



Water Innovation Trends

Wastewater Treatment & Reuse

Foreword



Eng. Abdulrahman Abdulmohsen AlFadley
His Excellency Minister of Environment, Water, and Agriculture

The Kingdom’s leadership believes in the importance of research and innovation to build a knowledge economy and achieve true diversification of the state’s resources, especially in the vital, priority sectors of environment, water, and agriculture. The Ministry of Environment, Water, and Agriculture aims to enable partners across the innovation ecosystem to stimulate and localize technologies to provide effective sustainability solutions within the Ministry’s sectors.



Eng. Mansour bin Hilal Al Mushaiti
His Excellency Vice Minister of Environment, Water, and Agriculture

Innovation has been a fundamental pillar in the success of the water sector in the Kingdom. It laid the foundation for our journey towards sustainability and strengthened the Kingdom’s global position in efficiently managing its water resources. This progress has been achieved through the support and empowerment of our wise leadership, the dedication of our passionate national talents, and our commitment to innovation and continuous improvement, in pursuit of our ambitious goals for a more sustainable future.



Eng. Abdullah Ibrahim Al-Abdul-Karim
His Excellency President of the Saudi Water Authority

In light of global challenges related to water and the growing demand, the water sector in Kingdom of Saudi Arabia today stands as a pillar of innovation—viewed not just as a strategic advantage but as a fundamental necessity.

From this perspective, the sector has adopted a forward-looking approach centered on innovation, considering it as a key driver toward achieving sustainability, enhancing operational efficiency, and enabling adaptability to future changes transforming challenges into promising opportunities.

This report aims to emphasize that innovation in the sector is not merely a theoretical luxury, but an institutional practice grounded in values and closely aligned with Kingdom’s ambitious vision of becoming a pioneering, knowledge-based society. It represents a clear pathway to opportunities, empowering innovation, and fostering the uncovering growth of both national and global partnerships.



Dr. Abdulaziz bin Muharib AlShaibani
Deputy Minister of Water

The Kingdom faces various water challenges in meeting the rising demand for water, as a result of the economic and social development, and the scarcity of natural water sources, this necessitates a collaborative effort to integrate effective water resource management to ensure sustainability, in alignment with the objectives of Saudi Vision 2030. Driven by the importance of innovation and modern technologies in enhancing water security, this report presents an overview of the key technological trends in the water sector, aiming to accelerate the adoption of innovative, integrated and effective solutions.



Dr. Abdulaziz bin Malik Al-Malik
Deputy Minister for Research and Innovation

The adoption of technologies and innovation in the water sector represents a key pillar in achieving the Kingdom’s water security objectives. The Ministry works to support the adoption of modern technologies through the development of the research and innovation ecosystem. This report aims to present key technological trends and identify solutions whose adoption will contribute to enhancing efficiency and sustainability in this vital sector.

About the report

The strategic direction of the sectoral innovation system requires continuous and extensive monitoring of the most important technology and innovation trends to enable stakeholders from various sectors to optimize their policies and plans to deal with an increasingly complex and competitive world, both technologically and economically. The Ministry of Environment, Water and

Agriculture established the NPRAS Platform, a platform that enables the use of monitoring and technical survey tools and methodologies to guide the innovation system in the environment, water and agriculture sectors to focus on technologies and innovations with the greatest sectoral potential.

This report is part of a series of periodic sectoral reports issued by NPRAS Platform, dedicated to tracking and analyzing innovation trends in the sectors of environment, water, and agriculture. This report specifically focuses on the water sector by taking an in-depth look at one of the

five technology priority groups with good potential across the value chain of the sector, providing insights into trends, developments, and opportunities that are shaping the future of the water sector.



This series aims to achieve several aspects:



Raising stakeholder awareness of emerging technologies, market dynamics, best practices, and global policies related to innovation in the environment, water, and agriculture sectors.



Accelerating efforts to localize and deploy water technologies by highlighting the most ready technologies that can enhance the efficiency and sustainability of the water sector.



Enable strategic decision-making by providing policymakers, industry leaders, and investors with data-driven insights to guide innovation initiatives.

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Executive Summary

- To ensure the report scientific rigor and practical relevance of its findings, the report — published by the NPRAS Platform— has been reviewed by subject matter experts and industry professionals. The report begins with an overview of the challenges faced by the water sector and emphasizes the importance of one technology priority group: **Wastewater Treatment & Reuse**. This technology priority group is included under the **Wastewater Treatment & Reuse** phase of the water value chain (refer to page 12) It focuses on purifying used water to remove contaminants, enabling its safe application in groundwater recharge. By conserving freshwater and transforming wastewater into a reliable resource, this approach supports sustainable development, enhances water security and climate resilience, reduces pollution, promotes the circular economy, lowers operational costs, and boosts infrastructure efficiency.
- Building on this foundation, the report follows a rigorous, three-stage methodology aligned with global best practices—specifically the **OECD Framework for Anticipatory Governance**—ensuring that its insights are not only robust and in-depth but also actionable for driving innovation and policy development.
- The first stage in the OECD framework is systematic monitoring, where the NPRAS Platform tracks **10,000+ sources** (scientific publications, patents, industry reports, and news) with **100M+ data points**, updated twice daily to identify signals of high-interest technologies. The second stage is technology trend analysis, where technologies are evaluated for momentum, innovation maturity, and relevance to national water challenges. Moreover, redundancy is removed by clustering similar innovations. The final stage is technology assessment. Where rapidly evolving, high-impact technologies are selected and then examined in greater depth to assess their strategic significance and inform relevant policy decisions.
- Additionally, to prioritize RDI investments, the report examines key shifts across the water sector’s social, economic, and political spheres. In Wastewater Treatment & Reuse, six major trends are shaping 2024*
 - Prolonged Droughts and Record Temperatures
 - Industrial Adoption of Water Recycling Technologies
 - Investments in Digital Technologies
 - Infrastructure Upgrades and Capacity Expansions
 - Strengthened Regulatory Frameworks
 - Regulations on Micropollutant Mitigation
- The report will highlight the key technology segments within the wastewater treatment landscape, detailing the most relevant technologies in each segment. A chart will assist in selecting the top technologies, with each one assessed based on Technology Readiness Levels (TRL), ease of implementation, and potential impact. The following five key selected technologies represent the top choices within each technology segment:
 - **Algal Turf Scrubber (ATS)** from the Biological Treatment segment
 - **Nanobubbles** from the Electrochemical & Catalytic Treatment segment
 - **Zero Liquid Discharge (ZLD)** from the Membranes & Filtration segment
 - **Thermal Hydrolysis** from the Resource Recovery & Energy Generation segment
 - **AI-Driven Treatment Optimization Methods** from the Digitalization & Decentralization segment

- In the following Technology Spotlight section, the report delves into detailed insights for each selected technology, highlighting key players, case studies, Market Readiness Level (MRL), Technology Readiness Level (TRL)*, and expected impact. Notable emerging solutions, such as real-time monitoring systems and digital twins, are explored in depth, supported by relevant case studies and trend analyses.
- The **selection criteria** used for scoring the five technologies are based on the technology chart described earlier. The three criteria are:
 - Technology Readiness level (TRL)
 - Potential Impact
 - Increase in Signals
- In conclusion, the report incorporates insights gathered from interviews with innovation leaders in the private sector, providing an overview of key priorities. These insights collectively serve as a guiding framework for policymakers, industry leaders, and investors to foster innovation and advance sustainable water management in alignment with Vision 2030.



*Technology Readiness Levels (TRL) are defined in the glossary section.

*2024 refers to the complete calendar year.

Introduction

Technology and innovation are essential to achieving Saudi Arabia's national water sector goals, enhancing security, sustainability, and efficiency. Recognizing the need for transformative solutions, the Kingdom is accelerating the adoption of emerging technologies to address critical challenges and unlock new opportunities. Building on the previous Water Sector Innovation in Saudi Arabia report—which identified 20 technology groups—this edition hones in on one technology priority group with high-impact within that broader landscape. This focus area address both the challenge of water loss within distribution networks and the opportunity to recover and repurpose water through advanced treatment and reuse, aiming to accelerate the adoption of transformative solutions in the sector. The report highlights six major technology sectoral trends shaping 2024, with a focus on water conservation as a critical priority. Currently, companies worldwide are increasingly aware of the financial risks associated with water-related challenges, driving greater investment in sustainable water management solutions.

One of the most significant developments is the rapid adoption of [smart metering, which is expanding globally and is expected to reach a market value of \\$7.36 billion by 2031](#). Governments are also stepping up their efforts, with major investments in water infrastructure—such as the \$11.5 billion U.S. water infrastructure upgrade—to modernize and enhance utility systems.

Key technological innovations driving this transformation include real-time monitoring systems, AI-driven analytics, digital twin platforms, and self-adapting water networks. These advancements are revolutionizing the way water resources are managed, making systems more efficient and resilient.

In line with these global trends, Saudi National Water Strategy aims to significantly reduce reliance on non-renewable water sources. Another strategic goal is lowering water production costs by 2035, underscoring the Kingdom's strong commitment to sustainable and efficient water management. These initiatives reflect a growing global shift toward smarter, more efficient water management solutions that balance economic and environmental priorities.

This report is designed to provide structured insights into water innovation trends and emerging technologies in Saudi Arabia. It begins with an overview of key national challenges in the water sector, followed by an analysis of technological advancements and strategic opportunities.

The report is divided into sections that explore and highlights emerging technologies, their implementation feasibility, and potential impact. **Readers can navigate through expert analyses, case studies, and sectoral trends, ensuring a comprehensive yet accessible understanding of the innovations shaping Saudi Arabia's water future.** Each section is crafted to support policymakers, industry leaders, and stakeholders in making informed decisions that align with vision 2030's water sustainability goals.



Scope of the Report [1/3]

The focus of this report covers “**Wastewater Treatment & Reuse**”, exploring emerging trends and technologies in it. The report evaluates its strategic relevance, technological readiness, and potential impact on the Kingdom’s water sector, providing actionable insights to drive innovation and sustainability.

Target Audience:

This report is developed for the key stakeholders driving the transformation and sustainability of Saudi Arabia’s water sector.



Leaders and Decision Makers

Senior officials and executives within Saudi ministries, authorities, and government-affiliated organizations who shape national strategies and lead sustainability initiatives across the Environment, Water, and Agriculture (EWA) sectors.



Policymakers

Government officials and advisors responsible for formulating water-related policies and regulations in line with Saudi Arabia’s Vision 2030, national priorities, and regional development plans.



Investors

Public and private sector stakeholders—including sovereign funds, local investment firms, and strategic partners—committed to financing innovative, high-impact water technologies and infrastructure projects within the Kingdom.



Researchers and Scientists

Experts from Saudi universities, research centers (such as KAUST and KACST), and specialized institutes driving R&D to advance sustainable water solutions tailored to the Kingdom’s unique environmental context.



Innovators and Entrepreneurs

Saudi-based startups, incubators, and technology developers creating localized, scalable innovations to address water scarcity, reuse, and efficiency challenges in alignment with national goals.

The report outlines key advancements in **Wastewater Treatment & Reuse** technology priority group and presents data on the economic and environmental impact of water loss, emphasizing the need for targeted investments and regulatory frameworks. These insights align with Saudi Arabia’s efforts under Vision 2030, reinforcing the importance of technology adoption and strategic planning to enhance national water security.

Saudi Arabia’s water sector faces a series of interconnected challenges across its value chain, from supply and transmission to distribution, wastewater treatment, and demand management. The Kingdom’s reliance on desalination and limited renewable water sources highlights the need for innovative solutions to optimize resource use, reduce costs, and enhance

sustainability. Critical challenges include high energy demands for water production, significant distribution losses, insufficient wastewater reuse, and increasing urban and industrial water consumption. These issues require targeted technological interventions to achieve the sustainable water management goals outlined in Vision 2030.

This report provides a detailed analysis on one of the technology priority groups. It provides an in-depth analysis of **Wastewater Treatment & Reuse** which fall under the **Wastewater Treatment & Reuse** phase.

1

Wastewater Treatment and Reuse
Increasing the reuse of treated wastewater to reduce reliance on non-renewable water sources.



Scope of the Report [2/3]

Strategic Benefits and Alignment with National Goals

In alignment with the national goals, this report focuses on **Wastewater Treatment & Reuse**, a significant technology priority group that plays a critical role in enhancing water efficiency, reducing losses, and promoting sustainability.

The selection is driven by the **impact it has on the sector and on the broader water ecosystem**, ensuring a **holistic approach** to water resource management where the following are strategic benefits and alignment with national goals for it:

In the pursuit of sustainable water management, it is essential to address challenges. Wastewater treatment is playing a transformative role in this effort. It is targeting different yet complementary aspects of the water cycle.

The following sections explore how these technologies contribute individually to enhancing water efficiency and reliability.



Wastewater Treatment & Reuse [Wastewater Treatment & Reuse]

- **Sustainability & Water Security:** Saudi Arabia is actively advancing its circular water economy, where wastewater treatment and reuse play a pivotal role in securing alternative water sources for agricultural, industrial, and urban applications.
- **Technological Advancements & Investment Potential:** Innovations in wastewater treatment, such as **advanced filtration, energy-efficient treatment systems, and resource recovery**, present significant opportunities for **scalability and deployment**.



Addressing Key Challenges Across the Water Value Chain

- **Wastewater Treatment & Reuse** directly contributes to **closing the water loop** by improving wastewater infrastructure, increasing treatment efficiency, and expanding the use of **treated wastewater as a sustainable alternative water source**.



Accordingly, **5 technologies segments** were listed to further go in-depth of this edition:

- | | |
|--|--|
| 1 Biological Treatment | 2 Electrochemical & Catalytic Treatment |
| 3 Membranes & Filtration | 4 Resource Recovery & Energy Genera |
| 5 Digitalization & Decentralization | |

Scope of the Report [3/3]

Value Chain	Supply	Transmission & Storage	Distribution	Wastewater Treatment & Reuse	Demand
Technology Priority Groups	Advanced reverse osmosis	Smart leakage management		Wastewater treatment & reuse	Innovative irrigation Innovative water consumption in homes
Challenges and Opportunities	Reduce production energy and major costs	Reduce transmission cost	Improve network coverage	Improve wastewater network	Reduce urban water consumption levels (LCD)
	Optimize environmental impact of desalination	Increase number of storage available days	Reduce distribution losses	Improve wastewater treatment	Reduce industrial water consumption levels
	Increase non-renewable water sources		Ensure uninterrupted and reliable water supply	Increase use of treated wastewater	Reduce use of non-renewable water sources (agri. water consumption)
	Improve preservation of groundwater quality				

The process to gather intelligence on technologies and compile the report consists of a three-staged approach – following established practices such as the [OECD Framework for Anticipatory Governance of Emerging Technologies](#).

Systematic Monitoring

The NPRAS Platform tracks 10,000+ sources (scientific publications, patents, industry reports, and news) with 100M+ data points, updated twice daily to identify signals of high-interest technologies.

Technology Trend Analysis

Technologies are assessed based on the speed of change, frequency of mentions, funding trends, and innovation milestones to gauge their development momentum.

Strategic Technology Assessment

High-impact technologies undergoing rapid evolution are selected for deeper analysis to determine strategic relevance and policy implications.

*“Innovation in the Water Sector in Saudi Arabia - Technology Adoption Roadmap“ 2024

Methodology

Specifically, the content of this report is based on a three-stage process for analyzing technology signals.

