



Research Article

Energy Efficient Wastewater Treatment System for Sustainable Water Conservation in Industry

Talvinder Singh ^{1*}, Dr. Pooja Khanna ²

¹ Ph.D. Scholar, Mittal School of Business, Lovely Professional University, Jalandhar, Punjab, India

² Associate Professor, Mittal School of Business, Lovely Professional University, Jalandhar, Punjab, India

Corresponding Author: Talvinder Singh

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Abstract

As industries face mounting pressure from water scarcity, rising energy prices, and stricter environmental regulations, the need for sustainable wastewater management has become more urgent than ever. This paper explores how energy-efficient technologies are reshaping industrial wastewater treatment, offering solutions that not only cut down on energy use but also promote water reuse and long-term sustainability. Drawing from academic research, real-world case studies, and collaborative efforts between governments and private sectors, the review highlights key innovations such as anaerobic digestion, microbial fuel cells, smart monitoring systems, and renewable energy integration. These technologies demonstrate how industries can recover energy from waste while significantly reducing their environmental footprint. By combining practical examples with emerging strategies, this study outlines a roadmap for industries seeking to transition toward more sustainable and cost-effective water management systems.

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INTRODUCTION

Water is a fundamental resource in industrial operations, serving functions such as cooling, processing, cleaning, and product formulation. However, the growing scale of industrialization has led to a significant rise in wastewater generation, often containing a complex mixture of pollutants including organic matter, heavy metals, microplastics, and hazardous chemicals. According to the United Nations World Water Development Report (2023), global water demand is projected to increase by 20–30% by 2050, driven largely by industrial expansion, population growth, and climate change. Industry already accounts for approximately 20% of global freshwater withdrawals, and in high-income countries, this figure exceeds 40%. This study aligns with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 6—which ensures the availability and sustainable management of water and sanitation for all—and SDG 9, which promotes sustainable industrialization and fosters innovation. These goals emphasize the critical role of energy-efficient and technologically advanced wastewater management in achieving long-term water security and environmental sustainability in industrial settings.

Despite this heavy reliance on water, a substantial portion of industrial wastewater is discharged without adequate treatment. The World Bank (2020) estimates that nearly 80% of wastewater globally is released untreated, contributing to the degradation of water bodies and threatening both ecosystems and public health. In India, for example, the Central Pollution Control Board (CPCB) reported that more than 60% of industrial wastewater is discharged directly into the environment, often due to outdated infrastructure, high treatment costs, and weak enforcement of environmental regulations.

Traditional wastewater treatment systems, while effective in pollutant removal, are energy-intensive and contribute significantly to greenhouse gas emissions. The International Energy Agency (IEA) notes that the water sector consumes about 4% of global electricity, with wastewater treatment alone accounting for 3–5% of energy use in developed nations. Aeration, chemical dosing, pumping, and sludge processing are particularly energy-consuming processes, often representing up to 60% of a plant's total energy use. These energy demands not only increase operational costs but also contradict efforts to achieve carbon reduction targets outlined in the Paris Agreement. In response to these challenges, there is increasing interest in energy-efficient wastewater treatment systems that align with the principles of sustainable development. Emerging technologies such as anaerobic digestion, membrane bioreactors, microbial fuel cells, and bio-electrochemical systems offer promising alternatives, enabling industries to treat wastewater while recovering energy and valuable resources. Moreover, the integration of renewable energy sources and smart monitoring systems powered by artificial intelligence and the Internet of Things (IoT) is transforming the sector toward more adaptive, low-carbon solutions. In the Indian context, policy initiatives such as the National Mission for Clean Ganga, Zero Liquid Discharge (ZLD) guidelines, and the Perform, Achieve and Trade (PAT) scheme under the Bureau of Energy Efficiency

(BEE) reflect a growing emphasis on sustainable industrial practices. However, widespread adoption of energy-efficient systems remains limited due to gaps in technology transfer, financing, and policy enforcement.

