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Review

Circular Economy Approaches in Industrial Wastewater Management Across Asia: Policy Frameworks, Water Reuse, and Resource Recovery Opportunities

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Abstract

The conventional linear "treat-and-discharge" model has been challenged due to rapid urbanisation and the increasing generation of complex industrial wastewater. To this end, circular economy (CE) approaches can be considered as a key strategy for resource efficiency, sustainability, and waste reduction. The current study aims to review CE principles in industrial wastewater management policies across Asian countries. Findings from our review indicate that countries such as Singapore, Japan, South Korea, and China have made significant progress through integrated institutional frameworks, standards of reclaimed water, eco-industrial park initiatives, advanced treatment technologies, and supportive policy mechanisms. However, some developing Asian economies still depend primarily on pollution-control regulations and effluent discharge compliance; have limited guidelines on application-specific water-reuse quality standards, limited financial and tax incentives for SMEs, and inadequate policy support for resource recovery and wastewater valorisation. Strengthening these policy and institutional frameworks can promote circular industrial wastewater management, thus enhancing water security, resource efficiency, and sustainable industrial development across Asia.

Keywords: circular economy; industrial wastewater; resource recovery; water reuse; Asia; policy instruments

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1. Introduction

Asia is experiencing rapid urbanisation and industrial development. The region accounts for approximately 60% of the world's population and includes some of the fastest-growing economies. These changes have significantly increased industrial wastewater generation [1,2]. Some of the major challenges with rapid industrialisation and urbanisation are water scarcity and industrial pollution issues. In particular, the traditional linear water management model of "take, use, and dispose" has contributed to overexploitation of freshwater resources which has affected aquatic ecosystems. For example, countries such as China, India, Vietnam, and Indonesia experiencing rapid industrialisation generate large volumes of complex wastewater containing heavy metals, organic pollutants, nutrients, and

other emerging contaminants [3]. However, most Asian countries lack adequate wastewater treatment technologies, posing significant risks to both ecosystem integrity and public health through widespread contamination of rivers, lakes, and coastal waters [4,5]. From the perspective of economic consequences, the Asian Development Bank has reported the pollution-related impacts on agriculture, fisheries, tourism, and the healthcare sector which resulted in annual economic losses equivalent to 0.5% to 2.5% of the gross domestic product (GDP) [6].

The continued expansion of urban populations has further intensified pressures on wastewater management systems. The urban population in the Asian region is expected to reach approximately 3.5 billion by the year 2050, representing a substantial increase compared to the year 2010 [7]. However, wastewater collection and treatment infrastructure have not expanded at the same pace in many countries. Peri-urban industrial areas are particularly vulnerable, since they usually lack adequate wastewater treatment facilities while accommodating a high concentration of industrial activities near densely populated residential communities. As a result, untreated or inadequately treated wastewater continues to threaten environmental quality, public health, and the long-term sustainability of regional water resources [8]. Conventional wastewater treatment systems were originally developed to minimise pollutant loads in treated effluent prior to environmental discharge [9,10]. However, such systems are increasingly considered inadequate for addressing the growing complexity and volume of industrial wastewater generated across Asia.

Several limitations can be associated with conventional approaches such as end-of-pipe treatment technologies which consume significant energy, i.e., 0.3 and 0.6 kWh per cubic metre of treated wastewater without recovering the energy embedded in organic compounds [11,12]. Next, conventional biological treatment processes often remove or destroy valuable nutrients such as phosphorus and nitrogen rather than recovering them for agricultural reuse, contributing to both resource depletion and eutrophication of receiving water bodies. In addition to that, the high capital and operational costs of advanced treatment technologies create financial barriers for small and medium enterprises (SMEs) particularly in developing Asian economies. Conventional systems are also poorly adapted to the variable and complex nature of industrial effluents, which require specialised treatment trains that may not be economically feasible for individual facilities.

These limitations are further exacerbated by existing regulatory frameworks, which primarily focus on compliance with effluent discharge standards rather than promoting resource recovery and circularity. As a result, industries often have limited incentives to invest in technologies that enable the recovery of valuable resources such as water, energy, nutrients, and reusable materials from wastewater streams. Although CE approaches to wastewater management have gained significant research interest in the past decade, existing reviews have mostly focused on individual countries, specific technologies, or particular aspects of water reuse and resource recovery. A systematic cross-country comparison of circular industrial wastewater management across Asian economies at different stages of regulatory and technological development remains limited. To this end, the current review addresses this gap by comparatively examining selected Asian countries across common policy and implementation dimensions, including regulatory frameworks, water reuse standards, resource recovery, technology adoption, economic mechanisms, and governance. This approach enables the identification of differences in CE maturity, common implementation barriers, and transferable policy practices across the Asian region.

1.1. Circular Economy in Wastewater Management: Resource Recovery and Water Reuse

The Circular Economy (CE) framework seeks to transform from the conventional linear "treat and discharge" model towards a resource-oriented approach that recognises

industrial wastewater as a valuable resource stream containing recoverable water, energy, nutrients, and other useful materials [8]. Through the principles of resource recovery, recycling, and reuse, CE provides a strategic pathway for Industrial Wastewater Management (IWM) by promoting waste prevention, resource efficiency, and long-term environmental sustainability. The CE-based approach to IWM is based on the principle of waste elimination, continuous resource recirculation, system regeneration, and sustainable economic growth. Through the closure of water, energy, and material loops, industrial wastewater is no longer regarded as a waste product but as a resource stream capable of generating economic, environmental, and social benefits.

There are three components for CE-based IWM approaches, i.e., reclamation and reuse of water, resource recovery and industrial symbiosis. Reclamation and reuse of water involve treatment of industrial effluent to meet water quality requirements for its reuse in non-potable or fit-for-purpose applications, thereby reducing freshwater consumption while minimising wastewater discharge to the environment. Resource recovery focuses on extracting valuable resources from wastewater streams, including nutrients such as phosphorus and nitrogen, energy through anaerobic digestion and biogas production, and high-value materials such as metals and biopolymers [13,14]. Industrial symbiosis extends the concept of resource efficiency beyond individual facilities by encouraging collaboration among multiple industries, where wastewater, by-products, energy, and treatment infrastructure from one facility can be used by another to develop mutually beneficial resource exchanges that improve operational efficiency, reduce waste generation, and reduce overall treatment costs. Such collaborative networks enable participating industries to achieve levels of resource optimisation and sustainability that would otherwise be difficult to achieve independently. Figure 1 illustrates the integration of circular economy principles within wastewater treatment systems, highlighting opportunities for water reuse, nutrient recovery, energy generation, and material valorisation through interconnected resource recovery pathways [15].

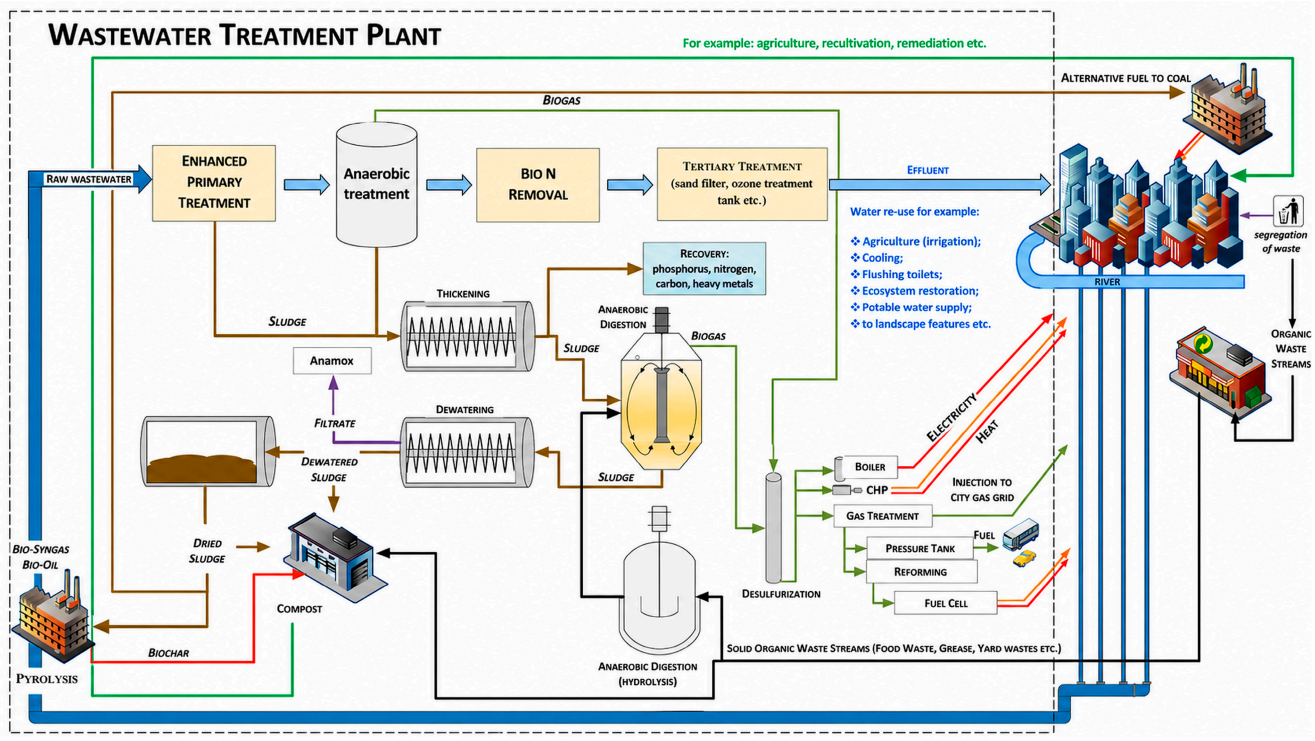


Figure 1. CE pathways for resource recovery and water reuse in wastewater treatment systems. Adapted from [15].

The CE frameworks are closely aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production). For example, the CE-based wastewater management practices that encourage water reuse, resource recovery, and efficient resource utilisation can contribute directly to sustainable industrial development and environmental protection. The increasing water stress in the Asian region coincides with rapid industrial growth and the adoption of CE practices in wastewater management can be considered as both an environmental necessity and a strategic economic opportunity to enhance resource security, industrial competitiveness, and long-term sustainability [16]. Figure 2 summarises the CE approaches in industrial wastewater management among Asian countries.