1. Signal Collection & Technology Identification

Considering established practices, such as the Framework for Anticipatory Governance of Emerging Technologies (OECD 2024), the first analysis step involved the systematic collection and evaluation of signals to identify relevant technologies. To achieve this, the team employed a scanning method that combines the advantages of human expertise and machine intelligence, utilizing a signals database that contains over 100 million data points (e.g., patents, industry reports, scientific publications, etc.). Over the past five years, about 27,000 signals related to Wastewater Treatment and Reuse were sourced. Using Retrieval-Augmented Generation (RAG) AI and human expert validation, a longlist of 132 distinct technologies mentioned in Wastewater Treatment and Reuse was compiled for in-depth analysis.

2. Technology Assessment & Landscape Creation

In the second step, a comprehensive technology landscape was created from the longlist of the technologies mentioned in the signals. First, all technologies were eliminated that can no longer be considered as emerging, i.e., which have already entered mainstream adoption in relevant markets – e.g., “Smart Water Meters”. In addition, conceptual overlap among the technologies was minimized by subsuming similar or idiosyncratic technologies (e.g., “Robotic Sensors”, “Free-Swimming”, and “Untethered Systems”). Finally, the technologies were clustered into technology segments based on the purpose of use and functional characteristics.

Finally, all technologies included in the landscape were evaluated on maturity level, impact potential, and ease of implementation following the criteria outlined in the [MEWA Water Technology Adoption Roadmap](#).

3. Detail Analysis & Spotlight Selection

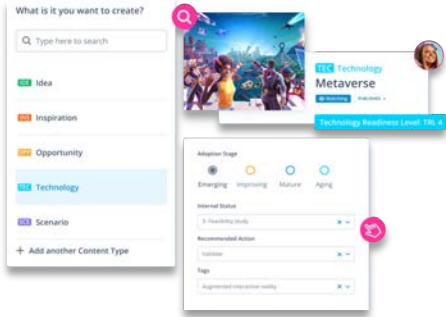
In the final step, the signals for each technology were examined in detail. Based on this, technology descriptions covering information such as global key players, current state of adoption, development outlook, and relevant case studies were created. In this report, one technologies in each of the identified segments were selected to be presented as a spotlight in this report. The selection was done by an assessment of the combination of three criteria (technology maturity, impact potential in Saudi Arbia, and the growth in the number and impact of signals throughout 2024). The rationale of this approach was to select highly-promising technologies with considerable advancements made in the past year.

The analyses leading to this report were conducted during the first iteration of MEWA’s NPRAS Platform – an AI-enhanced Innovation Operating System that enables the systematic scouting of technology signals, the continuous tracking of emerging technologies and innovation efforts, and the creation and continuous updating of comprehensive technology databases across various fields of innovation.



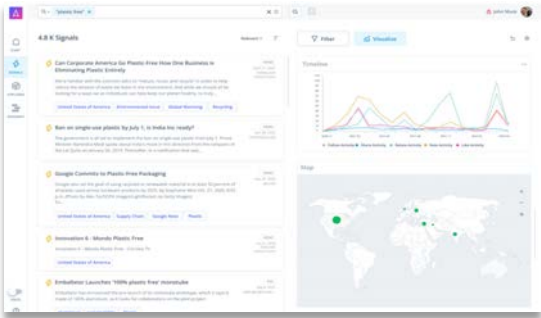
Technology Radar

In an interactive, visual radar view, emerging technologies can be analyzed and their relevance, maturity level (TRL), and application potential assessed. The Technology Radar helps identify new develop-ments early, strategically prioritize innovation fields, and continuously monitor technology trends.



Collaborative Evaluation

The platform enables a structured, collaborative evaluation of emerging technologies. The involvement of various experts minimizes subjective assessments and facilitates the efficient identification of innovation opportunities and risk evaluation.



Automated Monitoring

The platform's scouting function utilizes AI-powered analytics to continuously capture technological developments from various sources such as scientific publications, patents, industry reports, and news. Through intelligent filters and algorithms, relevant signals are identified, categorized, and updated in real time.

03

TECHNOLOGY PRIORITY GROUPS



Water Sector Challenges and Opportunities

The water sector vision statement states:

“A sustainable water sector that develops and preserves water resources, protects the environment, provides a secure supply and high-quality services, and efficiency contributes to economic and social development”

Investing in research, development, and innovation within the water sector is essential to overcoming both global and national challenges. Achieving sustainable water management requires a strategic focus on technologies that address country-specific priorities, while also fostering collaboration across public and private sectors. To succeed, ongoing monitoring of national and global trends, technological advancements, and evolving needs is critical. By aligning policies and innovation efforts, Saudi Arabia can drive impactful change across the water value chain. As outlined by RDIA, [the national goal is to reduce reliance on non-renewable water sources and decrease water production costs by the year 2035.](#)

Value Chain	Supply	Transmission & Storage	Distribution	Wastewater Treatment & Reuse	Demand
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	Increase non-renewable water sources		Ensure uninterrupted and reliable water supply	Increase use of treated wastewater	Reduce use of non-renewable water sources (agri. water consumption)
	Improve preservation of ground water quality				

Technology Priority Group focus for this edition

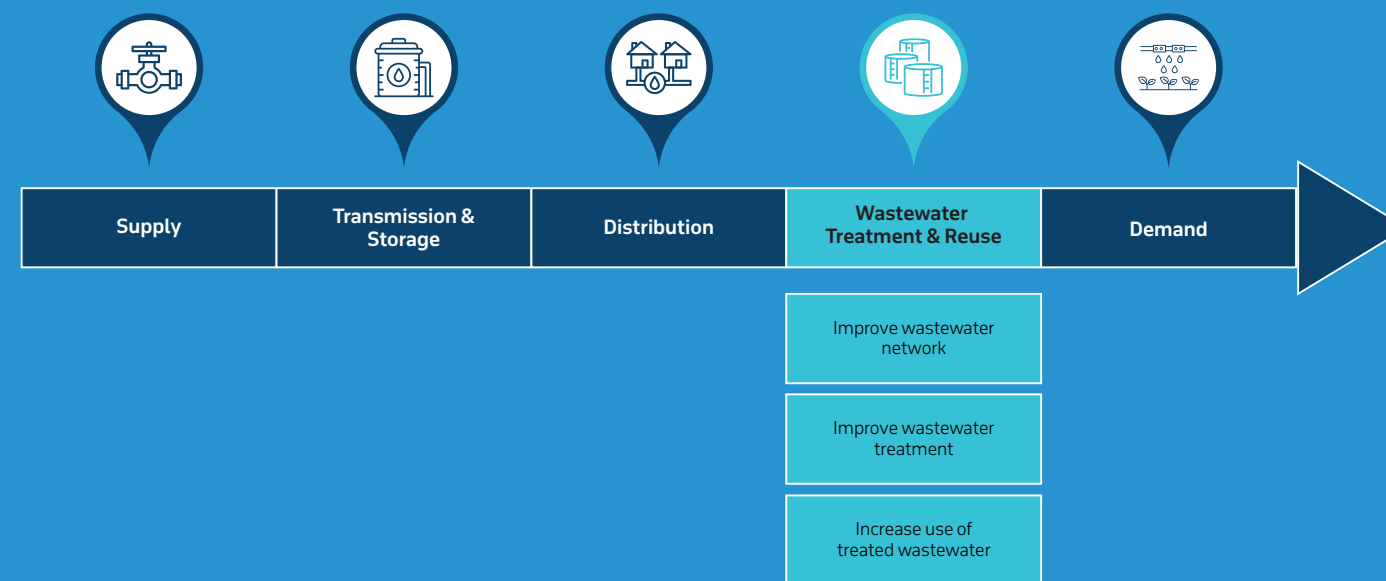
Value chain source: “Innovation in the Water Sector in Saudi Arabia - Technology Adoption Roadmap” 2024



TECHNOLOGY PRIORITY GROUP FOCUS

3.1 WASTEWATER TREATMENT & REUSE

The “Wastewater Treatment & Reuse” addresses wastewater challenges by leveraging solutions such as large-scale soil filters, hybrid Constructed Wetlands , and Enzyme-based treatment. This technology priority group can reduce water loss and lower associated costs.





Wastewater Treatment and Reuse

Wastewater treatment and reuse involve the process of treating wastewater to remove contaminants, making it suitable for various applications such as agricultural irrigation, industrial processes, and groundwater replenishment.

This practice plays a crucial role in conserving freshwater resources, protecting ecosystems, and enhancing water security, especially in arid regions. By reusing treated wastewater, the demand for freshwater is reduced, supporting sustainable water management.

Additionally, it contributes to environmental protection by preventing pollution, improving water quality, and restoring natural habitats. From an economic perspective, industries benefit from cost savings by reducing water procurement expenses and ensuring compliance with environmental regulations. Furthermore, wastewater reuse provides a reliable alternative water source, increasing resilience against climate challenges such as droughts.

Saudi Arabia has set an ambitious goal to achieve 100% reuse of treated urban wastewater by 2025, repurposing it for irrigation, industrial applications, and urban green spaces. This initiative is a key component of the Saudi's National Water Strategy and Vision 2030, aiming to enhance water sustainability and reduce reliance on non-renewable water sources.

Reusing treated wastewater plays a crucial role in optimizing water resource allocation. By redirecting high-quality treated effluent for non-potable uses—such as irrigating parks, landscaping, and agricultural fields—it

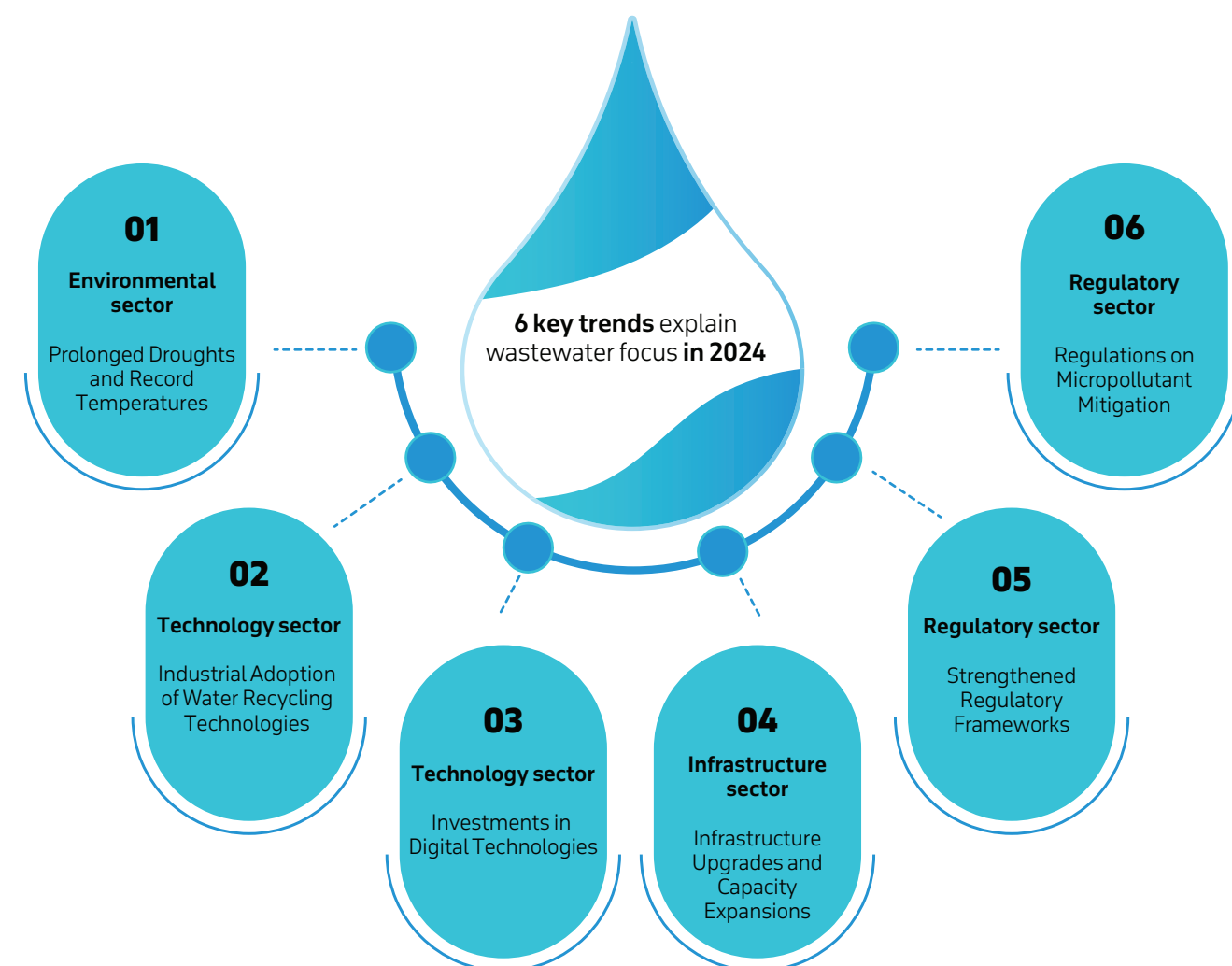
reduces the demand on limited freshwater sources. This approach allows freshwater to be preserved for essential domestic and industrial uses, while reclaimed water supports green infrastructure and food production.

As global water scarcity intensifies, integrating wastewater treatment and reuse into water management strategies is essential for sustainability, resource efficiency, and long-term environmental stewardship.

Sectoral Trends [1/3]

To identify technological opportunities and prioritize RDI investments, a **clear understanding of the broader sectoral context is essential**. Analyzing current trends in the water sector reveals shifts across social, economic, and political spheres, **shaping the landscape in which emerging technologies take root**. Navigating this evolving environment is key to anticipating and preparing for future developments.

In the context of Wastewater Treatment & Reuse, **six key trends stood out in 2024** either accelerating ongoing advancements or introducing new directions for change. Building on the technology landscape outlined above, this section highlights the most notable trends observed. The six trends in wastewater treatment and reuse span the environmental, technology, regulatory, and infrastructure sectors.





Sectoral Trends [2/3]

PROLONGED DROUGHTS AND RECORD TEMPERATURES

Driving the need of water treatment and reuse

In 2024, **NOAA* measured unprecedented heat**, with global temperatures [averaging 1.29°C above the 20th-century norm](#), marking it the hottest year since records began in 1850. This extreme heat led to severe droughts, [adversely affecting local ecosystems and economies](#). These prolonged droughts and soaring temperatures have intensified the need for effective wastewater treatment and reuse as **traditional water sources decline** and the demand for sustainable water management solutions

grows. Spain sought EU approval to redirect over €1 billion of recovery funds to enhance Valencia's climate resilience, [focusing on improving water systems and developing desalination plants after severe floods](#). In the USA, unusual dry falls prompted experts to advocate for long-term changes, including [increased groundwater replenishment and wastewater reuse](#), to prevent severe water shortages.

National Signal

The Saudi Irrigation Organization (SIO) announced 96 new projects to expand treated wastewater reuse across agriculture, urban, and industrial sectors, reducing freshwater reliance. This initiative strengthens climate resilience, ensuring water security amid intensifying heatwaves. [Smart Water Magazine](#)

INDUSTRIAL ADOPTION OF WATER RECYCLING TECHNOLOGIES

Showing signs of a global surge in the late 2020s and 2030s

In 2024, **industrial adoption of water recycling technologies was accelerating**, with the [global water recycle and reuse market valued at \\$18.3 billion and projected to grow at a 12.1% CAGR through 2034](#). Industries are increasingly implementing advanced water reuse systems to address water scarcity and environmental concerns. For instance, Amazon Web Services plans to

quadruple its data centers using recycled water in the U.S., [aiming to utilize 800 million gallons annually by 2030](#). Various industries, including semiconductors, mining, and plastics have seen a significant surge [in requests for high recovery systems and Zero Liquid Discharge \(ZLD\) solutions over the past two years](#), driven by regulatory pressures and the imperative to minimize risk.