In the Indian federal context, national regulatory oversight is provided by the Central Pollution Control Board (CPCB), which sets environmental standards and monitors compliance. At the state level, institutions like the Punjab Pollution Control Board (PPCB) play a pivotal role in enforcing these norms through inspections, permitting, and compliance tracking. Additionally, the Punjab Water Regulation and Development Authority (PWRDA) regulates industrial water abstraction, promoting sustainable water use, pricing, and accountability mechanisms for large-scale industries operating in the state. These bodies work in coordination with CPCB to ensure adherence to environmental safeguards, particularly in water-stressed industrial belts of Punjab.

This study aims to bridge these gaps by critically evaluating the design, performance, and applicability of energy-efficient wastewater treatment technologies in industrial settings. By drawing on global best practices, academic research, case studies, and regulatory frameworks, the research seeks to identify scalable, cost-effective solutions that can help industries reduce water consumption, lower energy use, and minimize environmental impact. Ultimately, the study contributes to the broader goal of achieving sustainable water conservation in industry through energy-conscious wastewater management strategies.

OBJECTIVE OF THE STUDY

The main goal of this study is to explore how energy-efficient wastewater treatment technologies can be effectively used in industries. It looks at how these systems can help lower energy consumption, encourage the reuse of water, and support more environmentally sustainable practices. The study also aims to uncover the key challenges industries face, highlight emerging opportunities, and suggest possible future directions for making industrial water management more sustainable.

Energy Consumption in Wastewater Treatment

reating wastewater is essential for protecting both the environment and public health—but it comes with a high energy cost. Wastewater treatment plants (WWTPs) are among the biggest energy users in both municipal and industrial infrastructure. According to the International Energy Agency (2022), these facilities are responsible for around 3–5% of the world's total electricity use, and in highly industrialized countries, this number can be even higher due to more advanced treatment requirements. As industries grow and cities expand, the need for wastewater treatment continues to rise. Naturally, so does the energy required to run these systems, highlighting the urgent need for more energy-efficient solutions.

One of the main reasons these systems use so much energy is aeration—the process that helps bacteria break down organic pollutants. Research shows that aeration alone can make up 50–60% of the total energy used in a typical activated sludge

treatment process (Henriques & Catarino, 2017). This becomes especially important in the case of industrial wastewater, which often has higher levels of organic pollutants and therefore needs more time and oxygen to treat properly.

Beyond aeration, energy is also used in pumping wastewater in and out of the plant, treating sludge (including thickening, digestion, and dewatering), and adding chemicals for nutrient removal and disinfection. All of these steps add to the plant's overall energy demand.

Energy use also varies widely depending on the type of treatment system in place. Basic treatment systems tend to consume between 0.3 and 0.6 kWh per cubic metre of water, while more advanced processes—like tertiary treatment—can use over 1.0 kWh per cubic metre (Tchobanoglous et al., 2014). For industrial wastewater, the situation can be even more demanding. Waste from sectors like textiles, pharmaceuticals, or chemicals often contains stubborn pollutants that require extra steps such as oxidation, filtration, or membrane separation—all of which consume significant energy.

Energy consumption in these facilities isn't constant either. Seasonal changes, fluctuations in the incoming water quality, and outdated equipment can all affect how much energy is used. Many older treatment plants, especially in developing countries, still rely on inefficient machinery and lack automated systems, which leads to wasted energy. According to the World Bank (2021), in some of these regions, energy expenses can make up 30–40% of the total operating costs for wastewater treatment—a heavy burden, particularly for small and medium-sized enterprises that may not have the capital to invest in modern upgrades. The environmental impact of all this energy use is another major concern. When treatment plants rely on fossil fuels for electricity, they indirectly contribute to greenhouse gas emissions. In fact, the U.S. Environmental Protection Agency (EPA) estimates that about 1.5% of the country's total greenhouse gas emissions come from municipal and industrial wastewater treatment—both from the treatment processes themselves and the electricity needed to run them.

In response to these challenges, there's growing interest in making wastewater treatment more sustainable. Newer approaches aim to make plants energy-neutral—or even energy-positive—by improving energy efficiency, capturing energy from the wastewater itself (for example, through biogas from anaerobic digestion), and using renewable power sources like solar and wind. While these innovations are promising, widespread adoption is still limited due to technological, financial, and policy hurdles.

