



VISTA INTERNATIONAL JOURNAL ON ENERGY, ENVIRONMENT & ENGINEERING



Technological Approaches for Water Conservation

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ABSTRACT

Water conservation is increasingly critical in energy and environmental sectors as water demand rises with population growth and industrial expansion. This study examines the role of advanced water-saving practices and technologies in reducing water consumption within energy-intensive industries. Focusing on novel solutions such as wastewater recycling, desalination, and sustainable irrigation, this paper provides insights into cost-effective and eco-friendly methods for minimizing water footprints. There are key findings derived from study and suggest that adopting these technologies leads to reduced operational costs and enhanced environmental sustainability.

1. Introduction

There is need for water conservation for its usage in various applications. The extensive usages of water in various sectors make the commodity vulnerable to water scarcity.

1.1 Background :

Water conservation is essential within the energy and environmental industries due to its direct effects on operational efficiency and sustainability goals. These sectors heavily rely on water for various processes—like cooling, cleaning, and energy generation—making them vulnerable to water scarcity. Efficient water use helps prevent operational disruptions, reduces costs, and enables companies to meet regulatory standards, ensuring long-term viability and minimizing environmental impact. The percent of water usage in the world is as shown in Fig.1 [1]. The global water usage has increased in the agricultural, domestic and industrial sectors. Evaporation from reservoirs is increasing at a slower rate. Projections for 2025 indicate that both global water use and evaporation will continue to increase. There is global consumption of water in various sectors as shown in Fig.2 [2,3]. This Fig. 2 shows water consumption, withdrawal and waste, in cubic kilometers per year, for the agricultural, domestic and industrial sectors. The time period covered as shown in Fig. 2 from 1900 to 2025 for the assessments and projections [2,3]. Percent distribution of water use among domestic use, industrial use, and agricultural use in the world, in high-income countries and in low- and middle-income countries is as shown in Fig 3 [4].

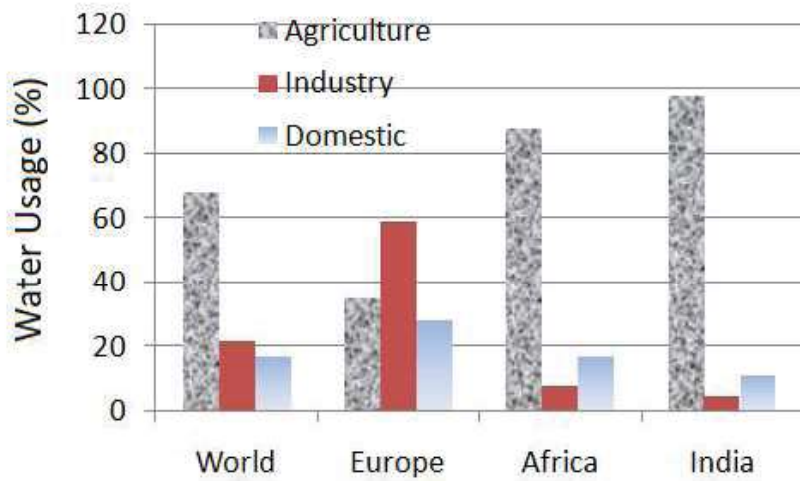


Fig. 1 Water usage in the world for Agriculture, Industry and Domestic Sectors [1]