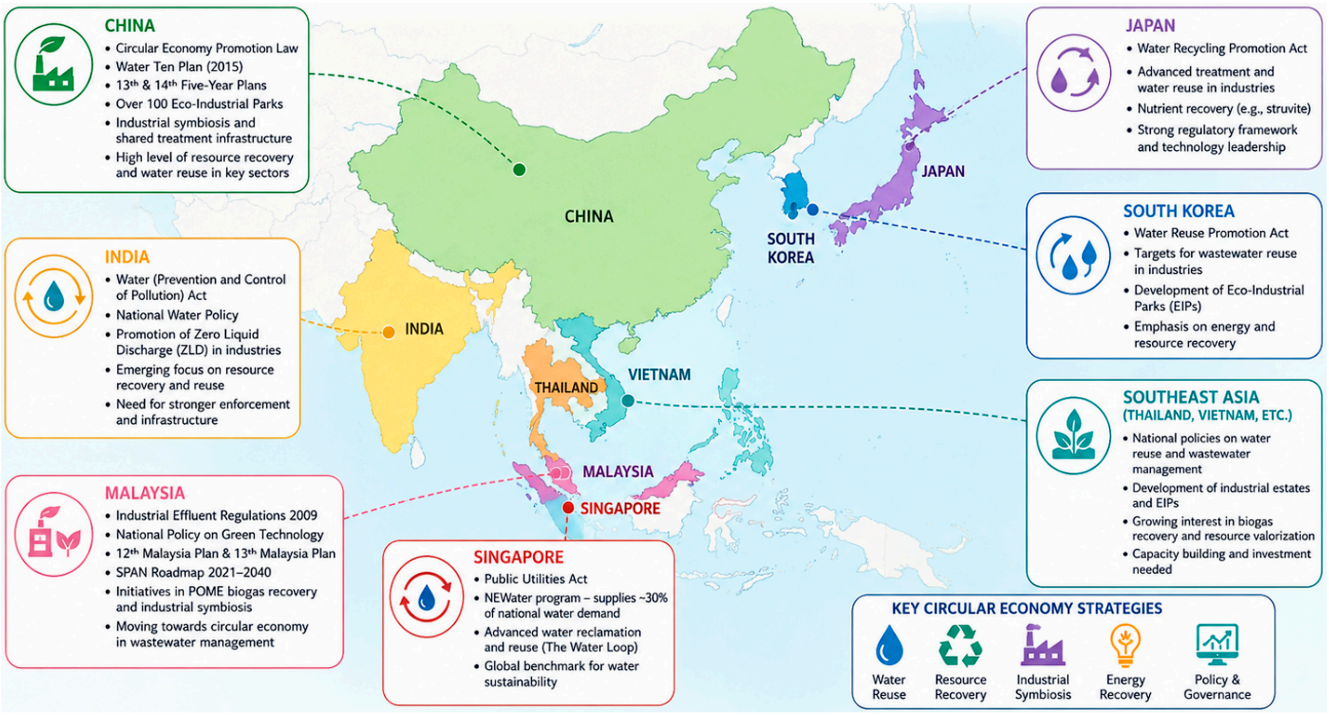


Figure 2. CE approaches in industrial wastewater management among Asian countries which include major policy instruments, water reclamation programmes, resource recovery initiatives, and eco-industrial park developments to promote sustainable wastewater management, resource efficiency, and water security.

An important consideration in CE-based wastewater management is the potential recirculation of emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) and pharmaceutical residues. Conventional wastewater treatment may not completely remove these contaminants; a recent global assessment of 402 wastewater treatment plants reported PFAS concentrations of up to 4220 ng/L in influent and 4310 ng/L in effluent, with some PFAS exhibiting low or apparently negative removal efficiencies [17]. Similarly, pharmaceutical contaminants are increasingly detected in wastewater across Asia; a Southeast Asian review reported mean influent concentrations of approximately 567.4 ng/L for ciprofloxacin and 26,000 ng/L for paracetamol [18]. This is particularly important within a CE framework because contaminants that are not completely removed may be transferred or recirculated through reclaimed water, biosolids, nutrient-recovery streams, or other treatment residuals rather than eliminated. Although advanced treatment processes such as reverse osmosis can improve the removal of micropollutants, their implementation introduces additional energy, cost, and residual-management requirements [19,20]. These

concerns also reveal an important policy gap, as wastewater and reuse regulations in many Asian countries remain primarily focused on conventional water-quality parameters, with limited contaminant-specific requirements for PFAS and pharmaceuticals in reclaimed water and recovered resources. Therefore, CE policies should incorporate risk-based monitoring, source control, appropriate advanced treatment, and contaminant-specific safety criteria to prevent unintended recirculation of persistent contaminants.

1.2. Research Design

A bibliometric analysis from the Scopus database was used to map the general growth and geographic distribution of CE–industrial wastewater research. The search was conducted in late May 2026 using the keywords "industrial wastewater" and "circular economy" for the period 2015–2025. This search showed a substantial increase in publication output, i.e., from three documents in 2015 to 452 documents in 2025, indicating increasing global interest in CE-based wastewater management (Figure 3A). Environmental Science, Engineering, and Chemical Engineering were the dominant subject areas, reflecting the interdisciplinary nature of the field (Figure 3B). India and China recorded the highest publication outputs among Asian countries, followed by Malaysia and South Korea, highlighting rising attention on wastewater reuse, resource recovery, and CE implementation (Figure 3C).

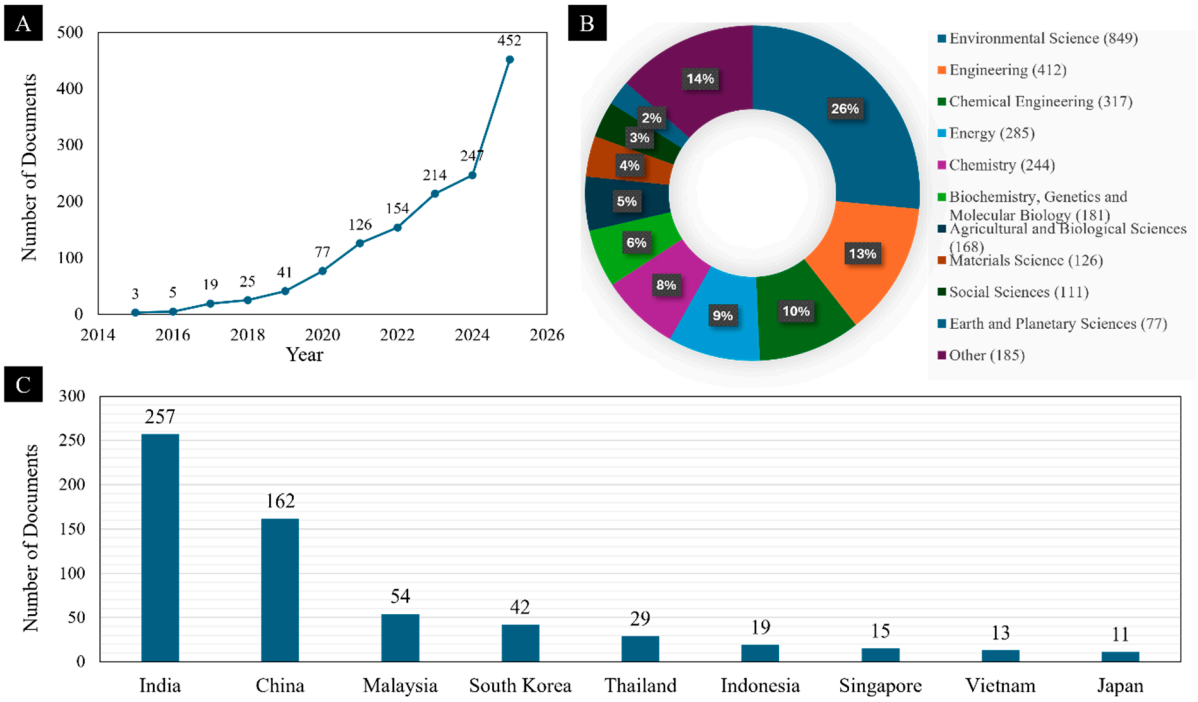


Figure 3. Bibliometric analysis of CE and industrial wastewater management research data based on Scopus database (2015–2025). (**A**) Annual publication trend (**B**) Distribution of publications by subject area (**C**) Publication output of selected Asian countries.

Based on this bibliometric mapping and on regional diversity in policy maturity, nine Asian countries were selected for in-depth review, i.e., Singapore, Malaysia, China, India, Japan, South Korea, Thailand, Vietnam, and Indonesia. From Figure 3C, it can be seen that China, India, Malaysia, and South Korea have contributed to most of the CE–wastewater research output in Asia. Other Asian countries are also included in this paper to span contrasting stages of regulatory maturity and CE adoption from established water-reuse regimes (Singapore, Japan) to industrialising economies with emerging CE frameworks (Thailand, Vietnam, Indonesia). This purposive sampling was intended to enable a compar-

ative policy analysis rather than an exhaustive survey of all Asian economies. To this end, the bibliometric scan (Figure 3) was used only as a scoping and selection tool and was not extended into network-level analyses (e.g., co-citation or keyword co-occurrence mapping), which fall outside the scope of a narrative policy review.

Country-level policy and regulatory information was compiled through a targeted literature and grey-literature search combining the core terms ("circular economy" AND "wastewater" AND "[country name]") with each country name, drawing on Scopus, Google Scholar, and national government/environmental agency publications. Sources were included if they addressed wastewater-related policy, regulation, water reuse standards, or resource recovery in the selected countries and were published in English; non-peer-reviewed sources without institutional or governmental attribution were excluded.

The analysis was structured around six policy and implementation dimensions: (i) regulatory frameworks, (ii) water reuse standards, (iii) resource recovery initiatives, (iv) technology adoption, (v) economic and financial mechanisms, and (vi) implementation and governance. The study compares these dimensions across countries and identifies common policy gaps, including limited financial incentives, weak enforcement, lack of water reuse standards, insufficient technical capacity, and low stakeholder acceptance. To ensure a consistent and transparent comparison across the selected Asian countries, these six analytical dimensions are operationally defined in Table 1.

Table 1. Operational definitions of the six analytical dimensions used in this review.