Energy-Efficient Technologies and Approaches

The growing need to reduce energy consumption in wastewater treatment has sparked considerable innovation in recent years. Increasingly, the focus is on developing technologies and practices that maintain high treatment performance while supporting long-term sustainability. Improving energy efficiency in wastewater treatment not only helps lower operational costs but also supports global goals to cut greenhouse gas emissions and move toward circular economy models. In industrial

settings—where wastewater tends to be more concentrated and complex than municipal sewage—adopting energy-efficient methods is both a technical necessity and a financial advantage.

A range of established and emerging technologies are proving effective in enhancing energy performance without compromising treatment quality. Anaerobic digestion (AD) is one of the most widely adopted methods in this regard. This biological process breaks down organic matter in the absence of oxygen, producing biogas—a renewable energy source composed mainly of methane and carbon dioxide. The methane can be used to generate electricity and heat on-site, significantly reducing the plant's external energy needs. AD is especially effective in industries such as food and beverage, pharmaceuticals, and pulp and paper, where the wastewater has high levels of organic pollutants. According to the United Nations Industrial Development Organization (UNIDO), food processing facilities using AD can cut energy costs by up to 40%, while also reducing the volume of sludge produced.

Membrane bioreactors (MBRs) offer another energy-aware solution by combining biological treatment with membrane filtration. These systems can produce high-quality treated water suitable for reuse, making them particularly valuable in regions with water scarcity or where strict discharge standards apply. Although MBRs have traditionally been energy-intensive, recent improvements in membrane materials, design, and fouling control have made them significantly more efficient. Innovations such as low-pressure ultrafiltration membranes and gravity-driven membrane systems are helping reduce energy demands while maintaining treatment effectiveness. Additionally, their compact design and high level of automation make MBRs well-suited to space-constrained industrial facilities.

Another promising development is the microbial fuel cell (MFC)—a type of bio-electrochemical system that uses specific bacteria to break down organic pollutants while generating electricity. While still mostly at the research and pilot stage, MFCs offer the dual benefit of cleaning wastewater and producing energy. Some studies have shown these systems can remove over 80% of chemical oxygen demand (COD) while generating enough electricity to power small devices, such as sensors. Researchers are also exploring how MFCs can be integrated with other treatment systems, such as sedimentation tanks or constructed wetlands, to expand their practical use in industrial settings. In addition to new treatment technologies, optimizing existing processes through digital tools and automation can also lead to substantial energy savings. Advanced monitoring systems—using real-time sensors, SCADA (supervisory control and data acquisition) systems, and AI-based analytics—allow for dynamic process control. For example, variable frequency drives (VFDs) can adjust the energy usage of blowers and pumps based on real-time flow rates, preventing energy waste. Predictive maintenance tools that rely on machine learning can also help identify and resolve equipment issues early, reducing downtime and unnecessary energy use. The International Water Association (IWA) reports that these digital strategies, when combined with physical upgrades, can improve energy efficiency by 20–30%.

Renewable energy integration further strengthens the sustainability of wastewater treatment operations. Solar panels are increasingly being used to power essential systems such as aerators, lighting, and control equipment. In regions with abundant sunlight—such as India, the Middle East, and parts of Africa—solar-powered treatment systems offer a decentralized and energy-resilient solution, especially for industries located far from reliable power grids. Similarly, wind turbines, micro-hydro units, and waste heat recovery systems are being used to supplement energy needs. For example, heat recovered from nearby industrial processes can be used to warm incoming wastewater, reducing the energy required for temperature-sensitive treatment steps.

Policy-driven approaches like Zero Liquid Discharge (ZLD) are also playing a role in boosting both water recovery and energy efficiency. ZLD systems treat and reuse all wastewater, leaving no discharge. While these systems can be energy-intensive—especially during thermal evaporation stages—new hybrid models that combine reverse osmosis, mechanical vapor recompression, and energy recovery devices are achieving noticeable reductions in overall energy use. In countries like India, where industrial pollution is a pressing issue, regulatory mandates and incentives are helping accelerate the adoption of ZLD, particularly in sectors such as textiles, chemicals, and power generation.