National Signal

The National Water Company (NWC) launched six Public-Private Partnership (PPP) projects in 2024. These initiatives aim to expand non-agricultural municipal and industrial water reuse, strengthening sustainability and reducing reliance on freshwater. [Smart Water Magazine](#)

INVESTMENTS IN DIGITAL TECHNOLOGIES

Picking up speed in the water treatment sector

In 2024, the water treatment sector was experiencing a **significant surge in investments in digital technologies**. North America alone is projected to allocate [US\\$169.5 billion towards digital water solutions between 2024 and 2033](#). This trend encompasses the [adoption of automation, IoT, and data analytics to enhance the efficiency and sustainability of wastewater treatment](#)

[plants \(WWTPs\)](#). For example, the implementation of digital twins—virtual replicas of physical systems — has demonstrated a [return on investment within 2 to 3 years by optimizing plant performance and reducing maintenance costs](#).

National Signal

Saudi Arabia is accelerating investments in digital technologies for water treatment with the launch of the International Water Research Center. This initiative focuses on water economics, pollution control, and digital monitoring systems, reinforcing the Kingdom's commitment to smart water treatment. [Saudi Press Agency](#)



*NOAA (National Oceanic and Atmospheric Administration) is a scientific agency within the U.S. Department of Commerce responsible for monitoring and managing oceanic, atmospheric, and climate-related activities. NOAA conducts research, provides weather forecasts, tracks environmental changes, and supports conservation efforts to protect marine ecosystems.



Sectoral Trends [3/3]

INFRASTRUCTURE UPGRADES AND CAPACITY EXPANSIONS

Paving the way for technological innovation

In 2024, **global investments** in wastewater infrastructure upgrades and capacity expansions **have surged**, paving the way for technological innovation. The U.S. Environmental Protection Agency (EPA) reported that [\\$630 billion is needed over the next two decades to modernize wastewater systems, a 73% increase from 2012 estimates](#). Similarly, European countries are projected to invest [approximately US\\$476 billion in water and wastewater infrastructure between 2024 and 2030](#). This substantial investment aims to renew aging systems, reduce non-renewable water, and integrate smart technologies for enhanced monitoring and control.

National Signal

In 2024, the **National Water Company [NWC]** completed 118 water and sanitation projects across the Kingdom, investing over SAR 5.57 billion (\$1.48 billion). These projects expanded wastewater treatment capacities by 478,000 cubic meters per day and constructed a combined storage capacity exceeding 250,000 cubic meters, benefiting approximately 1.8 million residents. [NWC](#)

STRENGTHENED REGULATORY FRAMEWORKS

Enhancing Global Regulations for Cleaner Water and Sustainable Reuse

In 2024, global **regulatory bodies intensified efforts to enhance wastewater management** through strengthened frameworks. The European Union revised its [Urban Wastewater Treatment Directive](#), mandating advanced treatments to remove pollutants like nitrogen, phosphorus, and microplastics by 2039. This initiative aims to achieve the 'Zero Pollution' ambition, ensuring cleaner water bodies and improved public health. In the United States, the Environmental Protection Agency's (EPA) [Water Reuse Action Plan \(WRAP\)](#) aim to advance water reuse planning and implementation across the country.

National Signal

The **Saudi Water Partnership Company (SWPC)** unveiled a comprehensive seven-year plan (2024-2030) to enhance wastewater treatment capacities. This strategy aims to increase the national wastewater network coverage from 64% to 95% by 2030, significantly boosting the collection and treatment of wastewater to mitigate environmental impacts. [SWPC](#)

REGULATIONS ON MICROPOLLUTANT MITIGATION

Emphasizing highest water quality and public health standards

In 2024, **global efforts to mitigate micropollutants** in wastewater intensified, emphasizing public health and environmental protection. The U.S. Environmental Protection Agency identified significant cancer risks associated with [PFAS chemicals in sewage sludge used as fertilizer, highlighting the urgency for stringent regulations](#). These developments necessitate the adoption of advanced wastewater treatment technologies, such as activated carbon filtration and advanced oxidation processes, to effectively eliminate harmful micropollutants and safeguard water quality.

National Signal

Researchers at KAUST have developed a method to remove harmful organic micropollutants from wastewater using high-intensity pulsed light (HIPL). This approach rapidly decomposes contaminants, including pharmaceuticals and industrial chemicals, within milliseconds, offering a scalable solution to enhance water quality and public health. [Smart Water Magazine](#)





From Sectoral Trends to Technological Advancements

The evolving landscape of wastewater treatment and reuse is being shaped by a combination of global environmental, industrial, and technological trends. Climate resilience has become a critical focus as regions worldwide face prolonged droughts, unpredictable weather patterns, and rising water scarcity. Simultaneously, industries are increasingly turning to water recycling and reuse to reduce reliance on freshwater sources, minimize environmental impact, and ensure operational sustainability.

Additionally, digital transformation is revolutionizing the water sector, introducing smart monitoring, predictive analytics, and automation to optimize wastewater treatment processes. Regulatory advancements are also playing a crucial role, with stricter policies driving the adoption of advanced treatment solutions to enhance water quality and reduce pollution.

To address these challenges, technological advancements are playing a pivotal role in transforming wastewater treatment and reuse. From biological and catalytic treatments to digitalization and resource recovery, cutting-edge technologies are driving impactful changes in how water is treated, reused, and managed. The following section explores these high-potential technologies, mapping their impact and feasibility in addressing the challenges posed by water management today.



Wastewater Treatment and Reuse Technologies Driving Efficiency and Sustainability






The integration of **emerging wastewater treatment technologies** will drive **efficiency, sustainability, and adaptability** in Saudi Arabia's water sector, supporting efforts to **reduce freshwater reliance, expand infrastructure, and enhance digital monitoring**. By improving **pollutant removal and resource recovery**, these advancements will strengthen **water quality, regulatory compliance, and climate resilience**. As investments accelerate, these technologies will **optimize projects, drive innovation, and ensure long-term water security**. The following section provides a

comprehensive overview of key innovations, extending awareness, informing RDI planning, and guiding further exploration in **wastewater treatment and reuse**.

The upcoming chart comprises **40 high-potential innovative technologies within the wastewater management family**, spanning short-term gains to long-term vision and ranging from exploratory research to market-ready solutions. It maps promising approaches for **enhancing wastewater treatment efficiency, optimizing resource recovery, and integrating smart**

monitoring systems. Beyond technology maturity, the chart also illustrates **impact and ease of implementation, balancing high-impact innovations with quick-win solutions** that require minimal adaptation. This ensures a strategic mix of **effective and feasible** technologies for sustainable water management.

Technology Segments in Wastewater Treatment & Reuse

 BIOLOGICAL TREATMENT	 ELECTROCHEMICAL & CATALYTIC TREATMENT	 MEMBRANES & FILTRATION	 RESOURCE RECOVERY & ENERGY GENERATION	 DIGITALIZATION & DECENTRALIZATION
Algal Turf Scrubber (ATS) Technology (TRL 8-9)	Electrodialysis (ED) (TRL 8-9)	Membrane Bioreactors (MBRs) (TRL 8-9)	Thermal Hydrolysis (TRL 8-9)	Mobile Wastewater Treatment Units (TRL 8-9)
Hybrid Constructed Wetlands (TRL 8-9)	Supercritical Water Oxidation (SCWO) (TRL 8-9)	Zero Liquid Discharge (ZLD) Approach (TRL 8-9)	Struvite Recovery (TRL 8-9)	Co-Treatment Facilities (TRL 8-9)
Moving Bed Biofilm Reactor (MBBR) (TRL 8-9)	Ultrasonic Reactors (TRL 8-9)	Forward Osmosis (FO) (TRL 6-7)	Solar-powered Treatment Plants (TRL 8-9)	Digital Twins of Treatment Plants (TRL 8-9)
Aerobic Granular Sludge (AGS) Systems (TRL 8-9)	Nanobubbles (TRL 8-9)	Polymeric Composites (TRL 6-7)	Hydrothermal Carbonization (HTC) (TRL 8-9)	Modular Graywater Treatment Systems (TRL 8-9)
High-Rate Algal Ponds (HRAPs) (TRL 6-7)	Solar Photocatalysis (TRL 6-7)	Membrane Distillation (MD) (TRL 6-7)	Microbial Fuel Cells (MFC) (TRL 6-7)	Sewer Mining (TRL 6-7)
Large-scale Soil Filters (TRL 6-7)	Electrochemical Advanced Oxidation (EAOP) (TRL 6-7)	Osmotic Membrane Bio-reactors (OMBRs) (TRL 4-5)	Biogas-to-Hydrogen Recovery (TRL 6-7)	Smart Sensor Networks (TRL 6-7)
Phytoremediation (TRL 6-7)	Electrocoagulation (TRL 6-7)	Graphene-based Membranes (TRL 4-5)		AI-Driven Treatment Optimization Methods (TRL 6-7)
Enzyme-based Treatment (TRL 4-5)	Microbial Electrochemical Systems (MES) (TRL 4-5)			
Nanocellulose (TRL 4-5)	PFAS Reductive Defluorination (PRD) (TRL 4-5)			
Genetically-enhanced Microorganisms (TRL 4-5)	Plasma Arc Water Treatment (TRL 4-5)			

The definitions of the listed technologies are in the glossary section

Chart of the technologies [EASE OF IMPLEMENTATION vs MATURITY]



This section began by outlining six key sectoral trends influencing the water sector innovation in 2024, with a strong focus on Saudi Vision 2030 and its role in transforming water management. It highlighted the challenges in sustainability and wastewater treatment emphasizing the need for advanced technologies. With regulatory incentives and infrastructure upgrades accelerating adoption, this section examines the wastewater treatment and reuse emerging technologies and showcasing their level of ease of implementation compared to their maturity.

The following section starts to direct its focus to the five selected technologies. Exploring and introducing an in depth analysis of each one.

The chart presents wastewater treatment and reuse technologies, a key part of the Wastewater

Treatment & Reuse stage in the water value chain.

The technologies are categorized into five segments:

- Biological Treatment
- Electrochemical & Catalytic Treatment
- Membranes & Filtration
- Resource Recovery & Energy Generation
- Digitalization & Decentralization

Each technology is assessed based on Technology Readiness Levels (TRL), ease of implementation, and impact potential, with technologies distributed across TRLs, ranging from early development to near-commercialization (X-Axis) and ease of implementation (Y-Axis).

Higher TRL technologies with high ease of implementation and high impact indicate great potential and may be prioritized for near-term deployment. Lower TRL technologies with high potential impact require further R&D investments, funding and grants, and strategic collaborations to accelerate their development and integration.



Ease of implementation, potential impact, and impact definitions are in the Glossary



Wastewater Treatment & Reuse

3.2.1 TECHNOLOGY SPOTLIGHT

The Wastewater Treatment & Reuse Most Promising Technologies

The selection of technologies featured in this spotlight section was selected based on three key criteria, ensuring relevance, impact, and diversity in addressing wastewater treatment & reuse:



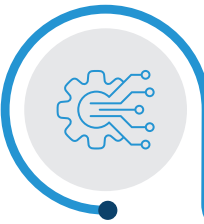
New and Notable Developments

Technologies were evaluated based on recent advancements, considering both novelty—the likelihood of introducing unprecedented innovations—and impact, which measures their contribution to progressing toward market readiness.



Relevance to KSA's Challenges

Priority was given to technologies with the potential to address Saudi Arabia's unique wastewater management challenges.



Diversity of Technologies

A balanced selection was maintained across different technology segments, ensuring representation in the spotlight. The selection also considers a mix of high-maturity technologies for near-term application and emerging innovations with long-term potential.

Refer to the Selection Criteria Scorecard in the Appendix section

Five technologies take the center stage

The selected wastewater treatment technologies align with the key criteria of innovation, relevance, and diversity. They incorporate advanced biological, chemical, filtration, thermal, and AI-driven approaches to enhance water reuse, resource recovery, and treatment efficiency. Addressing critical challenges like water scarcity, energy efficiency, and sustainability, these technologies support Vision 2030's goals. The selection balances high-maturity solutions for immediate deployment with emerging innovations for long-term impact.

Technology Segments	Technology	Maturity	Vision 2030 Relevance
Biological Treatment	> Algal Turf Scrubber (ATS) Technology	> TRL 8-9	> Offer a nature-based, low-energy approach, particularly effective at nutrient removal and enhancing reuse options.
Electro-chemical & Catalytic Treatment	> Nanobubbles	> TRL 8-9	> Improves oxygenation in wastewater at high levels of energy-efficiency, aiding water reuse and environmental sustainability.
Membranes & Filtration	> Zero-Liquid Discharge (ZLD) Approach	> TRL 8-9	> Addresses extreme water scarcity concerns by recovering nearly all water from wastewater streams.
Resource Recovery & Energy Generation	> Thermal Hydrolysis	> TRL 8-9	> Enhances resource recovery (biogas), cuts disposal costs, and ensures pathogen-free biosolids for agricultural use.
Digitalization & Decentralization	> AI-Driven Treatment Optimization Methods	> TRL 6-7	> Enhances overall plant performance and water reuse by optimizing key process parameters.



TECHNOLOGY SPOTLIGHT

A. Algal Turf Scrubber (ATS) Technology

Algal Turf Scrubber (ATS) Technology use algae grown on sloped surfaces to absorb nutrients from wastewater, improving water quality while producing biomass that can be utilized for biofuels, fertilizers, and other resource recovery applications.

Algal Turf Scrubber [ATS] Technology

Algal Turf Scrubber (ATS) Systems are engineered systems that cultivate an algal biofilm on inclined screens in shallow basins to treat wastewater. As water flows over the algal turf, the algae rapidly assimilate nutrients such as nitrogen and phosphorus while releasing dissolved oxygen through photosynthesis. This process not only [improves water quality by reducing nutrient loads that can cause eutrophication, but also produces high-yield biomass](#), which has applications in biofuels and fertilizers. [ATS systems have been successfully implemented in agricultural drainage and urban wastewater treatment](#), with promising pilot projects and implementations in the United States. Future developments focus on

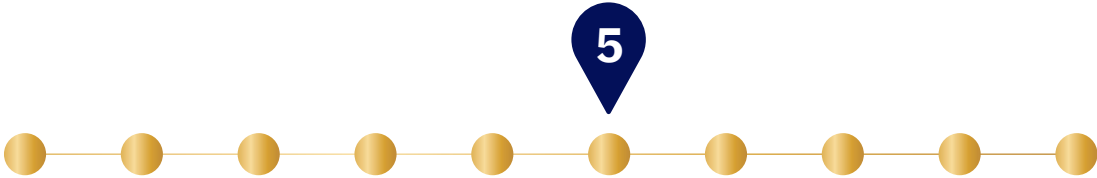
optimizing cultivation conditions and scaling up, although challenges remain in achieving consistent performance across varying wastewater compositions. ATS feasibility in Saudi Arabia’s arid climate poses challenges. Natural algal growth may be limited due to high temperatures, intense sunlight, and low humidity compared to tropical systems. However, with controlled environments, optimized flow conditions, and modular design adaptations (e.g., shading, temperature regulation), ATS systems can still be viable—especially for non-potable reuse or agricultural runoff treatment in rural or industrial zones.