Analytical Dimension	Operational Definition
Regulatory frameworks	National laws, regulations, policies, and institutional mechanisms governing industrial wastewater treatment, reuse, and resource recovery.
Water reuse standards	Standards, guidelines, and regulatory requirements governing the quality, safety, monitoring, and permitted applications of reclaimed wastewater.
Resource recovery initiatives	Initiatives for recovering water, energy, nutrients (e.g., N and P), metals, and other valuable materials/by-products from industrial wastewater and sludge.
Technology adoption	Application of treatment, reclamation, recovery, monitoring, and digital technologies that support circular wastewater management.
Economic and financial mechanisms	Financial incentives, subsidies, funding programmes, investment mechanisms, cost considerations, and other economic instruments supporting CE adoption.
Implementation and governance	Institutional coordination, enforcement, technical capacity, stakeholder participation, public acceptance, monitoring, and practical implementation barriers.

2. Circular Economy Implementation in Industrial Wastewater Management Across Selected Asian Countries

2.1. Singapore

Singapore can be considered a global leader in the implementation of CE principles for industrial wastewater management, attributed mainly to its limited freshwater resources and the need to ensure long-term water security as a highly urbanised city-state [9,21]. The country's integrated water management framework is governed by the Public Utilities Board (PUB) under the Public Utilities Act, which oversees water supply, wastewater collection, treatment, and water reclamation through a unified management system. Figure 4 illustrates Singapore's circular water management strategy and its implementation through the NEWater programme; where Figure 4A demonstrates the PUB water loop framework that integrates water collection, treatment, reclamation, and reuse within a closed-loop sys-

tem while Figure 4B presents the Changi NEWater treatment process, where wastewater is reclaimed through microfiltration, reverse osmosis, and ultraviolet disinfection to support industrial water reuse and enhance national water security.

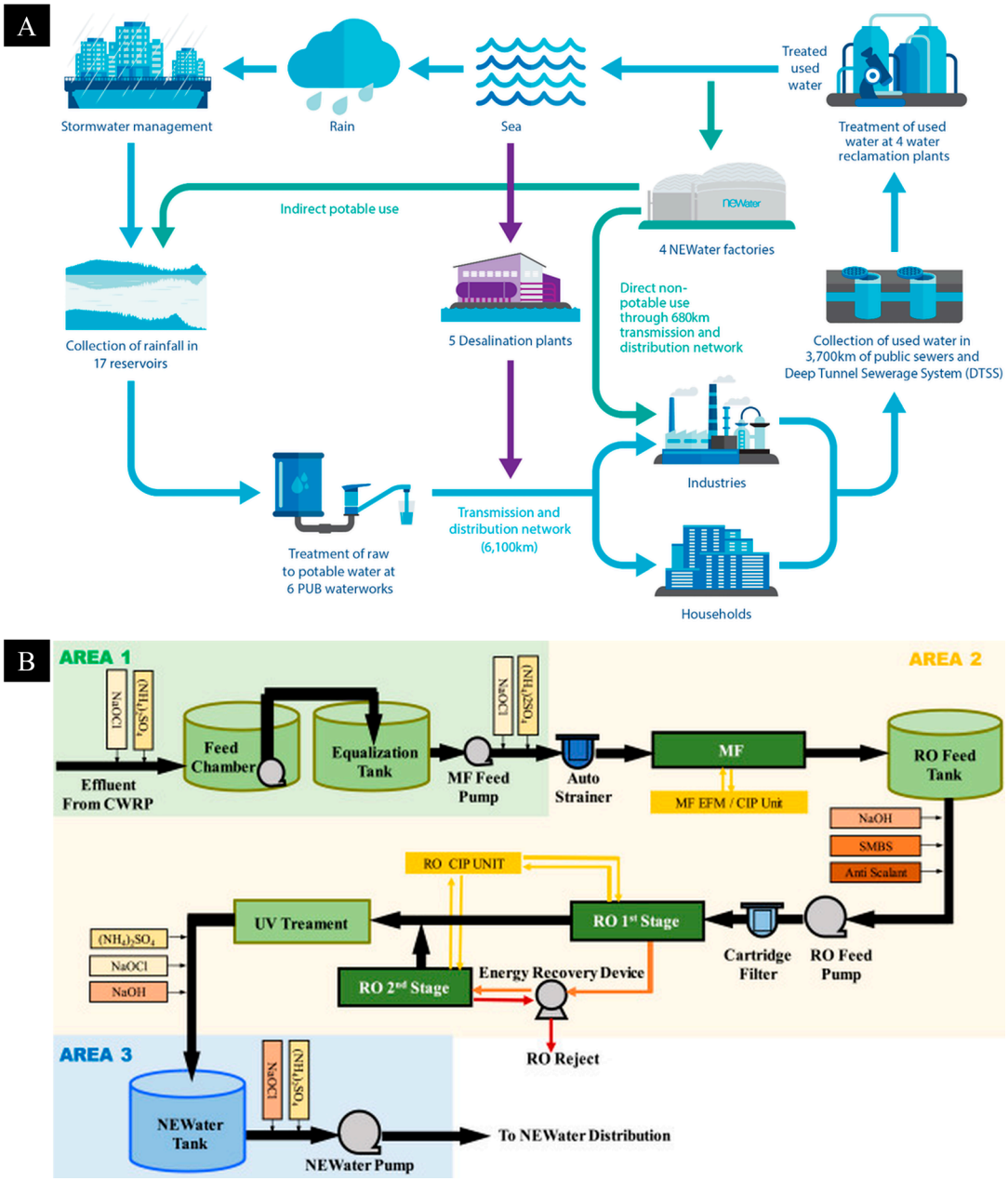


Figure 4. Singapore's circular water management strategy and implementation of the NEWater programme. (**A**) PUB water loop framework demonstrating the integration of water collection, treatment, reclamation, and reuse within a circular economy approach; extracted from PUB Singapore https://www.pub.gov.sg/public/waterloop (accessed on 23 August 2026). (**B**) Changi NEWater Project Phase 2 process flow diagram illustrating the microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) treatment stages used for water reclamation [21].

The NEWater programme is a clear demonstration of the application of circular economy principles to water management since the start of the NEWater programme in 2000, with the commissioning of the first NEWater reclamation plant and an increased number of reclamation facilities from one to five over time [22]. The upgraded facilities operate on a multi-barrier treatment method, which consists of microfiltration (MF), reverse osmosis (RO), and ultraviolet (UV) disinfection to produce high-quality reclaimed water from

treated wastewater effluent. NEWater presently contributes around 30% of Singapore's water supply and is primarily used in heavy industrial sectors such as electronics and semiconductors and in the indirect supply of potable drinking water through replenishing reservoirs.

To further promote industrial water reuse, Singapore has introduced various financial and technical support programmes that encourage industries to invest in water recycling and reuse technologies [23]. These initiatives help reduce dependence on freshwater resources while minimising wastewater discharge from industrial facilities. In addition, resource recovery has been integrated into wastewater management through the utilisation of sludge-derived biogas in combined heat and power (CHP) systems at water reclamation facilities, improving energy efficiency and supporting the long-term goal of energy self-sufficiency [24]. Singapore's experience demonstrates that successful implementation of CE principles in wastewater management requires strong institutional governance, sustained public investment, technological innovation, and effective stakeholder engagement [9]. The integration of water security objectives with industrial development policies has allowed the country to transform wastewater from a disposal challenge into a strategic resource.

Despite its success, the NEWater programme requires advanced membrane technologies that are associated with considerable capital investment and operational energy demand, particularly during reverse osmosis treatment. Long-term sustainability therefore depends on continuous optimisation of membrane performance, energy efficiency, and operational costs. Nevertheless, Singapore demonstrates that strong institutional governance, transparent public communication, and gradual public engagement have enabled reclaimed water to achieve high societal acceptance, providing an important lesson for other Asian countries seeking to expand potable and industrial water reuse.

2.2. Malaysia

The Environmental Quality (Industrial Effluent) Regulations 2009 (IER 2009) are the primary regulatory framework that governs industrial wastewater management in Malaysia [25]. The regulations establish effluent discharge standards for a wide range of industrial sectors and provide the legal basis for controlling industrial wastewater discharges into the environment. IER 2009 has introduced stringent limits for heavy metals, organic pollutants, and other contaminants compared to previous regulations, to enhance environmental protection and improve wastewater treatment practices across industries. However, from a circular economy perspective, the IER 2009 framework mostly focuses on effluent quality management such as pollution control and discharge compliance with limited provisions that promote water reuse, resource recovery, nutrient recycling, or energy recovery from wastewater streams. Hence, opportunities to transform industrial wastewater into a valuable resource remain underutilised within the IER2009 regulatory framework.

The National Green Technology Policy (2009) and the National Green Technology and Climate Change Master Plan broadly support CE principles by promoting resource efficiency, sustainable resource management, and environmental sustainability [26–28]. However, these policies have minimal provisions which addresses resource recovery from industrial wastewater. The previously established Twelfth Malaysia Plan spanning from the year 2021 to 2025 has incorporated CE objectives across multiple sectors and recognises wastewater as a potential resource rather than merely a waste stream, marking an important step towards the integration of CE principles into national policy. Currently, the Thirteenth Malaysia Plan (2026–2030) aligns with Phase 2 of the Water Sector Transformation 2040 (WST 2040), which focuses on accelerating the adoption of Integrated Water Resources Management (IWRM), developing indigenous water technologies to meet international standards, achieving economies of scale, and strengthening Malaysia's position as a regional

water industry hub. These strategic priorities provide a stronger policy foundation for advancing industrial water reuse, resource recovery, and circular wastewater management initiatives in Malaysia.

Emerging initiatives in Malaysia such as the Iskandar Malaysia development corridor in Johor have piloted an eco-industrial park concept that includes shared wastewater treatment infrastructure and resource recovery provisions [29,30]. In addition, Malaysia demonstrates the practical application of circular economy principles by converting agro-industrial wastewater, especially palm oil mill effluent (POME), into valuable resources. By installing anaerobic digestion systems, operators can capture biogas for renewable energy while reducing the environmental impacts related to the discharge of untreated effluent. These examples demonstrate that wastewater should not be regarded merely as a waste stream but rather as a valuable resource that can be converted into energy and other useful by-products. The summary of major policies, plans, and initiatives supporting circular economy practices in wastewater management in Malaysia is shown in Table 2.