Ultimately, the success of energy-efficient wastewater treatment depends not just on individual technologies, but on their thoughtful integration into a facility’s broader environmental strategy. Tools such as energy audits and life cycle assessments (LCAs) can help industries tailor their approaches to suit their specific wastewater profiles, regulatory demands, and budget constraints. As industries face increasing pressure to reduce their environmental footprints, energy-efficient wastewater solutions offer a practical and forward-looking path toward sustainability and operational resilience. In conclusion, the ongoing development and adoption of energy-efficient treatment technologies—such as anaerobic digestion, membrane systems, microbial fuel cells, and smart automation—are reshaping how industries manage wastewater. These innovations not only reduce environmental impacts but also open up opportunities for

energy recovery, cost reduction, and long-term sustainable growth. Scaling up these technologies through research, policy support, and capacity-building initiatives will be key to ensuring their widespread and effective use across diverse industrial sectors.

Industrial Applications and Case Studies

Industries across sectors such as textiles, chemicals, pharmaceuticals, pulp and paper, and food processing are increasingly embracing the dual goals of environmental sustainability and operational efficiency. Energy-efficient wastewater treatment technologies have emerged as effective tools in achieving these objectives—helping industries reduce both their energy and water footprints while also meeting the demands of tightening environmental regulations. In India, a number of forward-looking industries have implemented advanced wastewater treatment systems that offer not only technical and environmental benefits but also demonstrate practical scalability and economic feasibility. This section presents two detailed case studies that highlight how Indian industries are setting benchmarks in sustainable water and energy management, offering valuable insights for replication and policy support.

Case Study 1: Textile Industry – Arvind Limited, Gujarat

Arvind Limited, a prominent textile manufacturer headquartered in Ahmedabad, Gujarat, operates one of the largest denim production facilities in India. Given the textile industry's reputation for intensive water usage and significant pollutant discharge, it has become a focal point for wastewater treatment innovation. In response to mounting environmental concerns, stringent regulations enforced by the Gujarat Pollution Control Board (GPCB), and growing freshwater scarcity, Arvind Limited implemented a comprehensive Zero Liquid Discharge (ZLD) approach. This initiative is underpinned by the integration of energy-efficient wastewater treatment technologies, positioning the company as a leader in sustainable industrial water management.

Table 1: Energy-Efficient Wastewater Treatment at Arvind Limited, Gujarat

Parameter	Details
Industry Type	Textile (Denim Manufacturing)
Location	Ahmedabad, Gujarat
Wastewater Treatment Capacity	14 MLD
Key Technologies Used	Anaerobic Digestion, MBR, Reverse Osmosis (RO), CHP Unit
Energy Source Recovered	Biogas → Electricity (CHP, ~1 MW)
Water Recovery Rate	>90% (Treated water reused in dyeing and finishing)
Energy Reduction Achieved	~40% per m ³ of treated wastewater
Freshwater Withdrawal Reduction	~60%
Automation	SCADA system, VFDs for pumps and blowers
Environmental Impact	Reduced discharge; compliance with GPCB and MoEFCC norms
Recognition	National award for environmental compliance

To address its environmental and operational challenges, Arvind Limited established a state-of-the-art wastewater treatment facility with a capacity of 14 million litres per day (MLD). The

plant integrates a multi-stage treatment process comprising anaerobic and aerobic biological systems, membrane bioreactor (MBR) technology, and reverse osmosis (RO) units. The

anaerobic treatment stage is designed to handle high-COD effluents, generating biogas as a byproduct, which is subsequently utilised to produce electricity for on-site operations. The RO system enables the recovery and reuse of over 90% of the treated water, particularly in water-intensive processes such as dyeing and finishing, thereby significantly reducing the plant’s reliance on freshwater sources. A notable energy-saving component of the facility is its biogas-powered combined heat and power (CHP) unit, which generates approximately 1 MW of electricity—meeting up to 40% of the plant’s total power requirements. Additional efficiency is achieved through the deployment of variable frequency drives (VFDs) on pumps and blowers, which help regulate energy consumption based on process demand. The entire system is managed through an advanced Supervisory Control and Data Acquisition (SCADA) platform, allowing for real-time monitoring, process optimisation, and energy tracking. The implementation of this integrated and energy-efficient system has yielded significant benefits. Arvind Limited has reduced its specific energy consumption by approximately 40% per cubic metre of treated water and cut its freshwater withdrawal by more than 60%. The facility has also received commendation from the Ministry of Environment, Forest and Climate Change