Technology and Market Maturity

Algal Turf Scrubber [ATS] Technology have a high technology readiness level **[TRL 9]**, with decades of research validating their effectiveness in wastewater treatment and nutrient recovery. However, market maturity remains limited **[MRL 5]**, as large-scale commercial adoption is still emerging. Key challenges

include optimizing system efficiency across diverse wastewater types, lowering operational costs, and integrating ATS into existing infrastructure. Increased regulatory focus on nutrient pollution may drive broader adoption in the near future.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

- 1

[Smithonian Institute](#)
- 2

[University of Maryland's Algal Ecotechnology Center](#)
- 3

[HydroMentia, Inc.](#)
- 4

[Sandia National Laboratories](#)
- 5

[State University of New York at Buffalo](#)



Insights and Statistics

ATS technologies remove nutrients efficiently, improve water quality, and generate renewable biomass for biofuels and fertilizers, offering a scalable and cost-effective wastewater treatment solution.

Impact and Key Stats

- **High Nutrient Removal:** ATS systems are highly effective in nutrient remediation, capable of removing up to 99% of total phosphorus and 100% of total nitrogen within seven days, significantly outperforming many conventional wastewater treatment methods. [Front Bioeng Biotechnol](#)
- **Improved Water Quality:** ATS systems enhance dissolved oxygen levels and stabilize pH balance in treated waters. In field studies, ATS-treated water has shown oxygen saturation increases of up to 150% and pH stabilization within optimal biological ranges for aquatic ecosystems. [Front Bioeng Biotechnol](#)
- **Versatile Application:** ATS technology has been successfully deployed in multiple wastewater treatment contexts, including municipal wastewater treatment plants, agricultural runoff remediation, stormwater treatment, and eutrophicated water bodies. [HydroMentia](#)
- **Scalability:** Full-scale ATS technologies have been deployed with treatment capacities ranging from 1 million to 25 million gallons per day (MGD). Their modular design enables rapid expansion, making them suitable for both localized pollution control and large municipal-scale water treatment operations. [HydroMentia](#)
- **Renewable Energy Potential:** ATS systems produce biomass yields among the highest recorded in managed ecosystems—ranging from 5 to 30 g/m²/day—making them a valuable resource for fertilizers, animal feed, and biofuels like biodiesel, biogas, and ethanol through anaerobic digestion. [Bioresource Technology Reports](#)
- **Economic Viability:** ATS technology has been shown to provide a more cost-effective approach to nutrient pollution control—up to 69% cheaper than some nature-based solutions, such as engineered wetlands, which often struggle with high capital costs and land requirements. [University of Florida](#)

Technology Adoption

ATS adoption remains limited, with pilot projects primarily in the U.S., exploring nutrient removal, water quality improvement, and scalability for municipal, agricultural, and industrial wastewater treatment.

Current State

- **Municipal Implementations:** Municipalities in [Florida](#), [Maryland](#), and [North Carolina](#) have piloted ATS technology to combat nutrient pollution. In 2023, [Georgia Southern University](#) partnered with a municipal wastewater plant to implement ATS for onsite nutrient removal.
- **Agricultural Runoff Management:** ATS technologies treat agricultural runoff in intensive farming areas. Research on Maryland’s Eastern Shore demonstrated that ATS raceways effectively reduce nutrient loads before reaching sensitive aquatic ecosystems. [University of Maryland](#)
- **Industrial Applications:** Industries are exploring ATS for wastewater treatment, particularly where traditional methods fall short. Studies highlight large-scale ATS potential in treating industrial effluents, with ongoing research optimizing its efficiency and scalability. [HydroMentia](#)

Global Lessons Learned

- **Regional Customization for Maximum Impact:** Deployments in urban, agricultural, and industrial settings emphasize the need for site-specific customization, such as optimizing slope gradients and algae harvesting cycles to maximize treatment efficiency. [Maryland Port Authority](#)
- **Balancing Land Use and Treatment Capacity:** Large-scale ATS technologies require significant land area, making them more feasible in rural or industrial settings than in space-constrained urban environments. Modular configurations help address these challenges. [Bio Science](#)
- **Integration with Energy and Resource Recovery Systems:** Lessons from pilot projects suggest that combining ATS with anaerobic digesters or biogas systems can enhance economic feasibility, though biogas yield optimization remains an area for further development. [Maryland Port Authority](#)

Outlook

Advancements in ATS technology will enable broader adoption through scalable, modular designs and biofuel potential, positioning it as a sustainable solution for wastewater treatment and resource recovery.

Key Signals of Change

- **Algal Integration in Aquaculture:** Research highlights the potential of algal reactors in RAS for nitrogen removal but faces challenges in efficiency and cost. Innovations in reactor design and lighting could enhance feasibility, improving wastewater treatment and sustainability. Front. [Bioeng. Biotechnol.](#)
- **Water Purification and Biofuel:** Researchers are optimizing ATS technology by improving surface materials, refining flow rates, and integrating biofuel conversion processes. Enhanced scalability and cost reductions could drive widespread adoption. [Georgia Southern University](#)
- **Wastewater Energy Recovery:** Researchers identified how different microbial inocula impact methane yields from algae, revealing efficiency trade-offs that could optimize biogas production and energy recovery in wastewater treatment plants. [Biomass Conversion and Biorefinery](#)

Future Trajectory

- **Integration With Circular Bioeconomy Models:** ATS technologies will increasingly align with circular bioeconomy principles, converting wastewater nutrients into valuable biofuel and bioproducts while reducing greenhouse gas emissions. EU policies on phosphorus recovery and net-zero targets support this shift. [Separation and Purification Technology](#)
- **Enhanced Scalability Through Modular ATS Designs:** Modular, stackable ATS units will address space constraints in wastewater treatment plants, improving nutrient removal efficiency while enabling decentralized applications in aquaculture, agriculture, and industrial wastewater treatment. [Water Today](#)
- **Policy and Market Incentives Driving Adoption:** Stricter wastewater discharge regulations and financial incentives for nutrient recovery and biofuel production will accelerate ATS adoption, making it a competitive alternative to conventional nitrification-denitrification processes. [European Commission](#)





Case Study

Indian River Lagoon (U.S.)

In 2023, Florida launched one of the largest Algal Turf Scrubber (ATS) pilot projects to tackle nutrient pollution in the [Indian River Lagoon](#), a waterway plagued by harmful algal blooms and fish die-offs due to excess nitrogen and phosphorus. Partnering with HydroMentia Corporation and research institutions, the state deployed ATS technology as a cost-effective, nature-based solution for wastewater treatment.

The ATS technology successfully removed 70–85% of nitrogen and 60–75% of phosphorus, outperforming conventional treatment methods. Harvested algae were processed into biofuel, demonstrating a scalable pathway for renewable energy generation. The project also proved more cost-effective than dredging and chemical treatments, making ATS a competitive alternative for large-scale nutrient pollution control.

Encouraged by these results, Florida is considering broader ATS deployment to protect waterways statewide. As stricter water quality regulations emerge, ATS technologies could play a key role in sustainable wastewater treatment, aligning with circular bioeconomy principles and advancing global water management innovation.

TECHNOLOGY SPOTLIGHT

B.Nanobubbles

Nanobubble aeration is an emerging technology that advances water treatment and management by introducing ultrafine gas bubbles into water to enhance oxygenation and break down contaminants.

Nanobubbles

Nanobubble aeration introduces ultrafine gas bubbles, typically 70-120 nanometers in size, into water to enhance oxygenation and degrade contaminants. These nanobubbles remain suspended due to Brownian motion, providing uniform oxygen distribution and a high surface area-to-volume ratio, which improves gas transfer efficiency. Recent advancements include [energy-efficient nanobubble generation methods, such as friction-based techniques, and the application of ozone-infused nanobubbles for effective disinfection and pollutant removal](#) in water treatment processes. In 2024, Moleaer introduced the [Trinity Nanobubble](#)

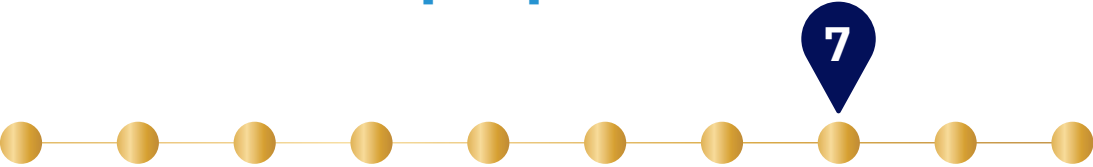
[Generator](#), designed to enhance oxygen transfer and improve water quality in agricultural applications. Additionally, the City of Lake Elsinore implemented nanobubble technology to improve lake water quality, [observing significant increases in dissolved oxygen levels and reductions in organic sediment](#). There are technical challenges regarding Nanobubble, particularly in maintaining stable bubble size and functionality across varying water chemistries and contaminant loads. These fluctuations can affect gas transfer efficiency and reduce overall treatment performance in complex or high-strength wastewater streams.

Technology and Market Maturity

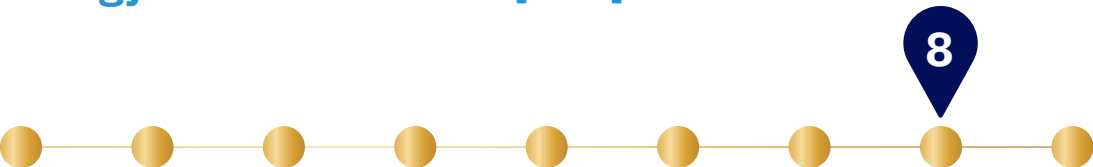
In the context of wastewater treatment, nanobubble technology is assessed at **[TRL 8]**, this indicates that nanobubbles technology demonstrates effectiveness in operational environments, however it remains not yet widely adopted. Companies like Moleaer have successfully implemented nanobubble systems in both

industrial and municipal wastewater treatment plants, demonstrating improved biodegradability and treatment efficiency. The market readiness of nanobubble technology in wastewater treatment is advancing, with a current assessment at **[MRL 7]**. This reflects a growing market presence with increasing adoption.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

- 1

[Moleaer Inc.](#)
- 2

[Trident Bubble Technologies LLC](#)
- 3

[NanobOX](#)
- 4

[AquaB Nanobubble Innovations Ltd.](#)
- 5

[Texas A&M University](#)



Insights and Statistics

Integrating nanobubble technology into wastewater treatment processes can lead to substantial improvements in operational efficiency, resource conservation, and cost reduction.

Impact and Key Stats

- **Increased Treatment Capacity:** Implementing nanobubble technology can expand the treatment capacity of existing wastewater facilities by up to 25%. This allows plants to handle higher volumes of wastewater without significant infrastructure investments. [Waste Management World](#)
- **Enhanced Pollutant Removal:** Nanobubbles have been shown to improve the removal of organic pollutants in wastewater by enhancing flotation processes. Their unique properties increase the efficiency of separating contaminants from water, leading to cleaner effluent. [AMB Express](#)
- **Energy Consumption Reduction:** The application of nanobubble technology can lead to a 40% reduction in energy consumption in wastewater treatment plants. This is achieved through more efficient aeration processes, which decrease the need for mechanical aeration and associated energy costs. [Smart Water Magazine](#)
- **Sustainable Practices:** The technology reduces the need for chemical additives in wastewater treatment, promoting environmentally friendly practices and reducing chemical exposure risks to workers and communities. [Offshore Technology](#)
- **Community Acceptance:** The implementation of nanobubble systems has been well-received in various regions, with communities recognizing the improvements in water quality and environmental health. [UBS](#)
- **Improved Oxygen Transfer Efficiency:** Nanobubble aeration can double the oxygen utilization rate and volumetric mass transfer coefficient compared to conventional aeration methods, enhancing the degradation of organic pollutants. [American Chemical Society](#)

Technology Adoption

Nanobubble adoption is growing, driven by efficiency gains, regulatory interest, and proven benefits, but cost, scalability, and industry scepticism remain challenges.

Current State

- **Scalability:** Scaling nanobubble generation for large-scale wastewater treatment remains challenging. Particulates can hinder nanobubble formation and potentially damage generators, necessitating technological advancements for consistent production in diverse environments. [Envir. Sci. & Tech](#)
- **R&D Focus:** Ongoing research aims to optimize nanobubble generation methods and understand their interactions with microbial communities. Efforts focus on enhancing the stability and efficiency of nanobubbles, facilitating broader adoption in wastewater treatment applications. [Water Res.](#)
- **Municipal Adoption:** Wastewater treatment plants are beginning to integrate nanobubbles for enhanced pollutant removal. The Goleta Sanitary District in California adopted the technology to mitigate inhibitory surfactants, resulting in improved total suspended solids removal and better treatment efficiency. [Moleaer](#)

Global Lessons Learned

- **Operational Challenges in Mixing:** While nanobubbles excel in oxygen transfer, they may not provide sufficient mixing in aeration tanks. Operators have observed that nanobubble systems might need to be supplemented with mechanical mixers to ensure adequate mixing and prevent sedimentation. [Eng Tips](#)
- **Gas Selection:** The choice of gas (e.g., oxygen, air, ozone) significantly impacts the efficiency and cost-effectiveness of nanobubble aeration. Oxygen nanobubbles improve microbial activity, while ozone nanobubbles provide additional disinfection benefits. [Envir. Sci. & Tech](#)
- **Proving ROI Beyond Aeration:** Many wastewater operators remain sceptical due to high upfront costs and unfamiliarity. Adoption succeeds when nanobubbles' benefits—reduced sludge, enhanced microbial activity, and lower chemical use—are demonstrated beyond just energy savings. [Offshore Technology](#)

Outlook

Nanobubble technology is poised towards wide adoption across various applications with projected advancements in micro-pollutant removal, decentralized treatment, and energy efficiency.

Key Signals of Change

- **Advancements in Ozone Nanobubble Research:** Recent studies have focused on the use of ozone-infused nanobubbles for effective disinfection and pollutant removal in water treatment processes, highlighting their potential in enhancing treatment efficiency. [WRF](#)
- **Nanobubble Implementation:** In 2024, Lake Elsinore, California, installed a nanobubble barge injecting 3.5 million gallons of oxygen-rich nanobubbles daily to improve water quality. The scale of this project highlights nanobubbles' potential for large-scale ecological restoration and algal bloom prevention. [Lake Elsinore](#)
- **Pilot Project in Denmark:** In Næstved, Denmark, a pilot project tested nanobubble technology to enhance a small biological wastewater treatment plant's efficiency, particularly during high organic load periods. This signals growing interest in decentralized, energy-efficient solutions for wastewater treatment. [Interreg](#)

Future Trajectory

- **Cost-Effectiveness Improvement through Advanced Generation Methods:** Driven by advancements in microfluidics, gas dissolution, and machine learning, nanobubble generators becoming 30-50% more energy-efficient by the mid-2030s can be expected. However, initial capital costs may still limit adoption in small and mid-sized wastewater treatment plants. [Bioresource Technology](#)
- **Increased Adoption for Micro-Pollutant and Pathogen Removal:** By 2035, nanobubbles are expected to be widely integrated into wastewater treatment processes for the removal of microplastics, pharmaceutical residues, and PFAS ("forever chemicals"). [Nanomaterials](#)
- **Decentralized and Mobile Wastewater Treatment Solutions:** Following general trends in wastewater treatment, portable, containerized nanobubble wastewater treatment units may emerge for off-grid use in emergency operations, rural communities, and industrial applications. [Acc Chem Res](#)





Case Study

Lake Elsinore (U.S.)

In January 2024, the [City of Lake Elsinore](#), California, deployed a large-scale nanobubble aeration system to combat persistent water quality issues, including low dissolved oxygen levels, algal blooms, and sediment accumulation. The system, installed on a floating barge, injects 3.5 million gallons of oxygen-rich nanobubbles per day, significantly enhancing oxygen transfer efficiency and improving aquatic health.

Within three months, monitoring data revealed a 40% increase in dissolved oxygen levels at deeper water layers, helping to mitigate algal growth and reduce organic sediment buildup. The project demonstrated how nanobubbles can support lake restoration without relying on chemical treatments.

