorination	Aquifer storage and recovery	Effective in augmenting water supplies and improving resilience to droughts.	Managing water quality and mitigating potential impacts on groundwater resources.

V. TREATMENT TECHNOLOGIES FOR WATER REUSE AND RECYCLING

Water quality is a critical aspect of water reuse and recycling systems to ensure the safety and suitability of recycled water for various applications. This section discusses key considerations related to water quality, including evaluation of standards and regulations, monitoring and control of contaminants, assessment of environmental and public health impacts, as well as economic considerations and cost analysis.

Evaluation of Water Quality Standards and Regulations for Recycled Water

Water quality standards and regulations govern the permissible levels of contaminants in recycled water for different applications [20]. These standards are typically developed based on scientific research, risk assessment, and public health considerations. It is important to evaluate and comply with these standards to safeguard human health and the environment. The assessment may involve analyzing parameters such as microbiological indicators, chemical contaminants, turbidity, and disinfection by-products.

Monitoring and Control of Contaminants in Recycled Water

Effective monitoring and control of contaminants are essential to ensure the quality of recycled water. This involves implementing robust monitoring programs to regularly test and analyze water samples for key parameters. Advanced analytical

techniques, including chromatography, spectrometry, and microbiological testing, are used to identify and quantify contaminants. Furthermore, appropriate treatment processes, such as advanced oxidation, membrane filtration, and disinfection, are employed to remove or inactivate contaminants, minimizing potential risks.

Environmental and Public Health Impacts

Assessing potential environmental and public health impacts associated with recycled water is crucial. This involves evaluating the fate and transport of contaminants in the environment, including their potential accumulation in soil, plants, and aquatic ecosystems. Additionally, the potential risks to human health through exposure pathways such as ingestion, inhalation, and dermal contact need to be considered. Epidemiological studies and toxicological assessments help identify potential health risks associated with the presence of specific contaminants in recycled water.

Mitigation Strategies and Risk Management

To mitigate potential risks, effective risk management strategies should be implemented. This includes identifying and addressing potential sources of contamination, optimizing treatment processes to remove or reduce contaminants, and implementing robust monitoring and control measures. Risk communication and public awareness campaigns are vital to ensure

transparency and build public confidence in the safety of recycled water. Regular review and updating of regulations and guidelines also help in adapting to emerging contaminants and evolving knowledge.

Economic Considerations and Cost Analysis

Evaluating the economic viability of water reuse and recycling systems is essential for their long-term sustainability. Cost-benefit analysis involves comparing the economic benefits, such as reduced water demand and associated costs, with the investment and operational costs of implementing and maintaining the recycling infrastructure. Factors such as energy requirements, treatment technologies, maintenance, and monitoring expenses need to be considered. Additionally, assessing the return on investment helps decision-makers prioritize and allocate resources effectively.

VI. CONCLUSION

Systems for water reuse and recycling provide practical answers to the problems of water scarcity and the need for more environmentally responsible water management. This study examines the many facets of water recycling and reuse and comes to the conclusion that these systems have great potential for increasing water availability, increasing water diversity, and relieving pressure on freshwater supplies. Increased water availability in areas such as irrigation, industrial processes, and potable water supply can be achieved by water reuse and recycling. These systems also help the environment since they reduce the requirement for additional water extraction and the amount of treated wastewater released into natural water bodies.

In order to guarantee the quality of recycled water, treatment methods play a significant role. Treatment techniques and sophisticated treatment methods for specific contaminants are shown to be effective in creating safe and appropriate water for reuse in a broad overview. Further validating the viability and effectiveness of these systems, case studies of completed water reuse and recycling

projects highlight their contributions to water sustainability and resilience.

In water recycling and reuse systems, water quality is of utmost importance. To make sure that recycled water is safe and acceptable, it is important to look at the rules and standards for water quality, watch and control contaminants, and look at the effects on the environment and public health. In order to deal with potential hazards and make them known to the public, mitigation methods and risk management practices should be put into place.

The long-term viability of water reuse and recycling systems relies heavily on monetary factors including cost-benefit analysis and return on investment. Decision-makers are able to manage resources efficiently and prioritize investments based on the results of economic viability analyses of these systems.

In conclusion, water reuse and recycling technologies present a viable strategy to reduce water shortages, broaden water supply options, protect natural resources, and realize sustainable water management. These systems can play a crucial role in guaranteeing a consistent and sustainable water supply for a wide range of uses by applying suitable treatment technologies, adhering to water quality regulations, and taking economic considerations into account.

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