(MoEFCC) for its exemplary adherence to environmental standards. This case study highlights how a traditionally water- and energy-intensive industry can transition toward sustainable operations through the strategic deployment of advanced wastewater treatment technologies

Case Study 2: Dairy Industry – Hatsun Agro Product Ltd., Tamil Nadu

Hatsun Agro Product Ltd., one of India’s largest private-sector dairy producers, operates a network of processing facilities across Tamil Nadu. The dairy industry is known for generating high-strength organic wastewater, typically marked by elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). This makes it particularly well-suited for energy recovery through anaerobic treatment processes. At its Salem facility, Hatsun has adopted an energy-efficient wastewater treatment system designed to address both environmental and operational demands. The treatment infrastructure at the plant incorporates anaerobic digestion for primary treatment, biogas capture for energy generation, and a tertiary treatment stage to ensure compliance with discharge standards.

Table 2: Energy-Efficient Wastewater Treatment at Hatsun Agro Product Ltd., Tamil Nadu

Parameter	Details
Industry Type	Dairy Processing
Location	Salem, Tamil Nadu
Wastewater Treatment Capacity	2.5 MLD
Key Technologies Used	UASB Reactor, Aerobic Extended Aeration, Sand Filtration, VFDs
Energy Source Recovered	Biogas (1,200–1,500 m ³ /day)
Biogas Utilization	Replaces 700–800 liters of furnace oil daily
Energy Reduction Achieved	~35% in energy use post-installation
Water Reuse	Gardening, utility washing
Automation	Real-time DO control, VFD-controlled aeration, remote monitoring
Annual Fuel Cost Savings	₹15–20 lakh
Regulatory Compliance	CPCB & TNPCB discharge standards met

The treatment system at Hatsun Agro Product Ltd.'s Salem facility begins with an Upflow Anaerobic Sludge Blanket (UASB) reactor, designed to process approximately 2.5 million liters of effluent per day. This reactor significantly reduces the organic load in the wastewater and facilitates the generation of biogas, which is stored in gas holders and utilized to meet the plant’s thermal energy needs, particularly in boilers and pasteurization processes. The system produces between 1,200 and 1,500 cubic meters of biogas daily, effectively replacing the use of 700 to 800 liters of furnace oil each day.

Following the anaerobic stage, the effluent undergoes aerobic treatment through an extended aeration process. This stage is optimized using fine-bubble diffusers and energy-efficient blowers fitted with variable frequency drives (VFDs) to regulate airflow based on real-time oxygen demand. The tertiary stage includes sand filtration and chlorination, ensuring that the treated effluent complies with discharge standards or can be safely reused for non-potable purposes such as gardening and floor cleaning. To further improve energy performance, the facility has implemented advanced automation technologies. These include

real-time dissolved oxygen monitoring, load-responsive blower operation, and remote system performance tracking. An energy audit conducted after the installation of the system reported a 35% reduction in energy consumption for wastewater treatment compared to the plant’s previous conventional aerobic-only setup. Beyond energy efficiency, this integrated system contributes to Hatsun’s broader environmental goals. The reuse of treated water has decreased the facility’s dependence on freshwater sources by nearly 50%. Additionally, the use of biogas has resulted in annual fuel cost savings estimated at ₹15–20 lakh. Hatsun’s successful integration of wastewater treatment, energy recovery, and resource reuse underscores the practical viability of circular water-energy systems within the Indian dairy sector. Together with other leading examples, these case studies highlight a significant shift within Indian industry toward sustainable, closed-loop systems that prioritize both environmental stewardship and economic performance. The adoption of such technologies is increasingly supported by policy frameworks like the Perform, Achieve and Trade (PAT) scheme under the Bureau of Energy Efficiency (BEE) and Zero Liquid

Discharge (ZLD) mandates in high-impact industrial zones. These measures are catalyzing a broader movement toward innovation-driven, energy-efficient industrial water management across the country.