Lake Elsinore's success signals growing municipal interest in nanobubble technology for sustainable water management. Cities facing hypoxia and eutrophication challenges are now considering similar solutions.

The project also supports broader research into decentralized nanobubble applications, reinforcing their viability for municipal and industrial wastewater treatment.



TECHNOLOGY SPOTLIGHT

C. Zero Liquid Discharge [ZLD] Approach

ZLD Approach is advanced wastewater treatment processes designed to eliminate liquid waste by recovering and recycling all water, leaving only solid residues. They integrate physical, chemical, and thermal methods to treat wastewater, enabling water reuse and minimizing environmental discharge.

Zero-Liquid Discharge [ZLD]

Zero-Liquid Discharge (ZLD) is an advanced wastewater treatment approach that eliminates liquid waste, recovering and reusing nearly all water while leaving only solid residues. It is crucial in industries facing stringent environmental regulations and water scarcity, reducing pollution and maximizing water efficiency. ZLD is [widely adopted in power plants, textiles, and chemical industries](#), particularly in water-stressed regions like China, India, and the U.S. Emerging membrane-based

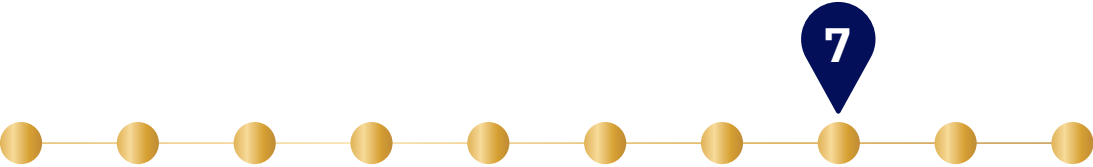
technologies, such as [reverse osmosis \(RO\)](#) and [forward osmosis \(FO\)](#), are improving ZLD's energy efficiency. However, challenges remain, including high costs and energy consumption. Managing the highly concentrated brine waste remains a key environmental and economic challenge in ZLD systems. Future advancements focus on integrating resource recovery and leveraging low-grade energy sources to make ZLD more sustainable and economically viable.

Technology and Market Maturity

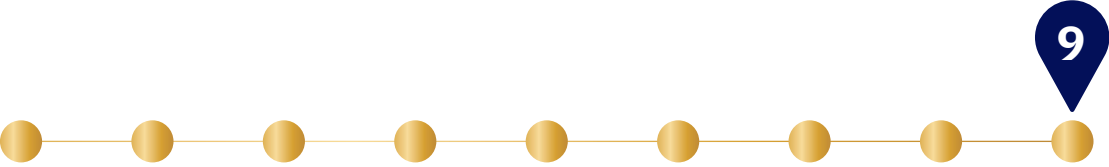
ZLD is a high-maturity technology (TRL 8-9), evolving from energy-intensive thermal systems to more efficient hybrid and membrane-based solutions like reverse osmosis (RO) and forward osmosis (FO). Its market adoption is accelerating, particularly in industries facing regulatory pressure and high wastewater disposal costs.

While large-scale implementations exist, widespread adoption is constrained by high capital expenditures and energy demands, driving innovation in energy recovery and resource recovery technologies.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

- | | | | |
|---|---|---|--|
| 1 | Veolia Water Technologies | 2 | Aquatech International LLC |
| 3 | GEA Group | 4 | Alfa Laval |
| 5 | Wetsus | 6 | General Electric |
| 7 | Mitsubishi Chemical | | |



Insights and Statistics

ZLD minimizes wastewater discharge, enhances water reuse, reduces pollutants, and enables resource recovery, but presents challenges in energy consumption, costs, and infrastructure.

Impact and Key Stats

- **High Water Recovery:** ZLD approach can recover almost 100% of wastewater, minimizing the impact on freshwater sources. Municipalities and industries such as textiles, chemicals, and power plants benefit significantly from high-efficiency water recovery solutions that help reduce consumption and costs. [Concept of ZLD](#)
- **Energy Consumption:** ZLD requires 20-25 kWh per cubic meter of treated water, significantly more than conventional wastewater treatment. While energy-intensive, ongoing technological advancements aim to reduce power consumption and improve cost-effectiveness. [Envir. Sci. & Tech](#)
- **Cost Implications:** ZLD implementation costs 2-3 times more than conventional treatment due to high capital and operational expenses. However, long-term benefits include reduced water procurement costs, lower regulatory penalties, and revenue from recovered resources. [LCCMR](#)
- **Resource Recovery:** ZLD approach not only treat wastewater but also extract valuable byproducts like sodium sulfate, sodium chloride, and other industrial salts. This resource recovery creates additional revenue streams for industries while supporting a circular economy approach. [Envir. Sci. & Tech](#)
- **Pollutant Reduction:** ZLD approach remove up to 99% of contaminants, such as heavy metals, pharmaceuticals, and microplastics, preventing pollution of rivers and lakes. This protects aquatic ecosystems and reduces long-term ecological damage. [Envir. Sci. & Tech](#)
- **Infrastructure Longevity:** By minimizing the volume of wastewater requiring treatment and discharge, ZLD can reduce the strain on existing municipal wastewater infrastructure, potentially extending its operational lifespan and reducing maintenance costs. [Journal of Environmental Management](#)

Technology Adoption

ZLD adoption is driven by water scarcity and regulations but faces challenges due to high costs, energy demands, and complex operational requirements.

Current State

- **Environmental Regulations:** Stricter global environmental policies are driving ZLD adoption. Regulatory bodies in the U.S. Europe, and India are mandating ZLD for industries like power generation and textiles, increasing compliance costs for non-adopters. [IMARC](#)
- **Regional Adoption:** The Asia-Pacific region leads ZLD adoption, accounting for the largest market share due to rapid industrialization and stringent wastewater treatment regulations. China and India, in particular, have imposed strict discharge limits, making ZLD a crucial solution for compliance. [M Heavy Tech](#)
- **Operational Costs:** The engineering, procurement, and construction costs for a full-scale ZLD approach can be substantial, often requiring customized solutions tailored to specific industrial needs. Efforts to reduce costs focus on optimizing process efficiency and utilizing waste heat for energy recovery. [M Heavy Tech](#)

Global Lessons Learned

- **Site-Specific Design Requirements:** ZLD approach must be tailored to the specific characteristics of the wastewater and local environmental conditions. A one-size-fits-all approach is ineffective; customized solutions are necessary to address unique contaminant profiles and regulatory requirements. [ESWP](#)
- **Material Compatibility Issues:** The high salinity and chemical composition of concentrated brines in ZLD approach can lead to corrosion and scaling in equipment. Selecting appropriate materials and implementing effective pretreatment processes are essential to mitigate these issues. [SAMCO](#)
- **Potential for Resource Recovery:** Beyond water reclamation, ZLD approach can facilitate the extraction of valuable materials, such as salts and minerals, from wastewater. This not only offsets operational costs but also promotes sustainable resource utilization. [Waterman Engineers](#)

Outlook

The future of ZLD is driven by technological innovations, regulatory pressures, resource recovery potential, and hybrid treatment approaches, balancing sustainability with cost and energy challenges.

Key Signals of Change

- **Advanced Computational Modeling for Process Optimization:** The development of sophisticated computational models has enabled the optimization of ZLD processes, balancing energy consumption, cost, and environmental impact. [Northwestern University](#)
- **Hybrid ZLD Systems :** The combination of thermal and membrane-based processes in hybrid ZLD systems has been shown to enhance overall efficiency, making the technology more accessible and cost-effective for various industries. [IDE Tech](#)
- **Selective Recovery of Critical Materials:** Advancements in supercritical water desalination now enable the extraction of valuable materials, such as neodymium, from wastewater, turning waste streams into resource recovery opportunities. [Chemical Physics](#)

Future Trajectory

- **Future Outlook:** The ZLD market is expected to reach \$14.9 billion by 2033, growing at a CAGR of 6.8%. Future developments will focus on cost-effective energy solutions, AI-driven process optimization, and integrating renewable energy to reduce carbon footprints. [IMARC](#)
- **Technological Advancements:** Emerging technologies such as forward osmosis (FO) and membrane distillation (MD) are improving ZLD efficiency and lower costs. These innovations could make ZLD financially viable for more municipalities, accelerating widespread adoption in wastewater management. [Role of Sci & Tech](#)
- **Policy and Regulatory Drivers:** Stricter environmental regulations and sustainability goals will increase ZLD adoption. Governments are implementing policies that limit wastewater discharge and promote water reuse, positioning ZLD as a compliance strategy, especially in water-scarce regions. [Envir. Sci. & Tech](#)





Case Study

King Salman Park [Saudi Arabia]

King Salman Park, a major urban development in Riyadh, Saudi Arabia, is implementing a Zero Liquid Discharge (ZLD) approach as part of its Water & Sewage Treatment Complex (WSTC). Developed by the King Salman Park Foundation (KSPF), this initiative ensures wastewater is treated and reused, supporting the park's sustainability goals.

Osmosys designed an advanced ZLD approach integrating softening, advanced oxidation, and membrane brine concentration (MBC). It treats high-salinity brine from a reverse osmosis (RO) membrane, starting with 34,000 mg/L TDS and achieving 82% water recovery with energy consumption below 5.4 kWh/m³. The process includes sodium hydroxide softening, Fenton oxidation, ultrafiltration, and Osmosys' proprietary Salinity Adaptive Multistep RO (SAMRO) and MBC technologies, concentrating brine to 200,000 mg/L TDS.

A thermal crystallizer further processes the brine, maximizing water reuse and minimizing waste. This high-efficiency ZLD approach aligns with Saudi Arabia's water sustainability vision, ensuring minimal environmental impact and responsible urban development.

TECHNOLOGY SPOTLIGHT

D. Thermal Hydrolysis

Thermal hydrolysis is a sludge treatment process that uses high temperature and pressure to break down organic matter before anaerobic digestion. This pretreatment enhances biogas production, reduces sludge volume, and produces pathogen-free biosolids suitable for agricultural use.

Thermal Hydrolysis

Thermal Hydrolysis (TH) is an advanced sludge pre-treatment technology used in wastewater treatment to enhance anaerobic digestion. The process applies high temperature (typically 160-180°C) and pressure to break down complex organic matter, improving biodegradability and increasing biogas production. TH is crucial for resource recovery, reducing sludge volume, minimizing disposal costs, and producing pathogen-free biosolids for agricultural use. Major utilities like [Thames Water](#) (UK) and [DC Water](#) (USA) have adopted TH to optimize energy recovery and sustainability. Future developments focus on

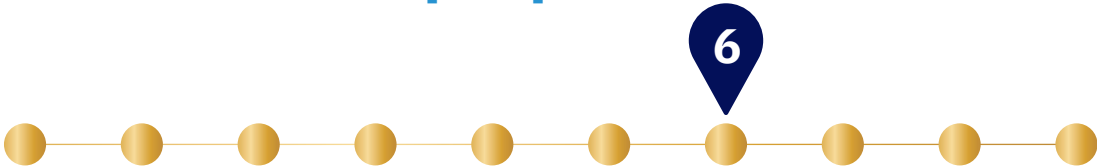
integrating TH with energy-neutral wastewater facilities and exploring decentralized applications. Challenges include high capital costs and operational complexities, but advancements in process optimization and renewable energy integration could enhance its feasibility worldwide. TH faces several challenges, including high capital and operational costs due to the need for pressurized, high-temperature equipment. The process also requires significant energy input, which can impact sustainability if not paired with energy recovery systems.

Technology and Market Maturity

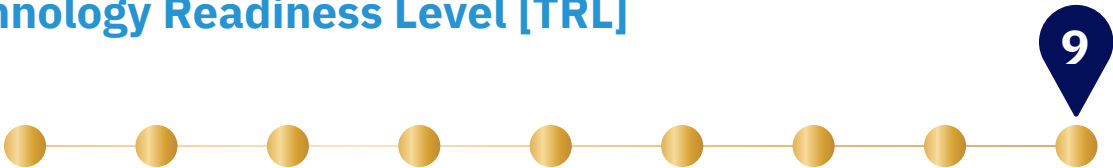
Thermal Hydrolysis (TH) has a high technology readiness level **[TRL 9]**, with proven deployment in large wastewater treatment plants, enhancing biogas production and sludge management. However, market maturity remains moderate **[MRL 6]**, as high capital costs and operational

complexity limit widespread adoption, especially in smaller facilities. Regulatory focus on energy recovery and biosolids reuse, along with cost reductions, could drive broader market adoption in the coming years.

Market Readiness Level [MRL]



Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players

- 1

[Cambi](#)
- 2

[Veolia Water Technologies](#)
- 3

[Lystek International](#)
- 4

[Stantec](#)
- 5

[Brown and Caldwell](#)



Insights and Statistics

Thermal Hydrolysis enhances biogas production, reduces sludge volume, improves biosolids quality, and increases wastewater treatment efficiency and sustainability.

Impact and Key Stats

- **Biogas Production:** Implementing TH can significantly boost biogas output during anaerobic digestion. Studies have reported increases in biogas production by approximately 75-80% when TH is applied to waste activated sludge, transforming waste into a valuable energy resource. [Water Sci Technol](#)
- **Sludge Reduction:** TH effectively reduces the volume of sludge generated in wastewater treatment processes. This reduction leads to decreased costs associated with sludge handling and disposal, as there is less material to manage. [Water and Wastewater](#)
- **Improved Dewaterability:** Sludge treated with TH exhibits enhanced dewatering characteristics. For instance, the total solids content of centrifuged sludge cake can increase by over 50% after TH at 170°C, facilitating more efficient water removal and reducing sludge volume. [University of Hawai'i](#)
- **Methane Yields:** Research indicates that TH can increase the specific methane yield of waste activated sludge by 31% to 53%. This enhancement boosts renewable energy production, contributing to the sustainability of wastewater treatment operations. [Water Res. Technol.](#)
- **Integration with Existing Infrastructure:** TH systems can be retrofitted into existing wastewater treatment facilities. This adaptability allows plants to upgrade their processes without the need for complete overhauls, improving performance and efficiency. [Water and Wastewater](#)
- **Economic Viability:** While the initial investment for TH infrastructure can be substantial, the long-term economic benefits are notable. Enhanced biogas production reduces energy costs, and decreased sludge volumes lower disposal expenses, contributing to overall cost savings. [Water and Wastewater](#)

Technology Adoption

Major wastewater facilities are integrating Thermal Hydrolysis, leveraging its ability to increase digester efficiency, reduce disposal costs, and support circular economy goals.

Current State

- **Global Market Growth:** The global TH technology market was valued at approximately USD 1.89 billion in 2024 and is projected to reach USD 3.10 billion by 2030, growing at a CAGR of 8.60%. [TechSci Research](#)
- **Major Installations:** Significant facilities have adopted TH, such as the Blue Plains Advanced Wastewater Treatment Plant in Washington, D.C., which operates the world's largest TH system, processing 135,000 tons of dry solids annually. [Cambio](#)
- **Technological Advancements:** Companies like [Veolia](#) and [Cambio](#) are developing high-solids thermal hydrolysis processes, optimizing sludge management, increasing biogas yields, and reducing facility footprints, enhancing circular economy integration in wastewater treatment.