Table 2. Summary of major policies, plans, and initiatives supporting circular economy practices in wastewater management in Malaysia.

Policy/Initiative	Year	Contribution to Circular Economy in Wastewater Management
Industrial Effluent Regulations (IER)	2009	Provides standards on industrial wastewater discharge; however have limited focus on water reuse and resource recovery
National Green Technology Policy	2009	Promotes resource efficiency, sustainable development, and green technologies
National Green Technology and Climate Change Master Plan	2017–2030	Encourages circular economy adoption and sustainable resource utilisation
Twelfth Malaysia Plan	2021–2025	Recognises wastewater as a resource and supports circular economy implementation across sectors
Thirteenth Malaysia Plan	2026–2030	Strengthens circular economy adoption, resource efficiency, environmental sustainability, and water security initiatives, providing further support for wastewater reuse and resource recovery practices
SPAN Water Reclamation Roadmap	Ongoing	Provides a framework for wastewater reclamation, recycling, and reuse
Iskandar Malaysia Eco-Industrial Initiatives	Ongoing	Promotes industrial symbiosis, shared wastewater infrastructure, and resource recovery
POME Resource Recovery Programmes	Ongoing	Facilitates biogas production, renewable energy generation, and nutrient recovery from wastewater

The relatively slow transition from the IER 2009 compliance-based framework towards CE-based industrial wastewater management can be attributed to Malaysia's divided institutional responsibilities. Industrial effluent discharge is regulated by the Department of Environment (DOE) under the Environmental Quality Act 1974 (Act 127) and the Environmental Quality (Industrial Effluents) Regulations 2009 [P.U.(A) 434/2009] [31], which primarily establish requirements and standards for the discharge of industrial effluent into inland waters. However, wastewater reclamation, water services, and broader water-resource management involve other federal and state institutions, creating a need for stronger inter-agency coordination. DOE itself has reported that only approximately 20–30% of pollution sources within a river basin fall under its jurisdiction, while the remaining 70–80% are under other agencies [32]. This division of regulatory responsibilities

can complicate the integration of effluent control with water reuse and resource-recovery objectives. Furthermore, IER 2009 remains primarily discharge-oriented and does not establish a comprehensive framework of reuse targets, economic incentives, or resource-recovery requirements. Consequently, stronger coordination between environmental, water-service, and state water authorities is required to accelerate Malaysia's transition from pollution-control compliance towards CE-based industrial wastewater management.

2.3. China

China has been widely recognised as a leader among other Asian countries, where they have integrated CE principles into industrial wastewater management through comprehensive policy and regulatory frameworks. The enactment of the Circular Economy Promotion Law in 2008, which was later revised in 2018, established a legal foundation for the adoption of CE practices across key sectors including manufacturing, agriculture, and energy production [33]. This legislation promotes resource efficiency, waste reduction, recycling, and industrial symbiosis to ensure favourable conditions for the implementation of circular wastewater management strategies.

China further strengthened its commitment to sustainable water management through the Water Pollution Prevention and Control Action Plan (commonly known as the Water Ten Plan) introduced in 2015 [34]. The policy established ambitious targets for industrial water conservation and reuse, particularly in water-intensive sectors. Key industries were encouraged to achieve high levels of water recycling and reuse, while water-scarce regions were required to adopt stricter water management practices and advanced wastewater treatment technologies to minimise freshwater consumption and pollutant discharges.

A notable example of China's CE implementation is the Eco-Industrial Park (EIP) programme, which was initiated in 2001 and expanded significantly during the Thirteenth and Fourteenth Five-Year Plans [35]. The programme has facilitated the development of more than 100 national-level eco-industrial parks that promote industrial symbiosis through the exchange of water, energy, materials, and by-products among co-located industries. Shared wastewater treatment facilities, water reuse networks, and resource recovery systems enable participating industries to reduce freshwater consumption, minimise waste generation, and improve overall resource efficiency. The success of China's EIP programme has been supported by strong regulatory oversight, standardised environmental performance requirements, financial incentives, and technical assistance from government agencies. As a result, industrial symbiosis has become a key mechanism for advancing circular economy objectives while improving the environmental performance and competitiveness of industrial clusters across China.

Figure 5 illustrates the key factors influencing industrial symbiosis performance within eco-industrial parks (EIPs). The framework highlights the importance of sectoral variety, sectoral anchorage, and sectoral specialisation of utilisers in facilitating resource sharing among industries. Sectoral variety, i.e., diversity, increases the availability of reusable resources, such as wastewater, energy, and industrial by-products, thereby providing greater opportunities for symbiotic performance. Sectoral anchorage is described as the presence of major industries that act as resource hubs, stabilising the industrial network and facilitating the flow of materials and utilities between participating firms. Meanwhile, sectoral specialisation enhances resource efficiency by fostering industrial symbiosis, where resource sharing among industries through integrated waste management and common treatment facilities is highly encouraged.

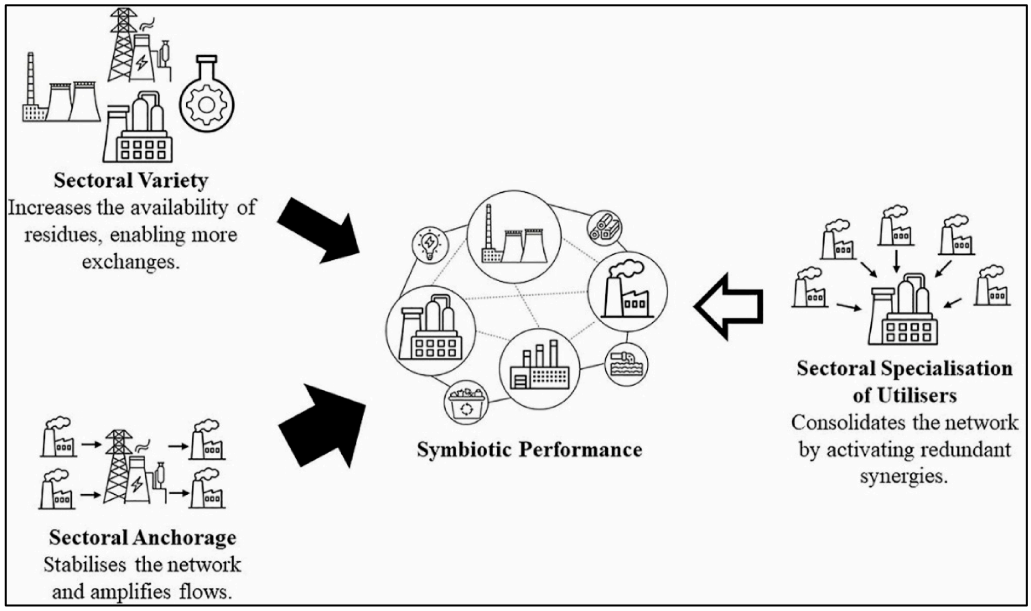


Figure 5. Conceptual framework of industrial symbiosis in eco-industrial parks supporting resource recovery and wastewater reuse. Adapted from [36].

These factors strengthen industrial symbiosis networks, improve resource circulation, and support the implementation of circular economy principles within industrial clusters. The EIP programme in China demonstrates how policy support, infrastructure sharing, and inter-industry collaboration can promote large-scale wastewater reuse and resource recovery, thus contributing to more sustainable industrial development. In addition, China has successfully integrated CE principles into national legislation, industrial strategies, and environmental policies through strong regulatory frameworks, financial incentives, technological innovation, and government support. This has enabled the development of one of the most comprehensive industrial wastewater circularity frameworks in Asia, providing valuable lessons for countries seeking to improve resource efficiency and advance sustainable wastewater management.

Although China's eco-industrial parks have demonstrated significant improvements in industrial symbiosis and resource efficiency, implementation performance varies considerably among regions because of differences in local governance capacity, industrial composition, and economic development. These differences suggest that national policies alone are insufficient without strong local institutional support and continuous performance monitoring.

2.4. India

The National Urban Sanitation Policy (2008) endorsed treated-water reuse and proposed a minimum wastewater reuse target of 20% in every city of India, while the Service Level Benchmarking Framework (2010) similarly encouraged reuse of at least 20% of treated wastewater [37]. The National Water Mission (2011) targeted a 20% improvement in water-use efficiency while the National Water Policy (2012) recognised reclaimed water as an important alternative resource and proposed preferential tariffs to incentivise its use. The CPHEEO Manual on Sewerage and Sewage Treatment Systems (2013) subsequently provided water-quality guidelines for different treated-water reuse applications. The National Mission for Clean Ganga (NMCG) has catalysed significant investment in wastewater treatment infrastructure along the Ganga basin, with emerging provisions for resource recovery from sewage treatment plants.

Wastewater reuse was further incorporated into broader urban-development programmes. The Swachh Bharat Mission (2014) promoted treated wastewater reuse through expansion of sewage collection and treatment networks, while the Atal Mission for Rejuvenation and Urban Transformation (AMRUT) (2015) supported improvements in urban water-supply and sewerage infrastructure. The Smart Cities Mission (2015) further incorporated water and wastewater management within sustainable urban renewal and retrofitting initiatives. In addition, the Water and Waste Management Strategy under the 12th Five-Year Plan (2013) promoted recycling and reuse of treated sewage in urban planning for applications including sanitation, landscaping, and central air-conditioning.

Further policy support has been provided through the Namami Gange Programme (2014–present), which promotes sewage treatment and industrial effluent management together with public–private partnership (PPP) models for reuse. Under this programme, an agreement was established for the reuse of 20 million L/day of treated sewage by the Indian Oil Corporation refinery in Mathura, while interventions in the pulp and paper sector were associated with a reported 45–50% reduction in freshwater consumption compared with 2012. The Ministry of Power Gazette Notification (2016) further strengthened industrial reuse by requiring thermal power plants located within 50 km of a city to use treated wastewater.