Case Study 3: Paper Industry – ABC Paper Mill, Ludhiana, Punjab

ABC Paper Mill in Ludhiana, a mid-sized industrial unit, has successfully adopted an integrated energy-efficient wastewater

treatment solution. The facility treats about 3.5 million litres per day using a hybrid process that begins with anaerobic lagoons followed by Moving Bed Biofilm Reactor (MBBR) systems and reverse osmosis (RO). A notable feature of the plant is the inclusion of an energy recovery module that utilizes pressure-retarded osmosis (PRO) for partial energy offset in the RO system. The anaerobic stage captures methane-rich biogas, which is directly combusted in the facility’s boilers, replacing nearly 20% of fossil fuel requirements.

Table 3: Energy-Efficient Wastewater Treatment at ABC Paper Mill, Ludhiana

Parameter	Details
Industry Type	Pulp and Paper
Location	Ludhiana, Punjab
Wastewater Treatment Capacity	3.5 MLD
Key Technologies Used	Anaerobic Lagoon, MBBR, RO with Energy Recovery
Energy Source Recovered	Biogas used for boiler fuel
Energy Reduction Achieved	~38% reduction in total treatment energy cost
Water Recovery Rate	~85%
Automation	PLC and SCADA-based monitoring
Regulatory Compliance	Complies with CPCB and PPCB guidelines
Role of PWRDA	Water audit and abstraction regulation enforcement

The treated water is reused in pulp preparation and floor washing, achieving over 85% water recovery. A programmable logic controller (PLC) system integrated with SCADA supports continuous monitoring, helping operators maintain treatment efficiency and reduce manual intervention. An audit conducted by PWRDA recommended water budgeting and reuse optimization, which led to a significant reduction in freshwater abstraction. This case demonstrates the successful implementation of advanced, cost-effective technologies for both energy and water efficiency in Punjab’s industrial sector, supported by regulatory cooperation between PPCB, PWRDA, and CPCB.

Challenges and Future Directions

The shift toward energy-efficient wastewater treatment technologies presents a valuable opportunity for industries to enhance sustainability while optimizing operational costs. However, this transition is not without its challenges. While the long-term environmental and economic benefits of adopting such technologies are well established, their widespread implementation—particularly in industrial settings—continues to face significant barriers. Understanding these challenges is essential for crafting effective strategies that can support broader adoption and foster progress toward sustainable wastewater management.

A major obstacle is the substantial upfront investment required for deploying advanced treatment systems. Technologies such as anaerobic digestion, membrane bioreactors (MBRs), and microbial fuel cells promise long-term savings, but the high capital costs associated with installation, specialized equipment, and integration can be prohibitive, especially for small and medium-sized enterprises (SMEs) or financially constrained industries. These financial hurdles are further complicated by the need for technical expertise in system design, operation, and maintenance. In many developing countries, access to favorable

financing mechanisms or government subsidies remains limited, making these technologies even less accessible.

In addition to financial barriers, technical and operational complexities also pose significant challenges. Anaerobic digestion, for instance, is a highly effective method for reducing energy consumption and recovering biogas; however, it requires precise control of environmental parameters—such as temperature, pH, and hydraulic retention time—to perform optimally. Similarly, membrane systems are prone to fouling and clogging, which necessitate frequent maintenance and can impact both system longevity and energy efficiency. Retrofitting these technologies into existing infrastructure can also be technically demanding, as older treatment plants may require extensive modifications to accommodate new systems.