Global Lessons Learned

- **Infrastructure Efficiency:** Implementing TH allows wastewater treatment plants to increase digester loading rates without expanding existing tank capacities, optimizing facility footprints and reducing capital expenditures. [Brown and Caldwell](#)
- **Versatile Configuration Options:** Various TH configurations, such as pre-digestion and post-digestion setups, offer unique advantages, including improved dewaterability and energy recovery, allowing customization based on specific plant needs. [Cambio](#)
- **Enhanced Digestion Efficiency:** TH pretreatment significantly improves anaerobic digestion, increasing biogas production by up to 20% and reducing sludge volume, leading to more efficient waste-to-energy conversion. [Veolia Water Technologies](#)

Outlook

Thermal Hydrolysis is transitioning into a driver of circular wastewater treatment, with decentralized expansion, stricter sludge regulations, and carbon sequestration shaping its future.

Key Signals of Change

- **Innovative Pilot Projects:** The City of Raleigh's Bioenergy Recovery Project utilizes TH with the aim to reduce biosolids volume by approximately 50%. The biogas generated will be refined into renewable natural gas, anticipated to fuel over 70 city buses daily. [City of Charlotte](#)
- **Advancements in TH Configurations:** Research into various TH configurations, such as pre-digestion and post-digestion setups, has highlighted their unique strengths in enhancing wastewater treatment efficiency and resource recovery. [Cambi](#)
- **Significant Infrastructure Investments:** The San Francisco Public Utilities Commission (SFPUC) is investing over \$3 billion to upgrade the Southeast Treatment Plant, incorporating Cambi's TH systems to enhance biosolids processing and energy recovery. [SFPUC](#)

Future Trajectory

- **Energy-Positive Wastewater Treatment:** TH can drive wastewater plants toward energy independence, integrating advanced digestion and biogas upgrading to generate renewable energy, reducing reliance on external power, and creating revenue-generating, carbon-neutral treatment facilities. [npj Clean Water](#)
- **Decentralized and Modular TH Systems:** TH adoption will expand to decentralized, containerized systems for remote and industrial sites. Advances in modular technology will enhance affordability, enabling wastewater treatment in developing regions. [Environments](#)
- **Carbon Sequestration and Biomaterials:** TH-treated biosolids will support carbon sequestration and biomaterial production. Emerging applications in biochar, regenerative agriculture, and CO₂ capture will create new revenue streams and regulatory incentives for utilities. [Biochar](#)





Case Study

DC Water (U.S.)

In 2014, the Blue Plains Advanced Wastewater Treatment Plant in Washington, D.C., became the world's largest facility to implement Thermal Hydrolysis (TH), setting a new benchmark for sustainable wastewater treatment. Facing increasing energy costs and stricter biosolids disposal regulations, [DC Water](#) invested \$470 million in an advanced biosolids management program, with TH as the centerpiece.

The TH process pre-treats wastewater sludge with high heat (165°C) and pressure before anaerobic digestion, dramatically improving biodegradability. As a result, biogas production increased by 50%, enabling the plant to generate 10 megawatts of renewable electricity, covering one-third of its energy demand and saving \$10 million annually in power costs. Additionally, biosolids volume was reduced by 50%, cutting disposal costs, and the facility now produces Class A biosolids, branded as "Bloom", a nutrient-rich fertilizer sold commercially.

Blue Plains' success has inspired global adoption of TH technology, proving how wastewater can be transformed into energy, revenue-generating biosolids, and valuable resources, leading the way toward a more sustainable, energy-independent future.



TECHNOLOGY SPOTLIGHT

E. AI-Driven Treatment Optimization Methods

This technology leverages artificial intelligence to analyze real-time and historical data from wastewater treatment processes, enabling predictive analytics and dynamic control. By optimizing parameters such as chemical dosing and aeration, AI enhances treatment efficiency, reduces operational costs, and improves effluent quality.

AI-Driven Treatment Optimization Methods

AI-Driven Wastewater Treatment Optimization leverages artificial intelligence to enhance wastewater treatment efficiency by analyzing real-time and historical data. AI-driven models optimize critical parameters such as chemical dosing, aeration, and sludge management, leading to improved pollutant removal, reduced operational costs, and enhanced effluent quality. Utilities like [EWE WASSER](#) (Germany) and [PUB Singapore](#) are integrating AI to improve process control and energy efficiency. This technology is crucial as water treatment faces growing pressures from urbanization and climate change. Future developments focus on expanding AI's

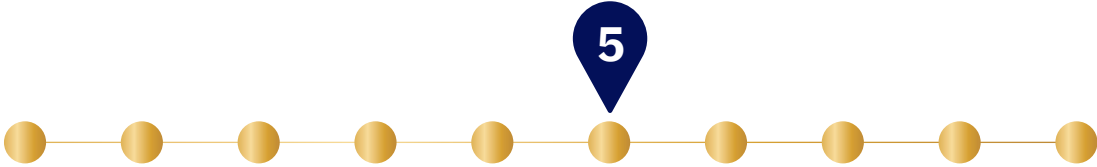
predictive capabilities, integrating with IoT sensors, and enabling decentralized treatment solutions. Challenges include high implementation costs, data quality concerns, and regulatory barriers, but advancements in automation and cloud computing are accelerating AI adoption globally. In Saudi Arabia, Aramco leverages AI and Big Data solutions to optimize various operations within the energy sector, including water management. By harnessing the power of AI, Big Data, and the Industrial Internet of Things (IIoT), Aramco aims to enhance industrial processes, improve efficiency, reliability, and sustainability.

Technology and Market Maturity

AI-Driven Wastewater Treatment Optimization is at a mid-to-high technology readiness level **[TRL 7]**, with successful pilot implementations proving its ability to enhance process efficiency through real-time data analysis and predictive control. However, market maturity remains moderate **[MRL 5]**, as adoption is still emerging

beyond early adopters. Key challenges include integration costs, regulatory uncertainties, and data quality concerns. Growing digitalization trends and sustainability mandates are expected to accelerate wider adoption in the near future.

Market Readiness Level [MRL]

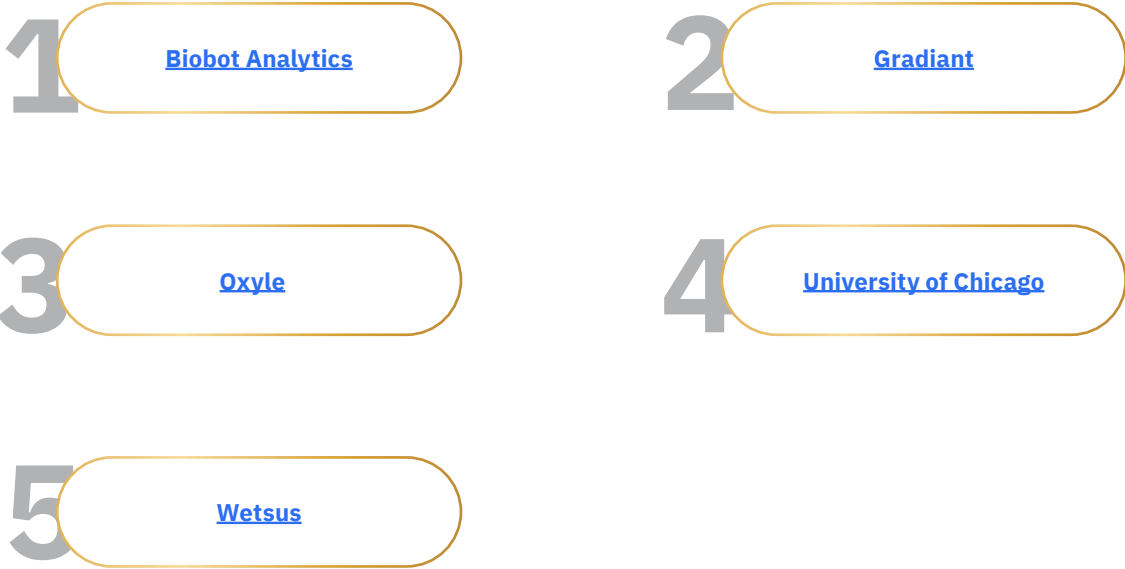


Technology Readiness Level [TRL]



Market Rediness Level (MRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Key Players



Insights and Statistics

AI-Driven Wastewater Treatment Optimization enhances efficiency, reduces costs, improves pollutant removal, and lowers emissions, driving sustainability and regulatory compliance in the water sector.

Impact and Key Stats

- **Energy Consumption:** Aeration, accounting for up to 60% of total energy consumption in treatment facilities, can be optimized with AI models that dynamically adjust aeration rates based on real-time water quality data, lowering energy usage in wastewater treatment plants by 30-50%. [Rockwell Automation](#)
- **Chemical Usage Savings:** AI-powered process control enables more precise dosing of coagulants, disinfectants, and other treatment chemicals, leading to a 10-30% reduction in chemical consumption, cost savings, and enhanced process stability. [Jacobs](#)
- **Pollutant Removal Accuracy:** AI models predict and enhance pollutant removal efficiency with an R² value between 0.64 and 1.00, meaning they provide highly accurate forecasts of treatment outcomes. This precision helps utilities meet regulatory standards and community expectations. [Water Sci Technol](#)
- **GHG Emissions Decrease:** AI-assisted wastewater treatment has reduced CO₂ emissions by up to 18% by optimizing aeration and sludge handling processes. This contributes to sustainability goals and aligns with global carbon reduction targets, making wastewater plants more eco-friendly. [Processes](#)
- **Operational Cost Reduction:** The use of AI for predictive analytics has led to a 10% reduction in operational expenses by streamlining maintenance schedules and optimizing resource allocation. Additionally, AI-Driven asset management extends the lifespan of critical equipment by 20%. [Processes](#)
- **Predictive Maintenance:** AI-based predictive maintenance reduces unexpected failures by 18%. By monitoring equipment performance and predicting failures before they occur, AI minimizes costly downtime and allows for proactive maintenance rather than reactive repairs. [Processes](#)

Technology Adoption

AI is reshaping wastewater treatment operations, with increasing adoption among digitally mature utilities, yet scalability, training, and regulatory clarity remain key challenges for broader market penetration.

Current State

- **Market Growth:** The global AI in water and sanitation market was valued at USD 3.77 billion in 2023 and is projected to reach USD 24.45 billion by 2031, growing at a CAGR of 26.8%. This significant growth indicates increasing adoption of AI technologies in wastewater treatment. [InsightAce Analytic](#)
- **Early-Stage Adoption:** AI adoption in wastewater treatment is still in its early stages. Larger utilities in digitally advanced regions are leading adoption, while smaller utilities lag. By the end of 2025, penetration is projected to rise to 25-30%, driven by cost reductions, proven ROI, and financial incentives. [Idrica](#)
- **Challenges in Adoption:** Despite the benefits, challenges such as laborious instrumentation maintenance, lack of process expertise in AI software design, and instability of control loops hinder wider AI adoption in wastewater treatment facilities. [Water](#)

Global Lessons Learned

- **Data Quality and Availability:** The effectiveness of AI in wastewater treatment heavily relies on high-quality, comprehensive datasets. Incomplete or inaccurate data can lead to erroneous predictions, underscoring the necessity for robust data collection and management systems. [Water Conditioning & Purification](#)
- **Integration Challenges:** Incorporating AI into existing wastewater treatment infrastructure can be complex and demanding. Compatibility issues between AI models and current systems require careful planning and design to ensure seamless integration and functionality. [Case Studies in Chemical and Environmental Engineering](#)
- **Economic Considerations:** The initial investment for AI technologies, including sensors, software, and training, can be substantial. However, these costs may be offset over time by operational efficiencies and cost savings, making it crucial to evaluate long-term benefits versus upfront expenditures. [Save the Water](#)

Outlook

AI-powered wastewater treatment is set to transform efficiency, resilience, and resource recovery, enabling smarter operations as digital adoption and regulatory frameworks evolve.

Key Signals of Change

- **Specialized Startups:** The water sector is witnessing a surge in startups focusing on AI applications for wastewater management. For instance, Kando raised \$10 million in 2024 to enhance its AI-based wastewater intelligence solutions, aiming to improve water quality and promote reuse. [StartupHub](#)
- **Venture Capital Investments:** In 2022, ZwitterCo, a company specializing in advanced filtration solutions, secured \$33 million in Series A funding, marking one of the largest investments in water technology startups. This signals growing investor confidence. [Global Water Awards](#)
- **Innovative Pilot Projects:** Drayton Valley's AI-driven ultrafiltration optimizes treatment in a small-town facility. This scalable model demonstrates AI's potential for decentralized, sustainable water treatment, benefiting resource-limited communities, setting a precedent for rural adoption. [Alberta Innovates](#)

Future Trajectory

- **AI-Driven Water Circularity:** AI can optimize real-time water reuse, dynamically allocating treated wastewater for industrial, agricultural, and potable use. This could enhance circular economy goals, improve resource efficiency, and support climate resilience strategies. [Nature](#)
- **Decentralized AI Micro-Treatment Units:** AI-powered, off-grid wastewater treatment units could autonomously manage processes, enabling water-stressed or disaster-prone areas to improve wastewater management without large-scale infrastructure, supporting decentralized, scalable, and adaptive treatment solutions. [Sustainability Directory](#)
- **Embedded AI in Smart Sensors:** AI-Driven sensors could autonomously detect pollutants, optimize treatment, and predict failures. These edge AI systems may reduce reliance on centralized computing, enabling faster, more efficient real-time wastewater optimization. [World Journal of Advanced Research and Reviews](#)





Case Study

WE WASSER [Germany]

In 2017, the Cuxhaven Wastewater Treatment Plant in Germany, operated by EWE WASSER GmbH, sought to improve energy efficiency and reduce operational costs while maintaining strict regulatory compliance. The plant partnered with [Xylem](#) to implement an AI-driven Treatment System Optimization, which analyzes real-time and historical data from the facility's SCADA system to predict optimal aeration set points.

Aeration, which accounts for nearly 60% of energy consumption in biological wastewater treatment, was a key focus for efficiency improvements. The AI solution continuously adjusted oxygen levels in response to influent variability, ensuring that energy was used only when necessary. Within the first year, the plant reduced aeration energy consumption by 30%, equating to annual savings of 1.1 million kilowatt-hours, enough to power 64 homes for a year. The system also optimized chemical dosing and sludge management, leading to additional cost reductions.

This case demonstrates how AI-driven wastewater treatment can enhance efficiency, sustainability, and cost savings, setting a precedent for broader adoption across utilities.

04

Leadership Insights





Innovating for a Sustainable Future: ENOWA on Water Technology Advancements



Water scarcity remains a pressing challenge worldwide, including in Saudi Arabia, due to population growth and climate change. The key water-related challenges are availability, cost, and energy use in water production and distribution. To address these challenges, innovative technologies are being developed to enhance efficiency and sustainability. One of the most promising advancements is brine valorization, which not only reduces water supply costs but also extracts valuable minerals from brine, such as sodium chloride. **“Brine valorization is not yet on everyone’s radar, but we are tracking it very closely because it has the great potential to transform the cost and energy for water production.”** In Saudi Arabia, a 1,000 m³/day Brine Valorization Plant in Duba has been established to validate these technologies. The extracted brine salt is crucial for producing liquid PVC, a strategic material for the GCC region. Saudi Arabia’s water innovation investments are primarily driven by the need to reduce energy consumption, lower water production costs, and minimize environmental impacts of desalination. Additionally, the country’s industrial expansion aligns with Vision 2030, which seeks to establish Saudi Arabia as a high-tech economic powerhouse.