Practical implementation of wastewater reuse can be seen across several Indian industrial sectors. In Chennai, the Chennai Petroleum Corporation Limited (CPCL) treats approximately 2.5 million gallons per day (MGD) of wastewater using tertiary treatment and reverse osmosis for reuse, while an additional 2.5 MGD sewage-recycling facility and a 5.8 MGD seawater-desalination plant have been developed to supplement industrial water supply. Madras Refineries and Madras Fertilisers Limited generate approximately 12 and 16 MLD of reusable water, respectively, while Rashtriya Chemicals and Fertilisers in Mumbai use approximately 23 MLD of treated water as cooling-tower make-up water. In New Delhi, Pragati Power Corporation Limited meets more than 90% of its cooling-water requirements using treated wastewater. Vadodara provides another example of large-scale industrial reuse, where approximately 75% of tertiary-treated industrial wastewater is available for non-potable reuse, with a reported treatment cost of INR 36 per 1000 L. These cases demonstrate that industrial wastewater reuse in India is already technically viable across petroleum refining, fertiliser production, power generation, and other industrial applications, although implementation remains geographically and sectorally uneven.

The Central Pollution Control Board (CPCB) in India has implemented zero liquid discharge (ZLD) on all water-polluting industries in India, which has made water recycling and reuse mandatory in industries [38]. Although ZLD systems substantially reduce wastewater discharge and improve water recovery, their wider implementation remains challenging because of high capital and operating costs, intensive energy requirements, and management of concentrated brine generated during evaporation and crystallisation. Disposal of high-salinity residues remains a technical and environmental concern, particularly where appropriate hazardous waste infrastructure is limited. These challenges demonstrate that ZLD is most effective when supported by adequate financial incentives, technical expertise, and robust regulatory oversight rather than being implemented as a standalone compliance measure.

2.5. Japan

Japan has a very comprehensive approach towards CE implementation in industrial wastewater management in Asia owing to its strong regulatory frameworks, advanced technologies, and long-term policy commitment [39,40]. The Basic Act for Establishing a Sound Material-Cycle Society (2000) and the Basic Act on Water Cycle Policy (2014)

provide the legislative foundation for resource circulation, sustainable water management, and wastewater reuse. In addition, Japan's Eco-Town Programme, which was initiated in 1997, has established 26 designated eco-industrial zones that promote industrial symbiosis through resource sharing, waste valorisation, and collaborative infrastructure development, including wastewater treatment and resource recovery systems. Notable examples include the Kitakyushu Eco-Town and Kawasaki Eco-Town projects, which facilitate the exchange of materials, energy, and water resources among industries while promoting recycling and waste minimisation.

Japan has also been a pioneer in the adoption of advanced wastewater treatment technologies, including membrane bioreactors (MBRs), reverse osmosis (RO), and water recycling systems within industrial facilities. High levels of water reuse have been achieved in several water-intensive sectors, contributing to reduced freshwater demand and improved resource efficiency [41]. Furthermore, phosphorus recovery through struvite (magnesium ammonium phosphate) crystallisation has been successfully implemented at selected municipal and industrial wastewater treatment facilities, producing a marketable slow-release fertiliser while reducing nutrient discharge to receiving waters. Reclaimed water reuse programmes have also been implemented in major cities such as Tokyo and Yokohama, where treated wastewater is utilised for industrial cooling, environmental enhancement, toilet flushing, and other non-potable applications. Among these initiatives, the Shinjuku district in Tokyo represents one of the most established examples of district-scale water reclamation and reuse.

Figure 6A shows the district-scale reclaimed water recycling system implemented in Shinjuku, Tokyo, where treated wastewater is reclaimed and distributed for non-potable applications such as toilet flushing and urban water services [42]. Figure 6B shows the major applications of reclaimed water in Japan, highlighting its use for river flow augmentation, landscape irrigation, snow melting, industrial processes, and urban water reuse. Despite Japan's advanced water management infrastructure, the adoption of reclaimed water remains relatively limited, with water reclamation facilities installed at only a small proportion of the country's wastewater treatment plants. River flow augmentation represents the largest application of reclaimed water, accounting for approximately 35% of total reuse, followed by landscape irrigation (21.6%) and snow melting (20.2%). Smaller proportions are utilised for agricultural irrigation, toilet flushing, recreational purposes, and industrial activities. These trends indicate that reclaimed water in Japan is primarily used to support environmental enhancement and urban sustainability objectives rather than direct industrial applications. Nevertheless, ongoing efforts to expand reclamation facilities and improve the economic viability of water reuse systems are expected to further strengthen circular water management practices in Japan.

In addition to water reuse and nutrient recovery, Japan has actively promoted energy recovery from wastewater treatment processes. Several municipalities have implemented co-digestion systems that combine sewage sludge with food waste and other organic residues to enhance biogas production and improve the energy self-sufficiency of wastewater treatment facilities. The recovered biogas is subsequently utilised for electricity generation and plant operations, supporting both resource recovery and greenhouse gas emission reduction objectives. Such initiatives demonstrate Japan's commitment to maximising the value extracted from wastewater streams through integrated circular economy strategies.

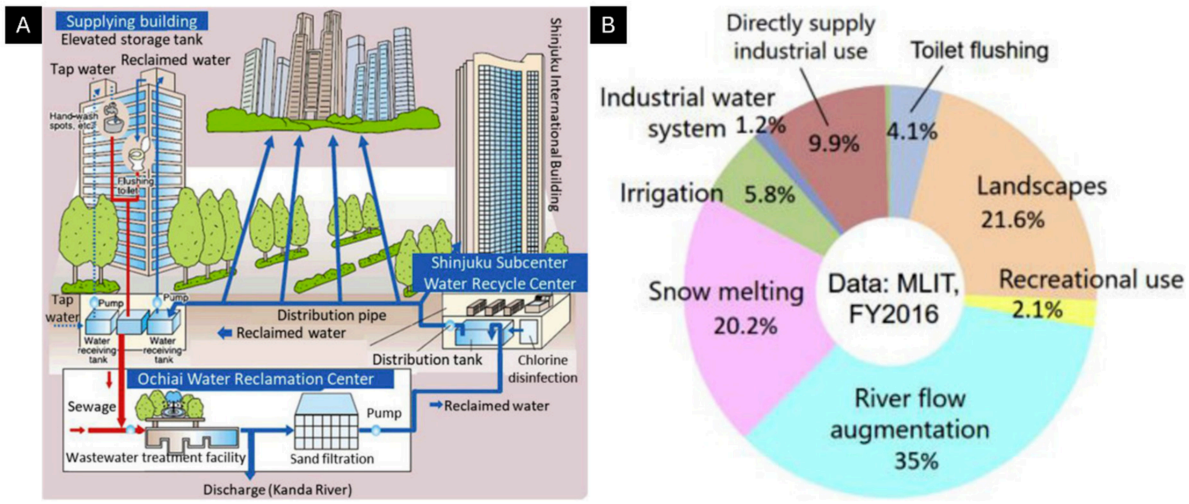


Figure 6. Water reuse practices in Japan. (**A**) District-scale reclaimed water recycling system in Shinjuku, Tokyo. (**B**) Major applications of reclaimed water reuse in Japan. Adapted from [42].

Unlike many Asian countries that continue to focus primarily on pollution control and discharge compliance, Japan has progressively incorporated resource circulation, industrial symbiosis, water reuse, and resource recovery into national environmental policy, positioning wastewater as a valuable resource rather than a waste product [43]. Japan's experience demonstrates that a combination of strong regulatory support, technological innovation, public–private collaboration, and long-term policy consistency can effectively promote circular economy principles in wastewater management while enhancing resource efficiency, environmental sustainability, and industrial competitiveness. These observations suggest that technological capability alone does not guarantee widespread implementation. Economic feasibility, local demand, and stakeholder acceptance remain equally important for successful circular wastewater management.

2.6. South Korea

South Korea has developed a comprehensive policy framework for integrating circular economy (CE) principles into water management such as the Water Reuse Promotion Act (2010) and further strengthened it through the Korean Green New Deal introduced in 2020 [44]. The Water Reuse Promotion Act provides the legal framework for wastewater reclamation and reuse by establishing water quality standards, promoting reclaimed water utilisation, and supporting investments in water recycling infrastructure. In addition, the Ministry of Environment promoted policies to encourage wastewater reuse through the Comprehensive Measures for Water Conservation (2020) and the revision of the Sewage Act (December 2000) which mandates the inclusion of a plan for treated water reuse. Existing sewage and wastewater treatment plants were required to recycle treated wastewater for various purposes within the plant such as industrial water or firefighting water. Later, the enactment of the "Water Reuse Promotion and Support Act" made it compulsory for large-scale development projects to reuse water. Industrial facilities in regions such as Busan and Daegu increasingly utilise reclaimed water for cooling systems, cleaning operations, and manufacturing processes, thereby reducing dependence on freshwater resources.

The Eco-Industrial Park (EIP) Programme in Korea has advanced industrial water circularity by promoting resource sharing and industrial symbiosis among co-located industries [45]. Several industrial clusters, including those associated with the electronics, automotive, petrochemical, and food-processing sectors, have implemented wastewater reuse and resource exchange initiatives to improve water efficiency and reduce environmental impacts. A notable example is the Ulsan Eco-Industrial Park, where interconnected

industries exchange wastewater, steam, energy, and industrial by-products through integrated resource-sharing networks. These initiatives have contributed to reductions in freshwater consumption, waste generation, and greenhouse gas emissions while enhancing overall industrial resource efficiency.

The Korea Water Resources Corporation (K-water) has played a significant role in promoting smart water management through the deployment of Smart Water Networks (SWNs), digital monitoring platforms, and integrated water management systems [46]. These technologies enable real-time monitoring of water quality, leak detection, operational optimisation, and improved regulatory compliance across industrial and municipal water systems.

Furthermore, the water component of the Korean Green New Deal supports investments in digital infrastructure, artificial intelligence (AI), and data-driven water management technologies to enhance water security and resource efficiency. Smart wastewater treatment facilities incorporating sensors, automation, and predictive analytics are increasingly being adopted to improve treatment performance and facilitate water reuse. South Korea's experience demonstrates how the integration of strong regulatory frameworks, industrial symbiosis, digitalisation, and technological innovation can accelerate the transition towards circular economy-based wastewater management. Compared with many developing Asian countries, South Korea places greater emphasis on smart water governance and Industry 4.0 technologies, providing a valuable model for the future development of intelligent and resource-efficient water management systems.