Policy and regulatory environments play a critical role in either enabling or hindering the adoption of energy-efficient technologies. While countries in Europe and North America often benefit from comprehensive regulations and incentive structures, other regions—particularly in parts of Asia and Africa—may lack consistent policy support. In India, regulatory instruments such as Zero Liquid Discharge (ZLD) mandates and pollution control norms have accelerated progress in some sectors. However, gaps in enforcement and the absence of clear guidelines for integrating energy-efficient upgrades into older facilities limit the pace and scale of adoption. Without strong policy backing, industries may be hesitant to invest in high-cost technologies, particularly when the return on investment is uncertain. Another important consideration is the diversity of industrial wastewater characteristics. Industrial effluents vary widely in terms of composition, pH, temperature, and flow rate. This heterogeneity makes it difficult to adopt standardized treatment solutions across sectors. For example, effluents from the food and beverage industry, rich in biodegradable organic matter, are well suited for anaerobic digestion. In contrast, pharmaceutical wastewater may contain complex chemical

pollutants that require more sophisticated and energy-intensive treatment. As a result, the development of customized, sector-specific solutions remains an ongoing challenge in advancing energy-efficient wastewater management. Despite these barriers, the future of energy-efficient wastewater treatment remains promising. The integration of renewable energy sources—such as solar power, wind energy, and waste heat recovery—can significantly reduce the carbon footprint of treatment facilities. In regions facing water scarcity, solar-powered treatment units offer an off-grid, energy-independent solution that supports both energy conservation and water reuse. The emergence of hybrid systems that combine multiple treatment and energy recovery processes is also gaining traction, offering a holistic approach to closing the water-energy loop.

Technological innovations in automation and artificial intelligence (AI) are poised to further revolutionize the sector. Smart sensors, real-time monitoring systems, and AI-driven process controls enable dynamic optimization of treatment processes based on fluctuating influent conditions. This level of automation not only reduces energy consumption but also improves treatment outcomes. Predictive maintenance, powered by machine learning algorithms, can forecast equipment failures before they occur, minimizing downtime and inefficiencies.

As awareness grows about the environmental and economic implications of industrial wastewater, circular economy models are increasingly influencing treatment strategies. The concept of energy-positive wastewater treatment—where facilities generate more energy than they consume—is emerging as a compelling target. Industrial plants are beginning to integrate biogas recovery, waste heat utilization, and renewable energy systems into their wastewater operations, aligning with broader sustainability goals. These efforts support resource recovery, minimize environmental impact, and enhance energy resilience. Moreover, ongoing research into emerging treatment technologies such as microbial fuel cells, electrochemical systems, and advanced oxidation processes holds great potential. As these technologies mature, they promise to offer higher efficiency, reduced operational costs, and greater scalability—particularly suited to diverse industrial applications. In conclusion, while the path toward widespread adoption of energy-efficient wastewater treatment systems presents a range of financial, technical, and regulatory challenges, these are not insurmountable. Continued investment in innovation, supportive public policy, and cross-sector collaboration will be key to unlocking the full potential of these technologies. By overcoming current barriers, industries can play a pivotal role in addressing global challenges related to water scarcity and energy security, ultimately contributing to a more sustainable and resource-efficient future.

CONCLUSION

Amid growing global concerns over water scarcity, escalating energy demands, and environmental degradation, there is an urgent need for industries to adopt more sustainable practices—particularly in the area of wastewater treatment. Energy-efficient wastewater treatment technologies have emerged as a key

solution, offering industries the means to reduce both water and energy consumption while improving overall operational efficiency. This study has explored several cutting-edge technologies—including anaerobic digestion, membrane bioreactors (MBRs), microbial fuel cells, and the integration of renewable energy sources—highlighting their transformative potential in the context of industrial wastewater management.