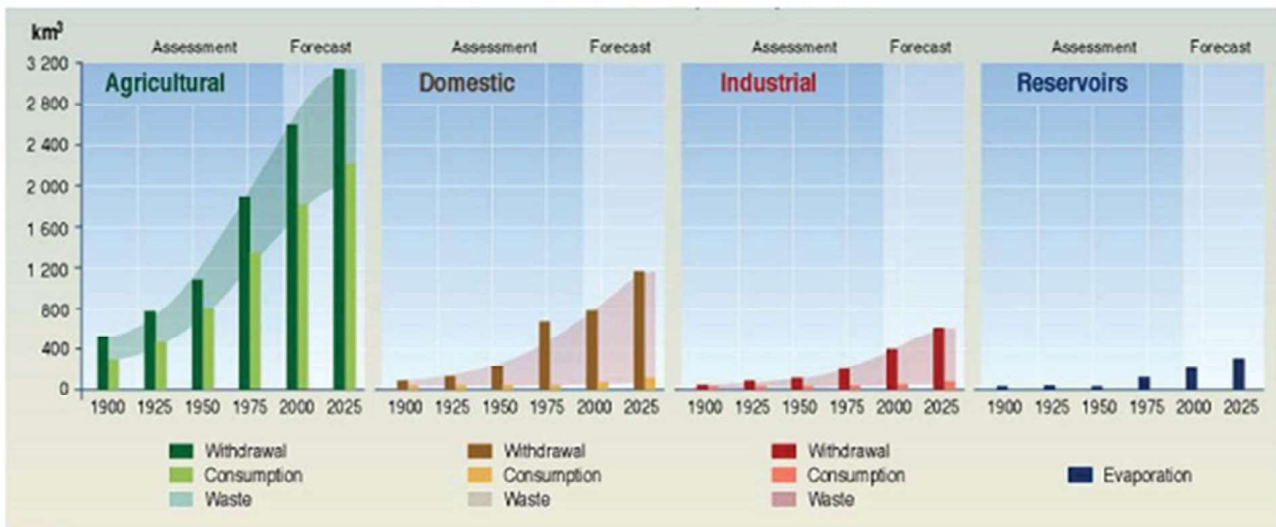


Fig.2 Evolution of global water use by sector (UNEP-2005) [2,3]

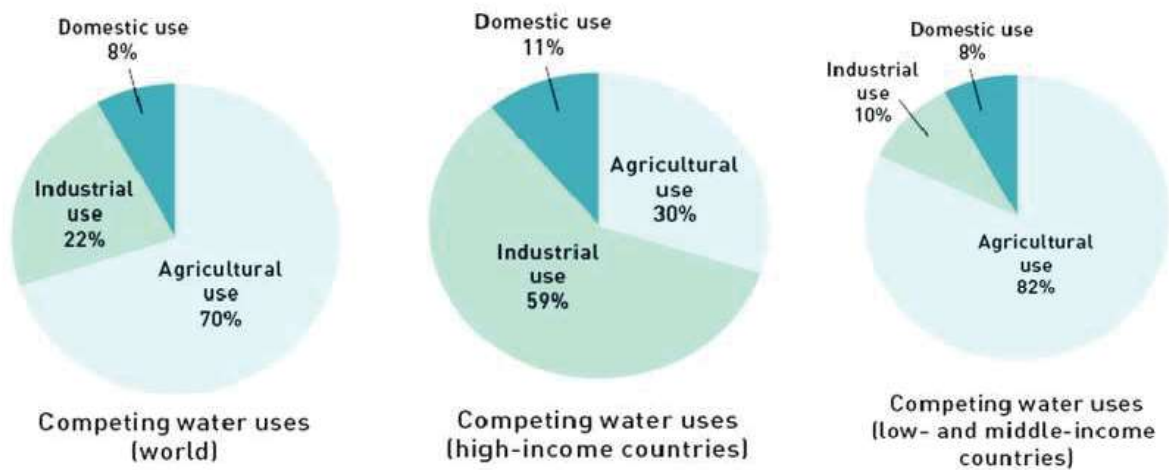


Fig.3. Water usage in different sectors in the world [4]

In addition, conserving water supports global sustainability targets by reducing energy needed for water treatment and distribution, which in turn lowers greenhouse gas emissions. This dual benefit makes water conservation a critical strategy for companies aiming to improve their environmental footprint and maintain responsible resource management.