2.7. Thailand

Thailand has advanced its industrial wastewater management and reclamation by various national environmental and water-resource policies [22]. For instance, the Enhancement and Conservation of National Environmental Quality Act (NEQA) 1992, the Factory Act 1992, and the Industrial Estate Authority of Thailand Act 1979 are some wastewater regulations established to ensure the quality of domestic, factory, and industrial-estate wastewater discharges. Later in 2018, Thailand incorporated wastewater resource management into the country's 20-year water resource management master plan spanning from 2018 to 2037, based on the six strategies established by the Office of the National Water Resources. Strategy 4 of the master plan aims to increase efficiency of municipal wastewater collection and treatment systems as well as wastewater reclamation, where the volume of reclaimed water to be achieved by the year 2037 was set at 0.132 x 10^9 billion m^3/year (i.e., 3.4% of wastewater generated in the country). Another wastewater management plan in the year 2019 by the government and related agencies was developed in accordance with the 20-year plan to strategize wastewater recycling(1) [4]. Via this plan, 842 WWTPs across Thailand were targeted, with 57% of total wastewater being treated to meet the national quality standards and 132 billion m^3/year of water being reclaimed.

During the droughts in 2020, the Ministry of Industry in Thailand allowed for the first time the temporary use of effluents from WWTPs in agricultural areas; however, it was important that the quality of treated wastewater should meet the industrial effluent standards and the amount of reuse was limited to 6.25 L/m^3 per day. Later in 2021, the Department of Industrial Works established the standard guidelines for reusing treated wastewater during drought, where it was recommended to treat effluents from cooling towers or final wastewater treatment ponds using ultrafiltration or reverse osmosis (RO) before reuse in cooling systems or production support equipment. The implementation of wastewater reuse is considerably more advanced in industrial estates than in the municipal sector. As shown in Figure 7, 80% of the 60 surveyed industrial-estate WWTPs reported wastewater reuse activities, compared with only 36% of 104 municipal WWTPs. Among

industrial-estate WWTPs implementing reuse, reclaimed wastewater was used for green-space irrigation (100%), road cleaning (92%), raw water for industrial-water production (69%), factory cooling (56%), equipment cleaning (48%), factory construction (13%), and second-grade water for factories (2%).

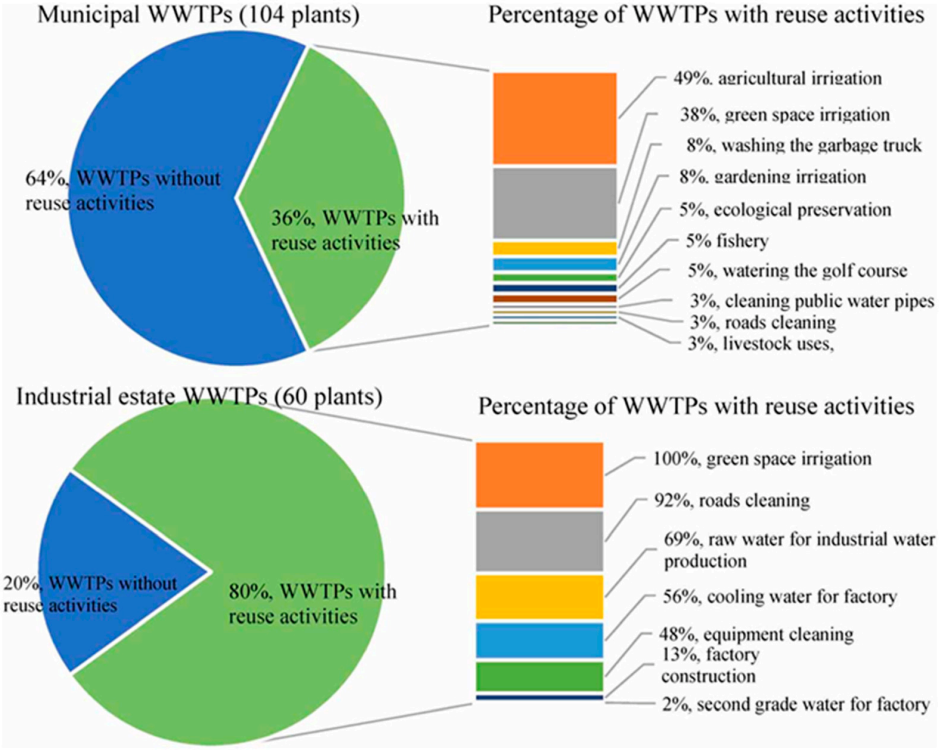


Figure 7. Wastewater reuse activities in municipal and industrial-estate wastewater treatment plants (WWTPs) in Thailand. Adapted from Ref. [4].

However, there are no regulations that control the quality of treated wastewater for specific reuse purposes. The absence of application-specific reuse criteria, together with the costs of advanced treatment, monitoring and distribution infrastructure, continues to constrain wider implementation in Thailand. Thus, Thailand represents a transitional CE model where national policy supports wastewater reclamation and industries demonstrate practical reuse, although regulatory and infrastructure development currently do not fully support large-scale circular water management.

2.8. Vietnam

Vietnam has increasingly incorporated wastewater reuse and circular resource management into its environmental and water policies. The principal frameworks that support the national interest in resource circulation and water sustainability include the Law on Environmental Protection (2020), the Law on Water Resources (2023), and the National Action Plan for Circular Economy (Decision No. 687/QĐ-TTg, 2022). Decree No. 08/2022/ND-CP, which provides incentive mechanisms such as preferential loans, interest-rate subsidies, and credit guarantees for environmental protection projects for waste collection, treatment, recycling and reuse through the Vietnam Environment Protection Fund. These incentives allow industries to reduce freshwater procurement costs as well as discharge fees through their internal water recycling.

Despite this policy support, Vietnam experiences major barriers that hinder large-scale wastewater reuse due to environmental pressures, infrastructure limitations and institutional constraints. The annual water demand is approximately 117.03 billion m^3, of which

industrial activities account for 8.3%, while only about 18% of domestic wastewater was treated before discharge as of 2025 due to limitations in treatment capacity [47]. Analysis of 118 wastewater-generating projects showed particularly strong reuse activity among manufacturing facilities, although implementation remains highly project-specific. For example, the Billion Union Textile Factory in Thanh Hoa reuses approximately 4835 m^3/day from a treatment capacity of 10,500 m^3/day, i.e., 45%, while the JAPFA Food Processing and Animal Feed Plant in Binh Phuoc with an installed ultrafiltration system recycles approximately 1000 m^3/day from 4850 m^3/day of wastewater which helps to address local freshwater scarcity [48]. Urban wastewater reuse in Vietnam remains limited with a few small-scale initiatives to demonstrate the potential of wastewater reuse. The wastewater treatment plant of Thu Dau Mot city in Binh Duong Province explored reusing water for landscaping and industrial applications to address issues of groundwater depletion and rising pollution levels. In Buon Ma Thuot city of Dak Lang Province, treated wastewater was reused for coffee irrigation during dry seasons which reflects the economic and environmental drivers.

Although wastewater reuse is encouraged under the Law on Environmental Protection (2020), Law on Water Resources (2023), and Decree No. 08/2022/ND-CP, there is a significant policy-implementation gap since Vietnam has not yet established purpose-specific water reuse standards or technical guidelines specifically for reclaimed wastewater. Existing regulations, including QCVN 08:2023/BTNMT for surface water, QCVN 14:2025 for domestic and municipal wastewater, and QCVN 40:2025/BTNMT for industrial effluent, primarily regulate water quality or wastewater discharge rather than defining quality requirements for specific reuse applications [48]. Vietnam therefore represents a transitional CE model in which policy recognition and successful industrial reuse cases are emerging, but regulatory and economic conditions have not yet enabled systematic large-scale implementation.

2.9. Indonesia

In Indonesia, the Environmental Protection and Management Law No. 32/2009, Government Regulation No. 22/2021 and Ministerial Regulation PUPR No. 04/2017 were developed to provide the regulatory basis for wastewater collection, treatment and discharge limits. However, wastewater reclamation in Indonesia is limited due to uneven regional regulations and substantial disparities in the treatment infrastructure, i.e., only 4% of water can be reclaimed from accumulated wastewater each day [5]. The Provincial Government of DKI Jakarta via the Jakarta Provincial Water Resources Agency prepared the Urban and Settlement Scale Domestic Wastewater Management System (Sistem Pengolahan Air Limbah Domestik (SPALD)) which consisted of wastewater treatment plants (Instalasi Pengolahan Air Limbah (IPAL)) and piping networks to improve access to wastewater services, enhance surface water quality and groundwater, and serve as an alternative source of clean water for the community. The construction of IPAL and piping networks in nine locations flowing through Setia Budi Dam can be reclaimed through an aerator which removes pathogens from the river water, in accordance with Pemen PUPR 4/2017. However, up to the year 2022, only 148 IPAL units have been successfully established in Indonesia and are mostly concentrated in urban areas such as Timika and Jayapura [5].

Wastewater regulations also vary between regions in Indonesia. In Makassar, the Metropolitan Sanitation Management Investment Project (MSMIP) was implemented to improve integrated and centralised urban wastewater management through the development of sewerage networks and wastewater treatment infrastructure, with financial support from the Asian Development Bank (ADB) and other development partners [49]. The Makassar WWTP was designed with a treatment capacity of approximately 16,000 m^3/day. The

project began in 2020 and was put in operation by February 2024. Nevertheless, it is noteworthy that specific wastewater policies for water reclamation are lacking especially in Eastern Indonesia which indicates that the transition toward circular water management remains constrained by poor and inconsistent policy implementation across regions and the lack of infrastructure.

3. Discussion

3.1. Cross-Country Comparative Analysis of Circular Wastewater Implementation

Table 3 shows the comparison of circular wastewater implementation across selected Asian countries using common criteria such as reclaimed-water applications, water-quality standards, quantitative reuse levels, sector-specific implementation, resource recovery, and economic evidence. The comparison enables differences in the maturity and implementation of CE-oriented wastewater management to be assessed across countries.