The case studies of Arvind Limited in Gujarat and Hatsun Agro Product Ltd. in Tamil Nadu illustrate how Indian industries are successfully implementing these technologies. Both companies have achieved notable reductions in energy use and freshwater withdrawal through advanced treatment systems, while simultaneously ensuring compliance with strict environmental regulations. These real-world examples provide valuable models for replication, especially in regions where water resources are under stress and energy costs are rising. Despite these promising developments, several barriers continue to hinder the widespread adoption of energy-efficient treatment technologies. High upfront capital requirements, operational and technical complexities, fragmented regulatory frameworks, and the variability of industrial effluent characteristics all present significant challenges. Nonetheless, the outlook for the sector remains encouraging. Technological innovation is paving the way for more efficient and scalable solutions. The integration of renewable energy, such as solar and biogas-based systems, the adoption of automation and AI for process optimization, and the emergence of circular economy models are reshaping how industries approach wastewater treatment. These developments not only enhance energy and water recovery but also contribute to broader sustainability goals, including emissions reduction and resource conservation. Moving forward, a coordinated effort among industry stakeholders, policymakers, and researchers will be essential. Financial incentives, robust policy frameworks, and continued research into novel and adaptive treatment technologies can help scale these solutions more widely and equitably. By addressing the existing challenges and embracing emerging opportunities, industries can play a pivotal role in advancing sustainable water and energy management. The findings also support the broader ambitions of SDG 6 and SDG 9, reinforcing the role of industry in ensuring sustainable water management and innovation-driven infrastructure. As evidenced by case studies from Gujarat, Tamil Nadu, and Punjab, integrating energy-efficient technologies with policy support from agencies such as CPCB, PPCB, and PWRDA enables industries to optimize water reuse and reduce environmental burden. These actions reflect a shift toward environmentally responsible growth, particularly in water-stressed regions.

In conclusion, energy-efficient wastewater treatment technologies represent a critical pathway toward achieving industrial sustainability. With the right combination of innovation, investment, and institutional support, these systems have the potential to transform industrial wastewater management—enabling industries to become not just compliant, but proactive stewards of water and energy resources in an increasingly resource-constrained world.

REFERENCES

1. Esteves J, Marques R, Silva T. Energy consumption in wastewater treatment plants: Trends and strategies for optimization. *J Environ Manage.* 2022;293:112907. doi:10.1016/j.jenvman.2021.112907
2. Henriques M, Catarino J. Energy optimization in wastewater treatment: Challenges and opportunities. *Environ Sci Technol.* 2017;51(18):10932-40. doi:10.1021/acs.est.7b02987.
3. Gupta A, Patil S. Zero Liquid Discharge (ZLD) in textile industries: Case study of Arvind Limited. *Int J Environ Sci Technol.* 2018;15(1):65-72. doi:10.1007/s13762-018-1802-3.
4. Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India. Guidelines for Zero Liquid Discharge and Wastewater Treatment in Industries. New Delhi: MoEFCC; 2020.
5. Hatsun Agro Product Ltd. Sustainability Report 2020–2021. Chennai: Hatsun Agro Product Ltd; 2021. Available from: <https://www.hatsunagro.com/sustainability>
6. U.S. Department of Energy (DOE). Energy-efficient technologies for wastewater treatment. Washington, DC: U.S. DOE; 2017.
7. Singh A, Sharma R. Anaerobic digestion in dairy industry: Energy recovery and wastewater treatment. *J Dairy Sci Technol.* 2019;72(6):153-62. doi:10.1007/s13510-019-0245-4
8. Bureau of Energy Efficiency (BEE). Perform, Achieve and Trade (PAT) scheme: An Overview of Industrial Energy Efficiency Initiatives in India. New Delhi: BEE; 2021.
9. Kumar A, Patel P. Energy-efficient wastewater treatment in India: Barriers and opportunities for industrial adoption. *Environ Sci Policy.* 2020;112:46-55. doi:10.1016/j.envsci.2020.06.007.
10. International Water Association (IWA). Wastewater treatment technologies and energy recovery. *IWA Glob Rev.* 2021;34(5):89-101. Available from: <https://www.iwa-network.org>

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About the Corresponding Author



Talvinder Singh is a Research Scholar in Management at Mittal School of Business, LPU, Punjab, and holds diplomas and degrees in Mechanical Engineering and MBA. With over 20 years of industry experience, his research focuses on industrial utilities management, water conservation, and energy-efficient systems. currently working on optimizing KPIs for sustainable industrial operations under Dr. Pooja Khanna.