1.2 Water conservation approaches:

Optimizing water conservation in the energy sector involves implementing efficient practices and technologies that reduce water usage and lower environmental impact. Here are some key approaches:

- 1. Adoption of Closed-Loop Cooling Systems:** Traditional thermoelectric power plants consume vast amounts of water for cooling. Replacing open-loop cooling with closed-loop systems significantly reduces water withdrawal, as these systems recirculate water, limiting the need for constant fresh water intake. This not only conserves water but also minimizes thermal pollution, which can harm local ecosystems
- 2. Use of Alternative Water Sources:** Many energy plants now use reclaimed water or treated wastewater for cooling and other processes, decreasing dependency on freshwater resources. This practice also supports local water conservation efforts by reducing stress on local water supplies and contributing to more sustainable water management
- 3. Enhanced Efficiency through Advanced Technology:** Technologies such as air-cooled condensers and dry cooling methods eliminate or greatly reduce water use in power generation. While these systems may require a higher initial investment, they provide long-term benefits by conserving water, particularly in water-scarce regions
- 4. Implementation of Water Monitoring and Management Systems:** Advanced monitoring systems track water usage in real-time, helping plants to identify areas where water can be conserved and improve efficiency. This data-driven approach enables better decision-making and reduces waste, contributing to overall sustainability goals
- 5. On-site Water Treatment and Recycling:** Treating and reusing water within facilities can significantly cut down on the need for fresh water. This is particularly effective in areas where water scarcity is a concern, as it helps to close the water loop within operations and minimize environmental impact

These practices not only support water conservation but also align with global sustainability initiatives by reducing the sector's overall environmental footprint. As regulations around water use tighten, these methods provide both economic and environmental advantages.

The purpose of this research is to explore and identify innovative solutions aimed at enhancing water efficiency in sectors with high energy consumption, such as power generation, manufacturing, and industrial processing. Water and energy systems are closely interconnected: energy production often requires significant water use, and water treatment and distribution rely on energy. Addressing inefficiencies in these areas is essential for reducing both water usage and environmental impact.

This research aims to analyze current practices, assess their effectiveness, and propose new approaches, such as advanced cooling technologies, water recycling, and integration of alternative water sources. These solutions are expected to contribute to more sustainable operations, lowering both water and energy footprints while meeting regulatory and sustainability goals.

1.3 Practices adopted for Water Conservation:

In recent studies, water conservation techniques such as water recycling, the use of gray water, and rainwater

harvesting have gained significant attention for their potential to reduce water consumption across industries and urban settings. The key practices adopted for water conservation are as follows:

1. Water Recycling: Studies highlight that water recycling is highly effective in industrial and agricultural applications. By treating wastewater for reuse, industries can reduce their demand for freshwater while minimizing wastewater discharge. This approach is particularly impactful in arid regions or areas facing water scarcity Fig.4 [5], where reclaimed water can support industrial processes or irrigation needs.

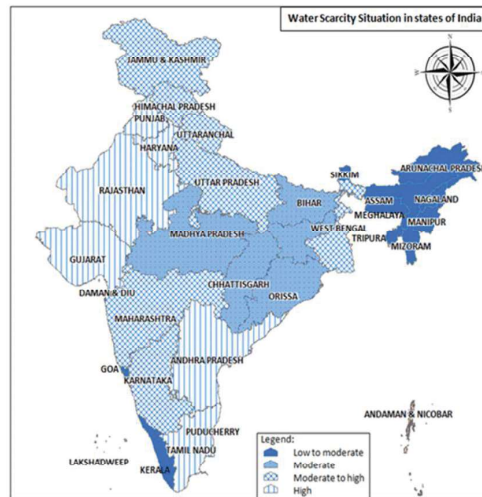


Fig. 4 State wise water scarcity in India [5]

2. Gray Water Usage: Research indicates that using gray water—relatively clean wastewater from showers, sinks, and washing machines—can be an efficient solution for non-potable applications, like irrigation and toilet flushing. Gray water systems are increasingly being adopted in commercial and residential buildings, as they can reduce freshwater consumption by up to 50% for specific uses, lowering strain on water resources and supporting sustainability goals.