The quantitative comparison demonstrates substantial differences in the scale and application of wastewater reuse among the selected countries. Singapore illustrates how sustained investment in advanced treatment infrastructure has supported large-scale wastewater reclamation. Since 2002, PUB has invested $77.01 million in research and development related to treatment processes. Infrastructure capacity has also expanded; in 2018, the Jurong Water Reclamation Plant increased its treatment capacity from 204,574 to 259,127 m^3/day through the implementation of thermal hydrolysis, representing an increase of approximately 26.7% [50]. Further expansion has been planned at the Changi Water Reclamation Plant, where treatment capacity is projected to increase from 918,310 to approximately 1 million m^3/day through membrane bioreactor technology. These investments demonstrate that Singapore's progress in circular water management is supported not only by regulatory frameworks but also by sustained financial investment, technological development, and expansion of treatment capacity. South Korea demonstrates a different implementation pathway, where approximately 1.113 billion m^3/year of treated sewage was reused in 2018, corresponding to about 15.5% of the total sewage treated, while industrial water capacity supplied from treated sewage increased five-fold from 15 million m^3/year in 2008 to 75.2 million m^3/year in 2018 [51]. On the other hand, water reuse in Japan has been established for several decades although the overall scale remains limited. In 2016, approximately 210 million m^3/year of reclaimed water was used outside wastewater treatment plants, i.e., 1.3% of approximately 14.7 billion m^3/year of wastewater generated nationally [42]. Furthermore, only 176 WWTPs, equivalent to approximately 8% of Japan's total WWTPs, were equipped with water reclamation facilities. Reclaimed water was used predominantly for stream-flow augmentation (35%), landscape irrigation (21.6%), and snow melting (20.2%), while comparatively smaller proportions were used for agricultural irrigation (5.8%), toilet flushing (4.1%), recreational applications (2.1%), and industrial activities (1.2%). While South Korea has progressively expanded industrial reuse, Japan demonstrated a more diversified but predominantly non-industrial reclaimed-water application profile.

India shows great potential for scaling wastewater reuse, although much of this capacity remains unrealised. It has been estimated that the collection and adequate treatment of 80% of urban wastewater could satisfy approximately 75% of industrial water demand and nearly 25% of drinking-water demand [52]. Similarly, the collection and treatment of approximately 38,000 MLD of urban wastewater could generate around 14 billion m^3 of reusable water annually, with the potential to irrigate approximately 3 million hectares. At the city level, estimated reuse potential varies considerably; treated wastewater could meet approximately 42% of municipal water demand in Pune, while a reuse potential of 78.2% has been estimated for Delhi under adequate wastewater collection and treatment.

Table 3. Quantitative comparison of reclaimed-water standards and implementation evidence in selected Asian countries.

Comparison Criterion	Singapore	Japan	South Korea	China
Reuse applications	Industrial/non-domestic reuse, including semiconductor wafer fabrication, petrochemical industries, power generation and cooling; indirect potable reuse	Toilet flushing; landscape irrigation; environmental use (aesthetic); environmental use (limited public contact); industrial water; train washing; stream augmentation	Toilet flushing; sprinkler water; recreation water; washing water; agricultural irrigation; industrial water and industrial cooling water	Urban miscellaneous reuse, including toilet flushing, green irrigation and pavement cleaning
Total coliform/microbial criteria	NEWater: *E. coli* < 1 CFU/100 mL; heterotrophic plate count < 1 CFU/mL	Toilet flushing: ≤1000 count/100 mL; landscape irrigation: ≤50 count/100 mL; environmental (aesthetic): ≤1000 count/100 mL; environmental (limited public contact): ≤50 count/100 mL	Toilet flushing: N.D.; sprinkler: N.D.; recreation: N.D.; washing: N.D.	Toilet-flushing standard: *E. coli* 300 CFU/mL
BOD_5 criteria	No specific NEWater BOD_5 criterion reported; WRP final-effluent discharge standard: ≤20 mg/L	Toilet flushing: ≤20 mg/L; landscape irrigation: ≤20 mg/L; environmental (aesthetic): ≤10 mg/L; environmental (limited public contact): ≤3 mg/L	Toilet flushing: <10 mg/L; sprinkler: <10 mg/L; recreation: <10 mg/L; washing: <10 mg/L	Toilet flushing: ≤10 mg/L
Turbidity criteria	NEWater: <5 NTU	Toilet flushing: Not specified; landscape irrigation: not Specified; environmental (aesthetic): ≤10 NTU; environmental (limited public contact): ≤5 NTU	Toilet flushing: <2 NTU; sprinkler: <2 NTU; recreation: <2 NTU; washing: <2 NTU	Toilet flushing: ≤5 NTU
pH criteria	NEWater: 7.0–8.5	Toilet flushing: 5.8–8.6; landscape irrigation: 5.8–8.6; environmental (aesthetic): 5.8–8.6; environmental (limited public contact): 5.8–8.6	Toilet flushing: 5.8–8.5; sprinkler: 5.8–8.5; recreation: 5.8–8.5; washing: 5.8–8.5	Toilet flushing: 6–9
Residual chlorine	NEWater: <2 mg/L	Toilet flushing: retained; landscape irrigation: ≥0.4 mg/L	Toilet flushing: >0.2 mg/L; sprinkler: >0.2 mg/L; recreation: not specified; washing: >0.2 mg/L	Toilet flushing: Cl_2 ≥ 1 mg/L after 30 min contact and ≥0.2 mg/L at the end of the pipeline
COD/organic-carbon criteria	NEWater: TOC < 0.5 mg/L	Not specified in supplied reclaimed-water criteria	CODMn < 20 mg/L for toilet flushing, sprinkler, recreation, and washing uses	Not specified

Table 3. *Cont.*

Comparison Criterion	Singapore	Japan	South Korea	China
Other water-quality criteria	Conductivity < 250 μS/cm; TDS < 150 mg/L; NH_3-N < 1.0 mg/L; nitrate-N < 11 mg/L; chloride < 20 mg/L; sulphate < 5 mg/L; silica < 3 mg/L; hardness < 50 mg/L as $CaCO_3$	Reuse-category-specific criteria include coliform, BOD, turbidity, residual chlorine, odour and pH	Colour < 20 Hazen; CODMn < 20 mg/L for specified reuse categories	Toilet flushing: NH_3-N ≤ 10 mg/L; colour ≤ 30 degrees; no unpleasant smell
Quantitative reuse evidence	In 2019, NEWater accounted for approximately 30% of Singapore's water supply. Tuas WRP designed for net process energy consumption of 0.1 kWh/m^3, reported as substantially below that of a typical MBR	In 2016, approximately 210 million m^3/year of reclaimed water was used outside WWTPs, equivalent to approximately 1.3% of the approximately 14.7 billion m^3/year of wastewater generated nationally	In 2018, approximately 1.113 billion m^3/year of treated sewage was reused from 7.16 billion m^3/year treated, equivalent to approximately 15.5%	In 2008, 1.66 billion m^3 of reclaimed wastewater was used, equivalent to approximately 8% of treated municipal wastewater
Sector-specific reuse and treatment/resource-recovery evidence	E.g. semiconductor, petrochemical, power-generation and cooling uses. Changi WRP reported approximately 89% COD, 98% BOD_5, 93% NH_3-N and 95% TSS removal. Anaerobic sludge digestion produces biogas containing 60–70% methane for plant energy use	Stream-flow augmentation (35%), landscape irrigation (21.6%), snow melting (20.2%), agricultural irrigation (5.8%), toilet flushing (4.1%), recreational applications (2.1%), and industrial activities (1.2%)	0.52 billion m^3/year (46.8%) of reused treated sewage was used for washing, cleaning, cooling and related internal uses in 2018. Industrial cooling-water pilot achieved turbidity 0.03–0.06 NTU, DOC 0.28 mg/L, T-N < 0.5 mg/L, and T-P 0.01–0.03 mg/L	Greywater MBR study: effluent COD 0–40 mg/L, BOD_5 0.7–2.1 mg/L, NH_3-N 0.1–0.3 mg/L, and turbidity 0.15–0.3 NTU. The study confirms that the effluent met China's toilet-flushing reuse requirements. BAF: COD 14–50 mg/L, BOD_5 1.1–3.5 mg/L, NH_3-N 0.1–0.3 mg/L, turbidity 0.4–1.6 NTU
Reuse standard/regulatory basis	Singapore NEWater quality requirements/PUB water-reuse framework	Japanese reclaimed-water criteria supplied in the source	South Korean medium-level water-reuse regulation	GB/T 18920-2002—The reuse of urban recycling water: Water quality standard for urban miscellaneous water consumption (AQSIQ 2003)
Ref.	[50,53]	[42,54]	[55,56]	[57–59]

Across the countries examined, the regional policy–implementation gap is rooted in structural differences in institutional coordination, regulatory enforcement, financing capacity, infrastructure development, technical capacity, and the availability of fit-for-purpose reuse standards. For example, fragmented regulatory responsibilities in Malaysia can complicate coordination between pollution control, water management, and resource-recovery objectives [32], while the limited wastewater-treatment and reclamation infrastructure reported in Indonesia [5] and Vietnam [47] constrains the practical implementation of CE policies. Financial constraints further widen this gap because advanced reclamation and resource-recovery systems require significant capital investment for long-term operation and maintenance costs, which can be challenging for SMEs and developing economies. These constraints are interconnected where inadequate financing limits reuse infrastructure development and technical capacity while weak institutional coordination can delay implementation and affect demand for reclaimed water. Consequently, differences in CE implementation across Asian countries are mainly influenced by the conditions that support implementation, rather than only by the availability of treatment technologies or CE policies. Addressing these gaps requires better coordination among institutions, continued investment in infrastructure, improved access to financing, stronger technical capacity, and clear water-reuse standards.

3.2. Environmental and Socioeconomic Challenges for Circular Wastewater Management in Asia

Figure 8 shows the various challenges for the implementation of circular wastewater management in Asia. Firstly, the high capital and operational cost of advanced treatment and recovery technologies hinder effective adoption among small and medium-sized industries. Many industries have focused on meeting discharge limits instead of investing in reuse and recovery systems which have longer payback periods. Although these regulations are important for environmental protection, they do not provide clear guidelines for water reuse, resource recovery, or wastewater valorisation. The overlapping responsibilities among environmental agencies, water authorities, industrial regulators, and local governments may impede policy implementation and enforcement.