Dr. Nikolay Voutchkov
Executive Director for Water Innovation Center - ENOWA



Innovating for a Sustainable Future: ENOWA on Water Technology Advancements



To support this transformation, the government has established the Research, Development, and Innovation Authority (RDIA) to accelerate water innovation. Over the next 5 to 10 years, the Saudi water innovation market is expected to experience rapid growth, driven by technological advancements, sustainability goals, and increased investments. For Saudi Arabia to become a global leader in water innovation, one strategic action is “to focus strategically on developing a 2030 roadmap for implementation of Saudi Water Innovation strategy in the field of desalination, **wastewater treatment and reuse** (Saudi Water Innovation Roadmap).” Other strategic action include establishing a centralized Innovation Hub with a steering committee to oversee and coordinate activities. Additionally, a strategic step that Saudi can take is encouraging entrepreneurship and startups through incubators, funding opportunities, and mentorship programs will help Saudi become a global leader. Another important strategic action is “Leveraging Digital Technologies by embracing digital transformation in water management through the use of **IoT, big data,** and AI. Implement **smart water management systems** that enhance efficiency, monitoring, and decision-making processes.”



Dr. Noura Chehab
Acting Head of Water Innovation Center- ENOWA

05

Appendix



Interviews – Questions for Private Sector Leader



Dr. Nikolay Voutchkov
(Executive Director for Water Innovation Center)
– ENOWA

Dr. Noura Chehab
(Acting Head of Water Innovation Center)
– ENOWA

1. What are the key water-related challenges, and how do technologies play a role in overcoming them?

The key water related challenges are: availability, costs and energy use to produce and convey water.

The world at large and KSA face water scarcity issues driven by population growth and global warming. New generation of water treatment and brine valorization technologies allow to significantly reduce cost of water supply by higher energy efficiency equipment. In addition, brine valorization technologies allow to extract valuable commercial minerals from brine which in turn can be sold commercially in order to offset the cost of water production.

2. What is not yet in everyone’s radar and you are closely following?

A. Brine Valorization is not yet on everyone's radar but we are tracking it very closely because it has the great potential to transform the cost and energy for water production. We are following very closely brine valorization and have created a 1000 m3/day Brine Valorization Plant in Duba, Saudi Arabia to develop and validate the next generation of brine valorization technologies. The main product from the brine valorization facilities is sodium chloride, which can be now produced at costs lower than that of terrestrial salt sources. Brine salt is used for production of liquid PVC, which of strategic importance of all GCC countries.

B. New generation plastic materials allowing multiple use via 3-D printing and replacement of high-pressure stainless steel piping with plastic piping - currently, most of the desalination plant capital and operations costs are associated with abating the corrosive nature of desalinated water. A number of plastics specialty contractors are looking forward to develop plastic piping that can withstand high pressures and thereby to eliminate the need to use high-pressure stainless steel piping.

C. Generation of energy by harvesting of osmotic pressure differential of brine and fresh water sources - brine mining results in the generation of very high salinity streams that along with specialty membranes for pressure retarded osmosis can generate electricity at low cost in membrane systems with low salinity liquids.

D. Multifunctional membranes - existing membranes can only perform one function - produce fresh water from saline water. Multifunctional selective membranes can not only produce fresh water but to also select and harvest specific mineral from the source seawater stream and ultimately produce two commercial products - drinking water and particular mineral.

E. Utilization of brine in constructions- exploring the use of brine or salt as a replacement for cement in concrete could significantly reduce CO2 emissions associated with traditional cement production.

3. What drives investments in water innovation in Saudi Arabia?

The need to reduce the energy, fresh water production costs and environmental impacts of desalination - these are main investment drivers. In addition, another driver is the expected industrial growth of KSA as the country is striving to implement vision 2030 where Saudi Arabia would attain a high-tech economic status.

4. How do you see the market for water innovation evolving in the next 5-10 years?

We see the innovation market in KSA entering an accelerated growth to respond to the needs defined in mission 2030. KSA has created a special government entity (RDIA) to support this water innovation growth.

5. How can Saudi Arabia position itself as a global leader in water innovation?

To become a global leader in water innovation, Saudi Arabia has to focus strategically on the following:

A. Develop a 2030 roadmap for implementation of Saudi Water Innovation strategy in the field of desalination, wastewater treatment and reuse (Saudi Water Innovation Roadmap).

B. Create an innovation Hub governed by a steering committee to coordinate all activities associated with the implementation of the Saudi Water Innovation Roadmap

C. Significantly increase investment in water innovation to implement the Saudi Water Innovation Roadmap

D. Create Joint council with industry to implement the advanced technologies developed as a result of the implementation of the water innovation roadmap.

E. Encourage Entrepreneurship and Startups: Create an ecosystem that supports water-focused startups and entrepreneurs through incubators, funding opportunities, and mentorship programs. This will stimulate innovation and bring new ideas to the market.

F. Leverage Digital Technologies: Embrace digital transformation in water management through the use of IoT, big data, and AI. Implement smart water management systems that enhance efficiency, monitoring, and decision-making processes.

Detailed Methodology

Following established practices such as the OECD Framework for Anticipatory Governance of Emerging Technologies, the content of this report was produced based using systematic horizon scanning — a continuous exploration of technological developments and early signals that highlight which innovations or socio-technical dynamics are gaining strategic relevance, whether as opportunities or potential threats.

By identifying and analyzing weak signals, horizon scanning uncovers nascent areas of technological interest, pinpoints key drivers of change, and provides insights into how these forces might evolve into transformative opportunities or critical risks. This initial, yet ongoing, phase functions as a comprehensive 360-degree assessment of early-stage technology landscapes, ensuring that decision-makers remain agile and informed in an era of rapid innovation.

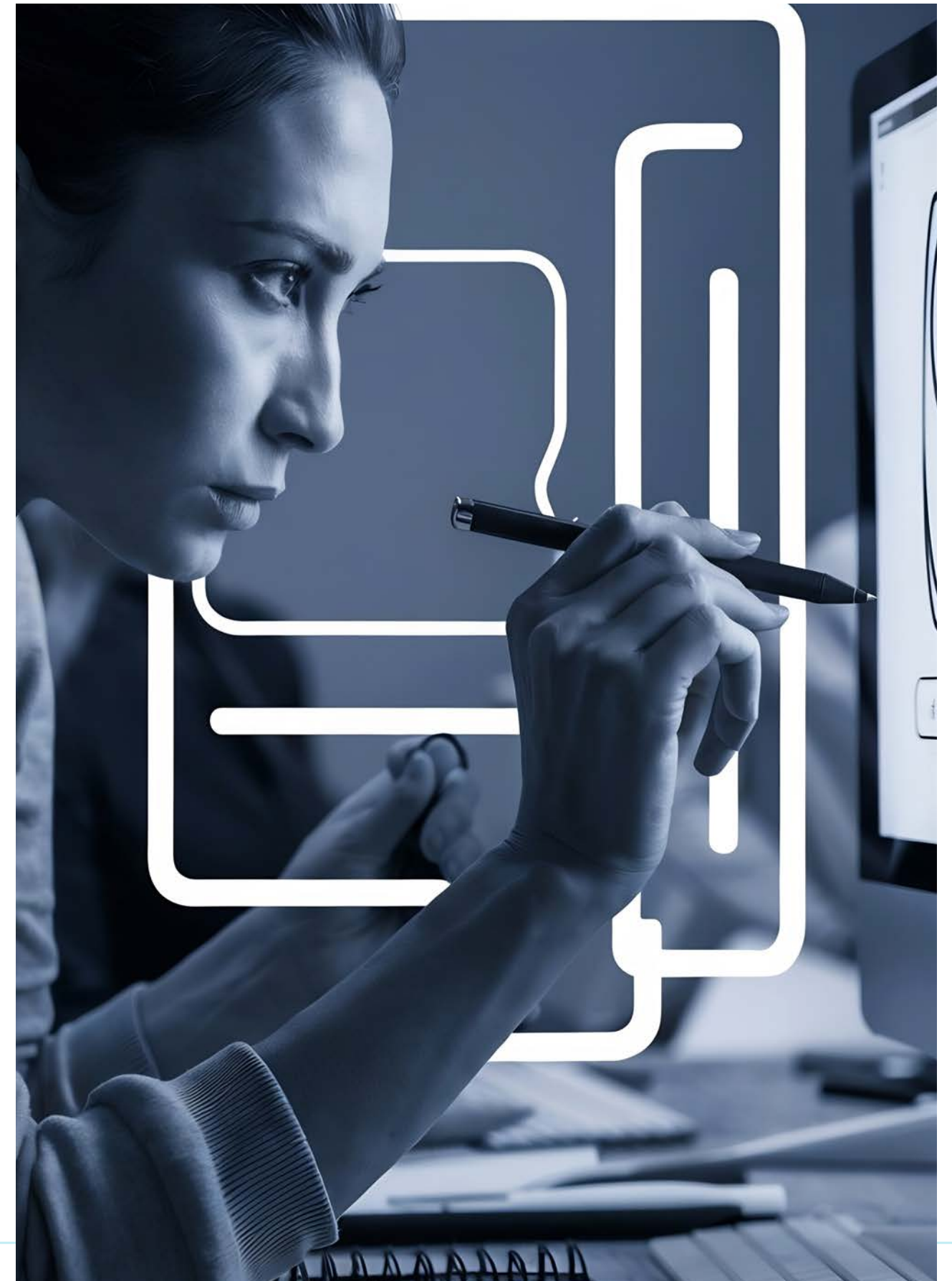
In an environment characterized by rapid technological advancements and new knowledge developed each day, information processing capacity is a key factor limiting the coverage of horizon scanning. To mitigate this challenge, MEWA deploys a scanning approach that combines the advantages of human expertise and machine intelligence, drawing on MEWA's NPRAS Platform database comprising over 10,000 source outlets (including scientific publications, patents, industry reports, and news) and over 100m datapoints which are updated twice daily.

Step #1 – Signal Collection & Technology Identification

Considering established practices, such as the Framework for Anticipatory Governance of Emerging Technologies (OECD 2024), the first analysis step involved the systematic collection and evaluation of signals to identify relevant technologies. To achieve this, the team employed a scanning method that combines the advantages of human expertise and machine intelligence, utilizing a signals database that contains over 100 million data points (e.g., patents, industry reports, scientific publications, etc.). Over the past five years, about 27,000 signals related to Wastewater Treatment and Reuse were sourced. Using Retrieval-Augmented Generation (RAG) AI and human expert validation, a longlist of 132 distinct technologies mentioned in Wastewater Treatment and Reuse was compiled for in-depth analysis.

Step #2 – Technology Assessment & Landscape Creation

In the second step, a comprehensive technology landscape was created from the longlist of the technologies mentioned in the signals. First, all technologies were eliminated that can no longer be considered as emerging, i.e., which have already entered mainstream adoption in relevant markets – e.g., “Smart Water Meters”. In addition, conceptual overlap among the technologies was minimized by subsuming similar or idiosyncratic technologies (e.g., “Robotic Sensors”, “Free-Swimming”, and “Untethered Systems”). Finally, the technologies were clustered into technology segments based on the purpose of use and functional characteristics. Finally, all technologies included in the landscape were evaluated on maturity level, impact potential, and ease of implementation following the criteria outlined in the MEWA [Water Technology Adoption Roadmap](#).



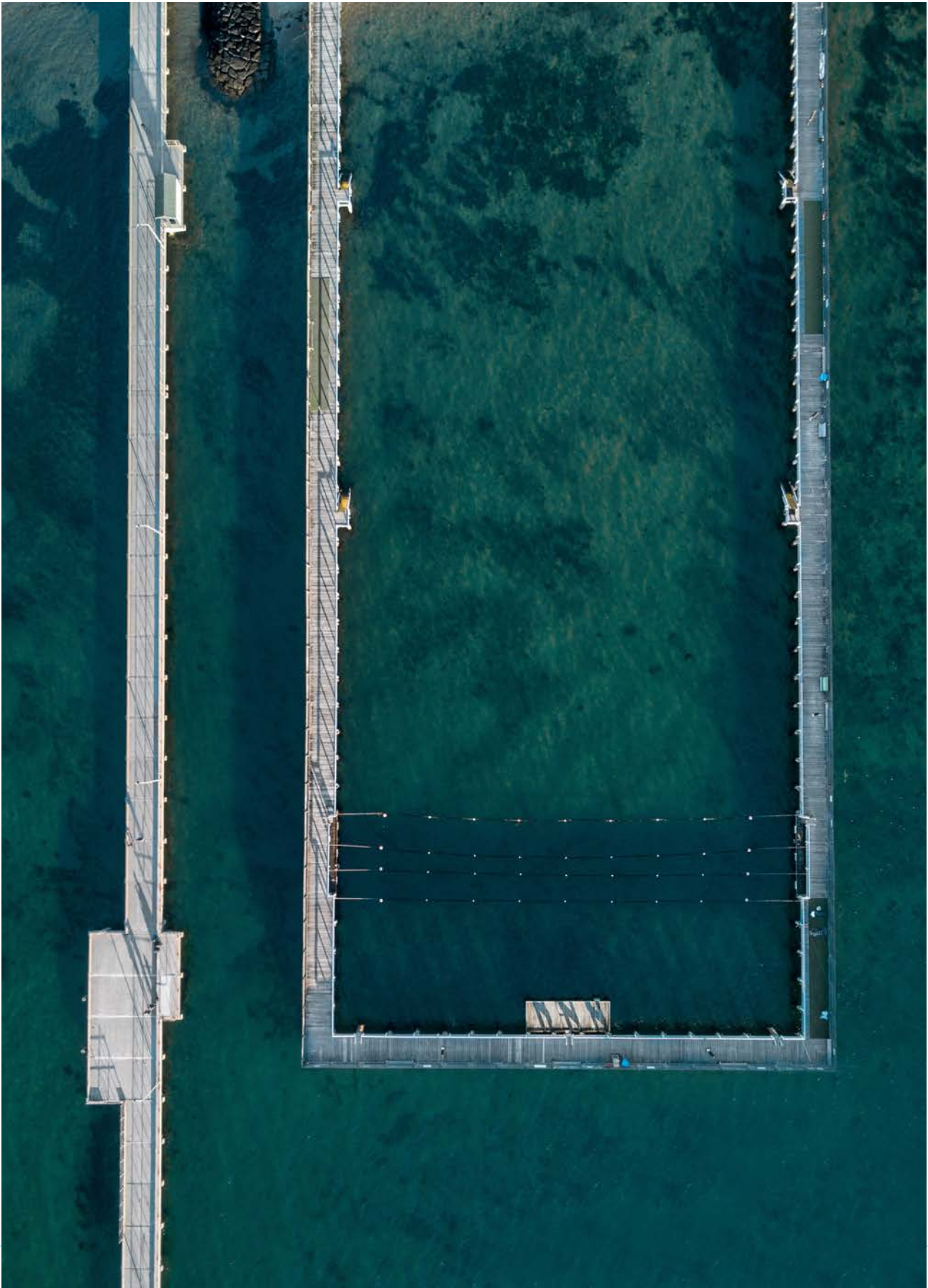
Selection Criteria Scorecard [1/2]

	Terminology	TRL	Impact Potential	Increase in Signals
1	AI-Enabled Treatment Optimization	6-7	Very High	Very High
2	Algal Turf Scrubber [ATS] Systems	8-9	Very High	High
3	Nanobubbles	8-9	Very High	High
4	Zero Liquid Discharge [ZLD] Systems	8-9	Very High	High
5	Thermal Hydrolysis	8-9	Very High	High
6	Digital Twins of Treatment Plants	8-9	Very High	High
7	Smart Sensor Networks	6-7	Very High	High
8	Microbial Fuel Cells [MFC]	6-7	Very High	High
9	Enzyme-based Treatment	4-5	Very High	High
10	Genetically-enhanced Microorganisms	4-5	Very High	High
11	Graphene-based Membranes	4-5	Very High	High
12	Moving Bed Biofilm Reactor [MBBR]	8-9	Very High	Medium
13	Membrane Bioreactors [MBRs]	8-9	Very High	Medium
14	Struvite Recovery	8-9	Very High	Medium
15	Co-Treatment Facilities	8-9	Very High	Medium
16	Hydrothermal Carbonization [HTC]	8-9	Very High	Medium
17	Solar Photocatalysis	6-7	Very High	Medium