3. Rainwater Harvesting: Rainwater harvesting is another widely studied conservation technique, with research showing that it can effectively reduce reliance on municipal water supplies, particularly in regions with seasonal rainfall. Harvested rainwater is often used for landscaping, irrigation, and even as an emergency water source. Many studies advocate for integrating rainwater harvesting systems into urban planning and infrastructure, especially in water-scarce cities, to enhance local water resilience. The case study has been reported related to rainwater harvesting in South Indian University Fig. 5 [6].

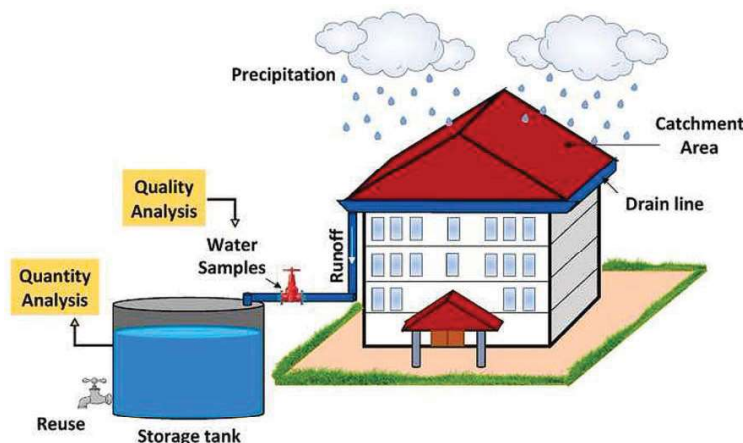


Fig. 5. Rainwater Harvesting [6]

Overall, these conservation techniques play a crucial role in managing water sustainably. As industries and cities seek to balance water demand with limited supply, the adoption of recycling, gray water systems, and rainwater harvesting continues to grow, supported by research emphasizing their environmental and economic benefits.

2. Technology driven approaches for water conservation:

Technology-driven approaches have led to significant advancements in water-saving technologies, particularly through smart irrigation systems, desalination, and closed-loop water management. These innovations aim to optimize water use across various sectors, from agriculture to industrial processing, supporting both conservation and sustainability goals. Here is an overview of recent advancements:

2.1 Smart Irrigation Systems: Smart irrigation utilizes sensors, weather data, and automated controllers to optimize water use in agriculture and landscaping. There is adjustment of water delivery based on soil moisture, weather forecasts, and plant needs, these systems help prevent overwatering, reduce water waste, and enhance crop health with smart irrigation architecture as depicted in Fig.6 [7]. Studies show that smart irrigation can reduce water usage by up to 40% in agricultural settings, offering a sustainable solution for one of the largest water-consuming industries.

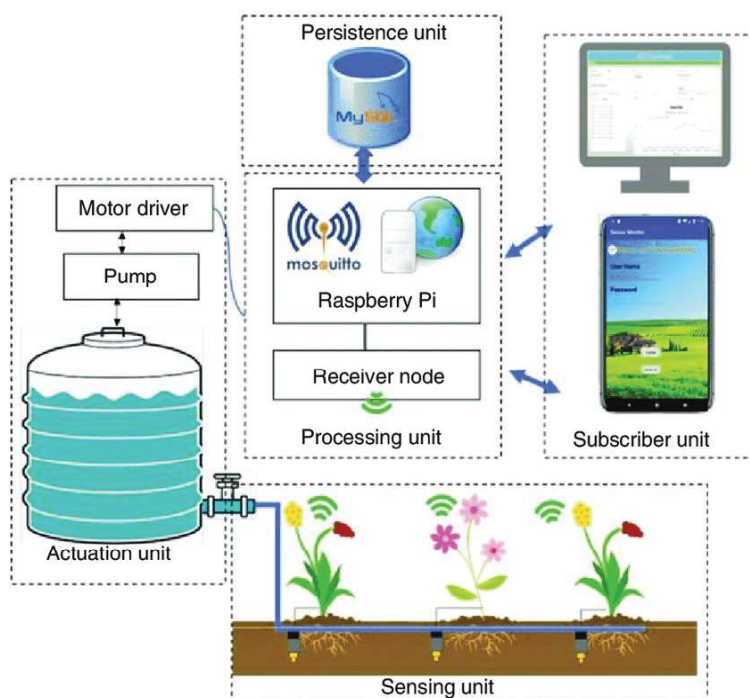


Fig. 6. Smart Irrigation System Architecture [7]

2.2 Desalination Technologies: As freshwater scarcity intensifies, desalination technology has become crucial in supplying potable water from seawater or brackish sources. Advancements in reverse osmosis (RO) and forward osmosis (FO) have improved desalination efficiency, reducing the energy costs historically associated with these processes. Innovations like energy recovery devices, membrane improvements, and solar-powered desalination systems are making desalination more sustainable and economically viable, particularly in regions facing severe water shortages.

2.3 Closed-Loop Water Management: Closed-loop systems recycle water within industrial or commercial processes, reducing both water intake and wastewater generation. In energy-intensive industries, closed-loop cooling systems, for example, reuse water for continuous cooling without discharging it after each cycle. These systems are designed to maintain water quality and minimize losses, supporting regulatory compliance and reducing environmental impact. These technologies help industries manage resources more efficiently, especially in areas with water scarcity by reusing water multiple times within a controlled loop. These technology-driven approaches are integral to modern water conservation strategies, combining efficiency with sustainability to meet increasing water demand without compromising environmental health. Continued research and investment in these technologies promise further improvements, making them even more accessible and impactful across industries.

3. Energy Sector Challenges:

The energy sector faces numerous challenges in reducing water use, particularly in thermoelectric power generation, where water is essential for cooling processes. These challenges are amplified by the industry’s high demand for reliable water sources and the environmental impacts of large-scale water withdrawals and thermal pollution.

3.1 High Water Demand for Cooling: In power generation, especially in coal, nuclear, and natural gas plants, large amounts of water are needed to cool and condense steam back into water for reuse. This cooling process typically involves open-loop or once-through systems, which withdraw and discharge vast quantities of water, often resulting in high water consumption. The typical air cooled cooling tower used for thermal power plant for hot water cooling as shown in Fig. 7. These power plants consume water for cooling in the condenser in large quantity creating a significant strain on water resources, especially in water-scarce regions.