	Terminology	TRL	Impact Potential	Increase in Signals
18	Forward Osmosis [FO]	6-7	Very High	Medium
19	Biogas-to-Hydrogen Recovery	6-7	Very High	Medium
20	PFAS Reductive Defluorination [PRD]	4-5	Very High	Medium
21	Aerobic Granular Sludge [AGS] Systems	8-9	Very High	Low
22	Solar-powered Treatment Plants	8-9	Very High	Low
23	Modular Graywater Treatment Systems	8-9	Very High	Low
24	Phytoremediation	6-7	High	High
25	Electrochemical Advanced Oxidation [EAOP]	6-7	High	High
26	Microbial Electrochemical Systems [MES]	4-5	High	High
27	Electrodialysis [ED]	8-9	High	Medium
28	Supercritical Water Oxidation [SCWO]	8-9	High	Medium
29	Ultrasonic Reactors	8-9	High	Medium
30	Mobile Wastewater Treatment Units	8-9	High	Medium
31	Large-scale Soil Filters	6-7	High	Medium
32	Membrane Distillation [MD]	6-7	High	Medium

Selection Criteria Scorecard [2/2]

	Terminology	TRL	Impact Potential	Increase in Signals
33	Sewer Mining	6-7	High	Medium
34	Electrocoagulation	6-7	High	Medium
35	Nanocellulose	4-5	High	Medium
36	Osmotic Membrane Bio-reactors [OMBRs]	4-5	High	Medium
37	High-Rate Algal Ponds [HRAPs]	6-7	Medium	Medium
38	Polymeric Composites	6-7	Medium	Medium
39	Plasma Arc Water Treatment	4-5	Medium	Medium
40	Hybrid Constructed Wetlands	8-9	Medium	Low



Glossary [1/4]

Maturity-Technical Readiness Level (TRL)

TRLs are used as a method of assessing the maturity of a technology being developed. It has a scale from 1-9 (from basic principles and research to actual proven systems and full commercial application)



Maturity-Market Readiness Level (MRL)

MRLs are used to assess the commercial readiness of a technology offering to give more context. It has a scale from 0-9 (from Ideation to scaling states)



sources:
1. TRL – Definition is designed by NASA https://esto.nasa.gov/files/trl_definitions.pdf. There is detailed description for hardware and software https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf
2. MRL - By a framework for Assessing Commercial Viability of [EU Cloud Services](#)

Glossary [2/4]

Terminology		Description
1	Moving Bed Biofilm Reactor (MBBR)	The Moving Bed Biofilm Reactor (MBBR) is a wastewater treatment process that utilizes free-floating plastic carriers within an aeration tank to support biofilm growth. These biofilms degrade organic pollutants, enhancing treatment efficiency and facilitating water reuse. MBBR systems are compact and adaptable to various wastewater types.
2	Hybrid Constructed Wetlands	Hybrid Constructed Wetlands integrate multiple wetland types, such as vertical and horizontal flow systems, to enhance the treatment of wastewater. This configuration effectively removes organic matter, nutrients, and pathogens, producing effluent suitable for reuse in irrigation or safe discharge.
3	Algal Turf Scrubber (ATS) technologies	Algal Turf Scrubber technologies utilize naturally occurring algae grown on sloped surfaces to treat wastewater. As water flows over the algal turf, the algae assimilate nutrients and contaminants, effectively improving water quality and enabling reuse.
4	Aerobic Granular Sludge (AGS) Systems	AGS systems utilize dense microbial granules to treat wastewater, offering efficient removal of organic matter and nutrients. The compact structure of these granules enhances settling properties, leading to improved treatment performance and reduced footprint compared to conventional activated sludge systems.
5	High-Rate Algal Ponds (HRAPs)	HRAPs are shallow, mixed ponds that utilize microalgae and bacteria to treat wastewater. Through photosynthesis, microalgae produce oxygen, which supports bacterial degradation of organic pollutants, effectively removing nutrients and contaminants. This process enhances water quality, making it suitable for reuse.
6	Large-scale Soil Filters	Large-scale soil filters are engineered systems that utilize soil's natural filtration capabilities to treat wastewater. As wastewater percolates through the soil matrix, physical, chemical, and biological processes remove contaminants, enhancing water quality for reuse. These systems are scalable for municipal and industrial applications.
7	Phytoremediation	Phytoremediation utilizes plants to remove, degrade, or stabilize contaminants in wastewater. Through processes like uptake and accumulation, plants such as Pontederia crassipes (water hyacinth) and Lemna minor (duckweed) effectively extract heavy metals and organic pollutants, enhancing water quality for reuse.
8	Enzyme-based Treatment	Enzyme-based treatment employs specific enzymes to catalyze the breakdown of organic pollutants in wastewater. These biocatalysts target contaminants such as phenols, estrogens, and other hazardous compounds, transforming them into less toxic or more biodegradable forms, thereby enhancing the efficiency of wastewater treatment processes.
9	Nanocellulose	Nanocellulose comprises cellulose nanoparticles derived from plant fibers, exhibiting high surface area and versatile surface chemistry. In wastewater treatment, nanocellulose-based materials serve as adsorbents and membrane filters, effectively removing contaminants such as heavy metals, dyes, and organic pollutants, thereby enhancing water quality for reuse.
10	Genetically-enhanced Microorganisms	Genetically-enhanced microorganisms are engineered to possess superior capabilities for degrading pollutants in wastewater. Through genetic modifications, these microbes can break down complex contaminants more efficiently, enhancing treatment processes and facilitating the safe reuse of treated water.

Terminology		Description
11	Electrodialysis [ED]	Electrodialysis employs an electric field to drive ions through selective ion-exchange membranes, effectively separating dissolved salts and impurities from wastewater. This process is particularly advantageous for desalination and the removal of specific ions, enhancing water quality for reuse.
12	Supercritical Water Oxidation [SCWO]	Supercritical Water Oxidation [SCWO] involves treating wastewater at temperatures and pressures above water's critical point [374°C and 221 bar], where it becomes a single-phase fluid. In this state, organic contaminants are rapidly oxidized into harmless byproducts like carbon dioxide and water, enabling efficient purification and potential water reuse.
13	Ultrasonic Reactors	Ultrasonic reactors utilize high-frequency sound waves to generate cavitation, disrupting sludge structures and enhancing the breakdown of organic pollutants in wastewater. This process improves biogas production and reduces residual sludge, facilitating more efficient wastewater treatment and promoting the reuse of treated water.
14	Electrochemical Advanced Oxidation [EAOP]	EAOPs involve the generation of hydroxyl radicals at the anode surface during electrolysis, which oxidize and decompose persistent organic pollutants in wastewater, leading to their mineralization and improved water quality for reuse.
15	Solar Photocatalysis	Solar photocatalysis utilizes sunlight to activate catalysts, generating reactive species that degrade organic pollutants and pathogens in wastewater. This sustainable method enhances water treatment efficiency, enabling the reuse of purified water in various applications.
16	Nanobubbles	Nanobubble aeration is an emerging technology that advances water treatment and management by introducing ultrafine gas bubbles into water to enhance oxygenation and break down contaminants.
17	Electrocoagulation	Electrocoagulation is a wastewater treatment process that uses electrical currents to dissolve sacrificial metal electrodes, releasing ions that neutralize and aggregate contaminants. This method effectively removes suspended solids, heavy metals, and emulsified oils, enhancing the quality of treated water for reuse.
18	Microbial Electrochemical Systems [MES]	MES utilize electroactive microorganisms to facilitate the conversion between chemical and electrical energy during wastewater treatment. These systems can degrade organic pollutants, generate electricity, and produce valuable chemicals, enhancing both treatment efficiency and resource recovery.
19	PFAS Reductive Defluorination [PRD]	involves the breakdown of per- and polyfluoroalkyl substances (PFAS) by cleaving the strong carbon-fluorine bonds through reductive chemical reactions. This process aims to degrade persistent PFAS contaminants in wastewater, facilitating safer water reuse and reducing environmental pollution.
20	Plasma Arc Water Treatment	Plasma Arc Water Treatment employs high-energy plasma arcs to generate reactive species that decompose organic pollutants and pathogens in wastewater. This advanced oxidation process effectively enhances water quality, facilitating its reuse in various applications.
21	Membrane Bioreactors [MBRs]	MBRs combine biological treatment processes with membrane filtration to effectively remove organic and inorganic contaminants from wastewater. This integration enhances effluent quality, making it suitable for various reuse applications, including irrigation and industrial processes.

Glossary [3/4]

	Terminology	Description
22	Zero Liquid Discharge [ZLD] Approach	ZLD Approach is advanced wastewater treatment processes designed to eliminate liquid waste by recovering and recycling all water, leaving only solid residues. They integrate physical, chemical, and thermal methods to treat wastewater, enabling water reuse and minimizing environmental discharge.
23	Forward Osmosis [FO]	Forward Osmosis utilizes a semipermeable membrane and an osmotic pressure gradient to draw water from wastewater into a concentrated draw solution, effectively separating contaminants. This process offers energy-efficient treatment and facilitates water reuse applications.
24	Polymeric Composites	Polymeric Composites are engineered materials combining polymers with fillers like carbon nanotubes or graphene oxide, enhancing mechanical strength and adsorption properties. In wastewater treatment, they are utilized in membranes and adsorbents to effectively remove contaminants, including heavy metals and organic pollutants, thereby improving water quality for reuse.
25	Membrane Distillation [MD]	Membrane Distillation is a thermally driven separation process where a hydrophobic membrane allows water vapor to pass through while retaining non-volatile contaminants. This technique is effective in treating high-salinity wastewater, enabling water reuse in various applications.
26	Osmotic Membrane Bio-reactors [OMBRs]	OMBRs integrate forward osmosis membranes with biological treatment processes, utilizing osmotic pressure to draw water through a semipermeable membrane. This approach effectively concentrates contaminants and enhances the removal of organic matter and nutrients, producing high-quality effluent suitable for reuse.
27	Graphene-based Membranes	Graphene-based membranes utilize the unique properties of graphene, such as atomic thickness and tunable functionalities, to enhance water purification processes. These membranes offer high permeability and selectivity, effectively removing contaminants and improving desalination efficiency in wastewater treatment and reuse applications.
28	Thermal Hydrolysis	Thermal hydrolysis is a sludge treatment process that uses high temperature and pressure to break down organic matter before anaerobic digestion. This pre-treatment enhances biogas production, reduces sludge volume, and produces pathogen-free biosolids suitable for agricultural use.
29	Struvite Recovery	Struvite recovery involves precipitating magnesium ammonium phosphate from wastewater streams, particularly from anaerobically digested sludge. This process not only mitigates scaling issues in treatment facilities but also produces a slow-release fertilizer rich in phosphorus and nitrogen, promoting sustainable agriculture.
30	Solar-powered Treatment Plants	Solar-powered treatment plants utilize photovoltaic systems to supply renewable energy for wastewater treatment processes. By harnessing solar energy, these facilities reduce reliance on fossil fuels, lower operational costs, and enhance sustainability, enabling efficient treatment and safe reuse of wastewater.
31	Hydrothermal Carbonization [HTC]	HTC is a thermochemical process that converts wet biomass, such as sewage sludge, into hydrochar by applying heat and pressure in a water medium. This process reduces sludge volume and produces hydrochar, a carbon-rich material with potential applications as a soil amendment or energy source.

	Terminology	Description
32	Microbial Fuel Cells [MFC]	Microbial Fuel Cells [MFCs] utilize the metabolic activities of microorganisms to oxidize organic matter in wastewater, generating electricity while simultaneously removing pollutants. This process offers a sustainable approach to wastewater treatment and facilitates the reuse of treated water.
33	Biogas-to-Hydrogen Recovery	In wastewater treatment, anaerobic digestion processes decompose organic matter to produce biogas, primarily composed of methane. This biogas can be utilized directly for heat and electricity generation or upgraded to biomethane. Additionally, advanced technologies enable the conversion of biogas into hydrogen, offering a clean energy source and reducing greenhouse gas emissions.
34	Mobile Wastewater Treatment Units	These units are portable, self-contained systems designed to provide immediate wastewater treatment solutions during emergencies, such as natural disasters or infrastructure failures. They can be rapidly deployed to restore sanitation services, ensuring environmental protection and public health safety. For instance, Veolia offers mobile water treatment systems that can be delivered to sites as needed, providing reliable and secure services.
35	Co-Treatment Facilities	Co-Treatment Facilities process multiple waste streams—such as municipal wastewater, industrial effluents, and septage—within a single treatment plant. This integrated approach optimizes resource utilization, enhances treatment efficiency, and reduces operational costs by leveraging existing infrastructure. For example, co-treating landfill leachate with municipal wastewater can effectively manage high-strength pollutants.
36	Digital Twins of Treatment Plants	Digital twins are dynamic, virtual replicas of physical wastewater treatment plants that integrate real-time data and advanced simulations. They enable operators to monitor processes, predict system behaviors, and optimize performance, enhancing treatment efficiency and facilitating the safe reuse of treated water.
37	Modular Graywater Treatment Systems	Modular graywater treatment systems are compact, scalable units designed to treat and recycle graywater from sources such as showers, sinks, and washing machines. Utilizing physical, biological, and chemical processes, these systems purify water for non-potable uses like toilet flushing and irrigation, promoting water conservation and sustainability.
38	Sewer Mining	Sewer mining involves extracting untreated wastewater directly from municipal sewers, treating it on-site, and producing high-quality water for non-potable uses such as irrigation or industrial processes. This decentralized approach addresses urban water scarcity by enabling localized water reuse and reducing the demand on centralized treatment facilities.
39	Smart Sensor Networks	These sensors utilize Internet of Things [IoT] technology to continuously monitor wastewater parameters such as pH, turbidity, and chemical composition. They provide real-time data, enabling prompt detection of anomalies, enhancing treatment efficiency, and ensuring compliance with environmental standards.
40	AI-Driven Treatment Optimization Methods	This technology leverages artificial intelligence to analyze real-time and historical data from wastewater treatment processes, enabling predictive analytics and dynamic control. By optimizing parameters such as chemical dosing and aeration, AI enhances treatment efficiency, reduces operational costs, and improves effluent quality.

Glossary [4/4]

Terminology		Description
41	RAG AI	Retrieval-Augmented Generation [RAG] AI technique combining search and AI responses.
42	Smart Metering	The use of digital devices equipped with sensors and communication technologies to automatically measure, record, and transmit water usage data in real time or at scheduled intervals.
43	Ease of Implementation	The level of practicality and feasibility in deploying a technology within an existing system. This includes factors such as infrastructure readiness, technical complexity, cost of adoption, and required expertise. Technologies with high ease of implementation can be integrated with minimal modifications, while those with low ease of implementation may require extensive adjustments, new infrastructure, or specialized training.
44	Potential Impact	The expected effectiveness and long-term benefits of a technology in addressing key challenges in water management. This includes its ability to enhance efficiency, reduce costs, improve sustainability, and optimize resource use. In wastewater treatment, high-impact technologies contribute to water reuse, energy recovery, and environmental protection, while in smart leakage management, they help reduce water loss, improve network resilience, and enhance operational efficiency.
45	Impact	The measurable outcome and influence of a technology on improving water systems. This includes its contribution to reducing waste, increasing efficiency, conserving resources, and enhancing service reliability. In wastewater treatment, impact is measured through improved water quality and sustainability, whereas in smart leakage management, it is assessed by the reduction of non-revenue water [NRW], enhanced leak detection, and improved infrastructure lifespan.



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