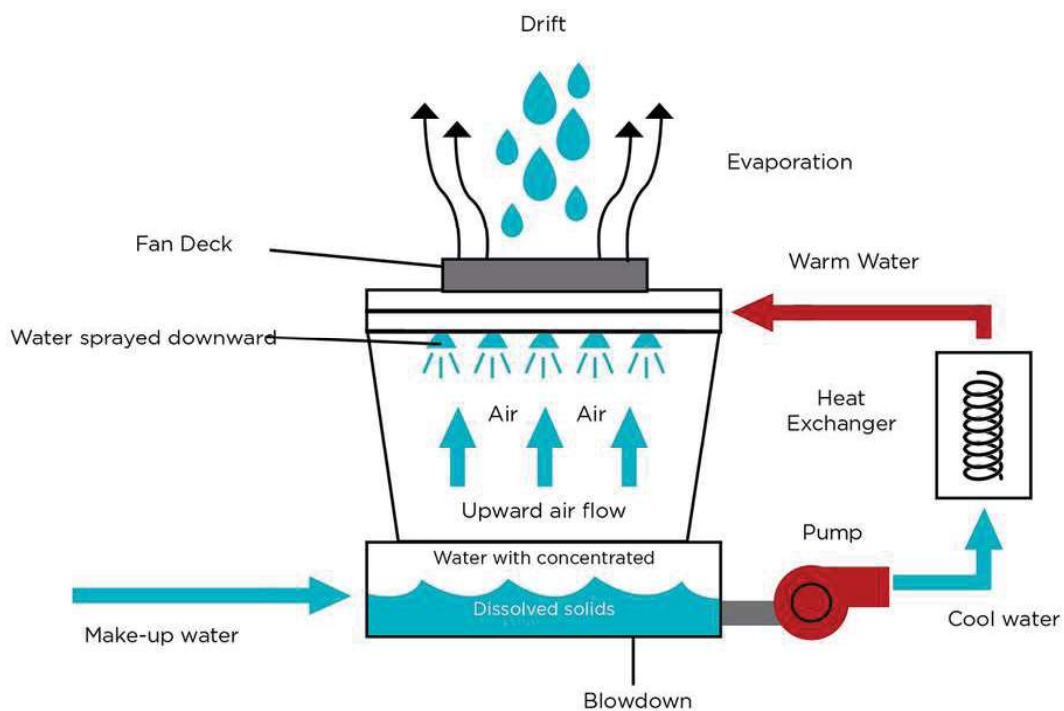


Fig. 7. Air cooled cooling tower for hot water spray in the power plant

3.2 Environmental Impact of Water Withdrawals: Extracting water for cooling affects local water ecosystems, especially when withdrawals occur in rivers, lakes, or coastal areas. The removal of large volumes of water can disrupt aquatic life and habitats, while discharge of heated water (thermal pollution) can raise temperatures in natural bodies of water, adversely affecting fish populations and biodiversity. These impacts often prompt stricter regulations, increasing operational costs for energy companies to comply with environmental standards

3.3 Balancing Efficiency and Water Conservation: Implementing alternative cooling methods, like closed-loop or dry cooling systems, reduces water usage but often requires higher initial investments and may reduce plant efficiency. For instance, dry cooling systems are less effective in hot climates, as they rely on ambient air for cooling instead of water, potentially lowering power output during peak energy demands

3.4 Regulatory Pressures and Sustainability Goals: As environmental concerns grow, the energy sector is under pressure to adopt sustainable practices, including water conservation and efficient resource management. Regulations around water withdrawals and thermal discharge continue to evolve, pushing companies to find innovative solutions, such as water reuse and recycling, to meet compliance and align with sustainability targets. Balancing these requirements with operational efficiency remains a complex challenge for the industry. These challenges highlight the need for ongoing research and investment in technologies that can help the energy sector reduce its water footprint while maintaining operational efficiency.

4. Methodology

The data is collected to evaluate water conservation practices in the energy sector. The data will be collected from various sources to provide a well-rounded perspective on existing methods and their effectiveness. Key data sources included as follows:

- 1. Case Studies:** Detailed case studies from energy companies implementing water-saving technologies will be examined. This will provide insights into specific methods, challenges faced, and real-world outcomes.
- 2. Industry Reports:** Reports from energy and environmental organizations, such as the International Energy Agency (IEA) and World Resources Institute (WRI), offer comprehensive data on water use, regulatory compliance, and conservation strategies within the industry.
- 3. Empirical Research:** If applicable, direct measurements or surveys within a set of energy plants will be conducted to gather data on water usage, costs, and efficiency before and after conservation strategies are implemented.
- 4. Secondary Data Sources:** Peer-reviewed articles and governmental databases on energy and water resource management will be referenced to provide broader context and comparative data across different regions and technologies.

5. Result and discussion:

5.1 Analysis Techniques:

The collected data will be analyzed using a combination of qualitative and quantitative methods to evaluate the effectiveness and applicability of various water conservation strategies:

- 1. Comparative Analysis:** By comparing data across case studies, industry reports, and empirical findings, this technique will help determine which water-saving practices have the highest efficiency and economic feasibility.
- 2. Statistical Analysis:** Quantitative data, such as water usage metrics, cost savings, and efficiency gains, will be analyzed statistically to assess trends, variances, and significance. Tools such as regression analysis may be used to evaluate the relationship between conservation efforts and reductions in water use or costs.
- 3. Cost-Benefit Analysis:** This approach will assess the financial feasibility of water-saving technologies by comparing the costs of implementation to savings achieved in water use and regulatory compliance.
- 4. SWOT Analysis:** A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis will provide a strategic overview of different conservation practices, helping to identify both the strengths of highly effective methods and the challenges limiting adoption in specific energy sectors.

This mixed-methods approach allows for a thorough understanding of the practical, economic, and environmental impacts of water conservation strategies, helping to identify best practices and provide actionable recommendations for sustainable water management in the energy industry.

5.2 Discussion:

The research findings have revealed that implementing water conservation measures in high water-use industries, such as oil refining and power generation, can lead to substantial reductions in water footprint and operational costs. Key results are as follows:

- 1. Operational Cost Reductions:** Water-saving practices like water recycling and closed-loop systems reduce the need for freshwater intake, lowering both water costs and regulatory compliance fees. For example, power plants using advanced cooling technologies, such as dry cooling or hybrid systems, have reported water use reductions of up to 80%, directly impacting operational expenses by minimizing water withdrawal and discharge costs.
- 2. Water Footprint Reduction:** Conservation measures significantly decrease water use, which is especially valuable in regions facing water scarcity. Case studies of oil refineries implementing recycling technologies have shown a 30–40% reduction in freshwater use, while desalination plants that recover and treat brine achieve sustainable water sourcing without impacting local freshwater supplies.

5.3. Case Studies:

The researchers have experience in implementation of water conservation in the Industry and narrated following brief case studies.

5.3.1 Power Plant with Closed-Loop Cooling:

A power generation plant in a water-scarce region implemented a closed-loop cooling system Fig. 8 [8], which recycles water for continuous use in cooling. This system reduced the plant's freshwater demand by over 50%, cutting costs associated with water withdrawal permits and treatment. Moreover, the plant reduced its thermal discharge, alleviating environmental impact on nearby water bodies.

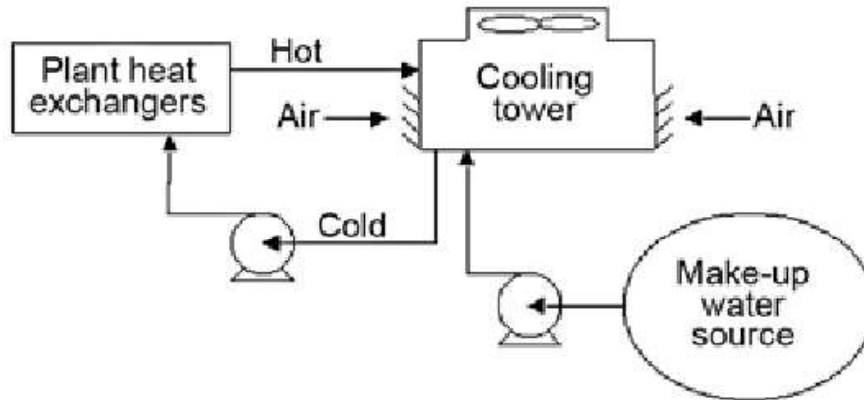


Fig. 8. Typical schematic closed loop cooling for power plant [8]

5.3.2 Oil refinery with gray water use and recycling:

An oil refinery in a desert region began treating and reusing gray water from nearby urban areas for its processing needs. By reusing treated wastewater, the refinery minimized its freshwater dependency and achieved a 40% reduction in water use. The initiative provided an eco-friendly solution and cut operational costs, while the treated wastewater reuse contributed to the local community's sustainable water management.

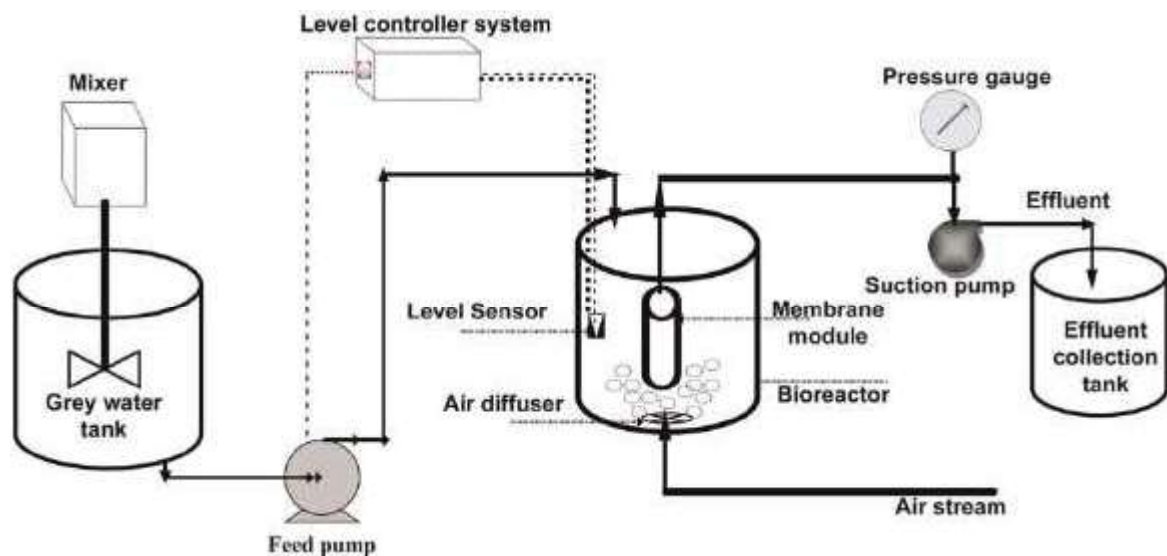


Fig. 9. Typical schematic of grey water recycling [9]

The adoption of water conservation practices has significant environmental and economic implications as follows:

1. **Cost Savings:** Water-efficient technologies, while often requiring initial investment, lead to substantial cost savings in the long term. For instance, by reducing water dependency, companies can mitigate risks associated with rising water prices, regulatory fees, and potential scarcity.
2. **Environmental Impact:** Reducing water withdrawal and discharge alleviates pressure on local ecosystems, helping to maintain biodiversity and avoid thermal pollution. Companies implementing sustainable practices contribute to global efforts in reducing environmental degradation, enhancing their reputation in the process.

3. Scalability and Future Potential: These conservation methods are scalable and can be tailored to meet the needs of various sectors, from heavy industries to commercial facilities. As technology advances and costs decrease, the adoption of water-saving practices is expected to grow, further contributing to global water sustainability goals.

These findings underscore the value of water conservation in energy-intensive industries and illustrate the potential for these practices to foster both environmental stewardship and economic resilience. Conserving water goes beyond just saving water; it plays a vital role in conserving energy and reducing greenhouse gas emissions (GHGs) [10].

6. Conclusions :

This research has explored the significance and impact of water conservation practices within energy-intensive sectors, particularly oil refining and power generation. Findings demonstrate that adopting advanced water-saving technologies, such as closed-loop systems, smart irrigation, and desalination, can significantly reduce both operational costs and the water footprint of these industries. These practices not only contribute to economic sustainability by lowering costs but also align with environmental goals by reducing the strain on local water resources, enhancing biodiversity, and lessening thermal pollution.

Researchers have recommended that industries should prioritize the integration of closed-loop cooling, wastewater recycling, and smart monitoring technologies to maximize the benefits of water conservation in the energy sector. Investing in these approaches can yield substantial long-term savings and support regulatory compliance. Governments and industry bodies should promote and incentivize the adoption of water-efficient technologies, particularly in water-scarce regions, to encourage broader implementation and shared responsibility for the sustainable usage of water.

There is potential for further studies to explore advancements in desalination, particularly in improving energy efficiency and reducing costs to make it a more viable option for industries. Additionally, research into the development of sustainable water resources in extreme climates (e.g. arid regions) could expand the reach of water conservation practices. Researchers should assess the impact of water conservation on local ecosystems and community resources. These studies offer further insight into the broader implications of water-saving technologies, providing a holistic understanding of their role in global sustainability efforts.

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