These barriers are also influenced by underlying political and economic conditions. Unclear responsibilities among environmental agencies, water authorities, industrial regulators, and local governments can create bureaucratic delays, weaken policy coordination, and limit effective enforcement. Water-pricing structures also strongly influence the economic attractiveness of wastewater reuse. For example, in Beijing, conventional non-residential water costs approximately RMB 9.0–9.5/m^3, whereas reclaimed water was previously subject to a government-guided ceiling of RMB 3.5/m^3 [60,61], providing a substantial economic incentive for reuse; reclaimed-water users also benefit from exemptions from water-resource tax and wastewater-treatment fees. Similarly, in Singapore, non-domestic potable water is priced at \$3.24/m^3 compared with \$2.50/m^3 for NEWater from April 2025, providing a direct economic incentive for industrial reuse [62]. Singapore also reduces investment barriers through financial support for water-recycling projects, including funding of up to 50% of capital costs, subject to a \$5 million project cap [62]. In India, tertiary-treated industrial wastewater in Vadodara has been reported to cost approximately INR 36/m^3 [37], illustrating that the economic feasibility of reuse depends strongly on local freshwater tariffs, treatment requirements, and distribution infrastructure. These examples demonstrate that wastewater reuse is determined not only by technological feasibility but also by water-pricing policies, subsidies, access to affordable financing, and institutional coordination. Therefore, developing Asian economies may require appropriate tariff structures, targeted financial incentives, shared infrastructure, and stronger institutional

coordination to make circular wastewater management economically competitive with conventional freshwater supply.

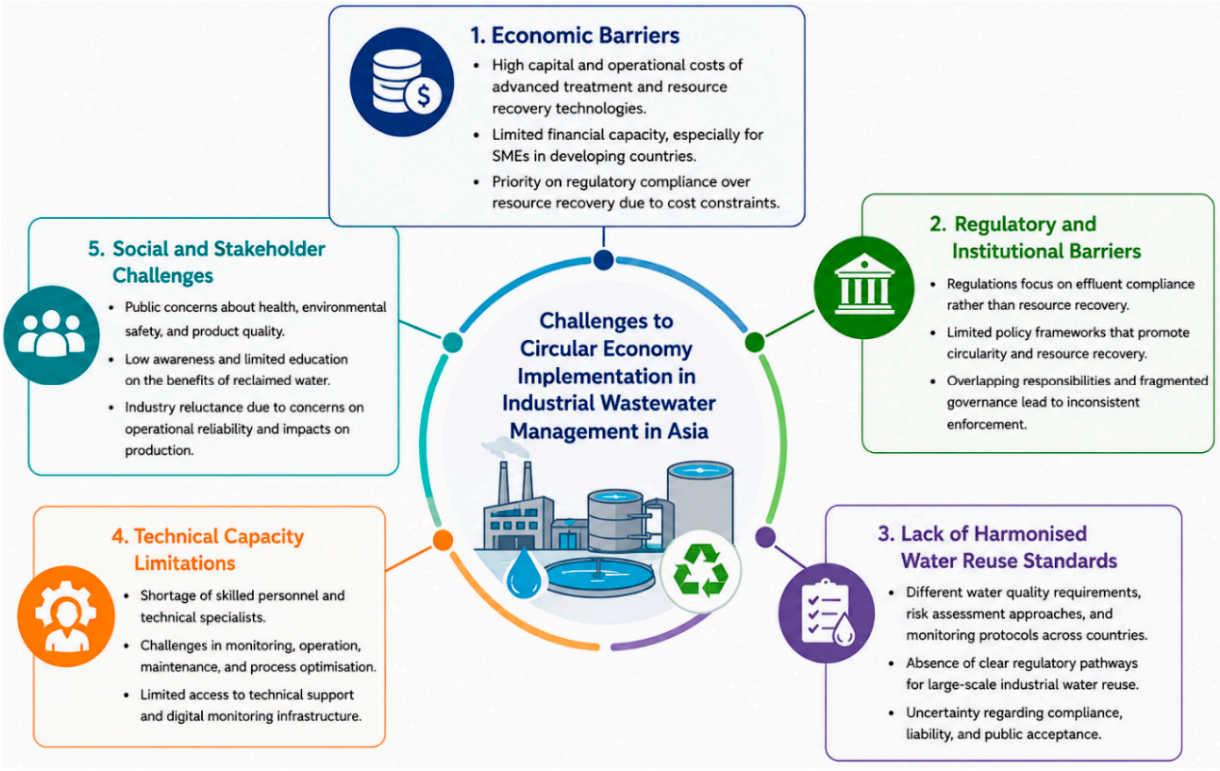


Figure 8. Key challenges hindering the implementation of circular economy principles in industrial wastewater management across Asia.

The next challenge is the lack of water reuse standards [38]. It is noteworthy that Singapore has established well-defined quality-control systems for reclaimed water. However, clear standards for industrial reuse applications remain limited in many Asian countries. Without well-defined standards on compliance, liability and operational safety, industries can be reluctant to substitute freshwater with reclaimed water although advanced treatment technologies are readily available. In addition to that, circular wastewater systems require skilled personnel for design, operation, monitoring, maintenance, and process optimisation. However, the availability of trained engineers, operators, and regulatory personnel who can handle advanced treatment systems in developing countries remains limited. This, in turn affects system performance, requires higher maintenance costs, and causes a lack of trust among industries.

In addition, concerns about potential health risks, environmental safety and the quality of reclaimed water may influence public and stakeholder acceptance. NEWater in Singapore shows that public acceptance can be improved through transparent communication, strong government support, reliable treatment performance, and long-term public engagement. However, in many Asian countries, public awareness and stakeholder engagement remain limited which reduces acceptance of reclaimed water. The challenges above are interconnected; i.e., (i) weak regulatory frameworks may reduce stakeholder trust, (ii) insufficient incentives may hinder the adoption of advanced technologies and (iii) low technical capacity increases operational risks. Therefore, addressing CE barriers requires integrated policy responses rather than individual technical solutions.

3.3. Policy Recommendations for Accelerating Circular Economy Adoption in Industrial Wastewater Management

The implementation of CE practices across several Asian countries shows that industrial wastewater management requires technology, innovation, regulatory support, economic incentives, and stakeholder engagement. While Asian countries are at various stages of implementation, some CE policy measures have been important to shift from conventional treatment practices toward circular and resource-efficient water management.

The first policy recommendation to accelerate CE adoption in industrial wastewater management is to standardise water reuse standards and regulatory frameworks within Asian countries. These include the specifics of reclaimed water quality, regulations on industrial water reuse, and requirements on monitoring and compliance. This measure would reduce regulatory uncertainty, enable easier and faster technology transfer and develop confidence among investors or multinational firms to fund the reclamation infrastructure. Furthermore, economic incentives can encourage adoption of circular wastewater management practices since the high upfront cost of advanced treatment, water recycling, and nutrient or energy recovery systems has been considered the biggest challenge for successful CE adoption among Asian countries. As such, governments can provide support by tax reductions, tax exemptions, lower interest loans, providing green technology grants and preferential tariffs for reclaimed water, and carbon credits related to resource recovery. Such measures would improve the economics of CE projects and lower the risk faced by industries adopting CE approaches in industrial wastewater management. This is consistent with recent techno-economic assessments showing that although advanced recovery technologies such as membrane bioreactors are technically mature, their broader deployment remains constrained by high capital and operating costs relative to conventional treatment, reinforcing the need for targeted financial de-risking mechanisms [63].

Regional water-reuse policies should also address the potential recirculation of emerging contaminants such as PFAS and pharmaceutical residues through reclaimed water and recovered resources. This concern is particularly relevant in Asia; for example, a recent study of 10 sewage treatment plants in Penang, Malaysia reported PFOA concentrations of up to 2634.6 ng/L in influent and up to 672.5 ng/L after treatment, indicating that conventional treatment may not completely prevent PFAS transfer into treated effluent [64]. In contrast, Singapore provides a useful risk-management approach, where NEWater is monitored for approximately 300 water-quality parameters, including emerging contaminants such as pharmaceuticals and endocrine-disrupting compounds [65]. Regional CE policies should therefore progressively incorporate risk-based monitoring of priority emerging contaminants, industrial source-control measures, and fit-for-purpose advanced treatment according to the intended reclaimed-water application.

In addition, industrial symbiosis and eco-industrial parks (EIPs) should be prioritised with stronger policy support across Asia to encourage shared treatment infrastructure, by-product exchange, and collaborative recovery systems. These efforts will provide significant benefits such as reduced freshwater withdrawals, lower wastewater generation, and decreased operational costs. As such, wastewater management should be incorporated in the early planning stages of industrial cluster development, where policy measures are designed to encourage collaborative rather than independent resource management practices.

Another policy recommendation to accelerate CE adoption in industrial wastewater management is to promote Public–Private Partnerships (PPPs) such as those among governments, industries, technology providers, universities, and research institutes. This partnership can accelerate technology transfer, enhance capacity building, support demonstration projects as well as the commercialization of new recovery technologies. It should also be noted that these partnerships can reduce the financial burden of large infrastructure projects while facilitating knowledge exchange across sectors. In addition to that, regional cooperation and knowledge-sharing platforms should be enhanced. For example, Singapore's NEWater programme, China's eco-industrial parks, Japan's nutrient recovery initiatives, and South Korea's water reuse policies have demonstrated successful water reuse and resource recovery initiatives. The underlying principles can be adapted to other economic, institutional, and regulatory environments to accelerate adoption of circular water management practices and improved resource efficiency. The Association of Southeast Asian Nations and the Asian Development Bank can provide support by facilitating policy coordination, providing technical assistance, promoting capacity building, and mobilising financial resources to promote CE efforts in industrial wastewater management.

Digital technologies and smart water management systems such as artificial intelligence, digital twins, digital monitoring, and real-time process optimisation should also be integrated into future policy frameworks to enhance operational efficiency, improve regulatory compliance, and maximise water and resource recovery at lower operating costs. Recent technical reviews confirm that digital twins are moving from pilot-scale demonstrations toward full-scale deployment in wastewater treatment plants, improving prediction accuracy and operational resilience [66]. In parallel, carbon footprint accounting is emerging as a necessary complement to CE-based wastewater policy, since energy- and chemical-intensive treatment and recovery processes include greenhouse gas costs that should be considered with the resource recovery gains to avoid shifting environmental burdens [67]. Table 4 shows the policy priorities and recommended implementation actions for advancing CE-based wastewater reuse and resource recovery in Asia.

Table 4. Policy priorities and recommended implementation actions for advancing CE-based wastewater reuse and resource recovery in Asia.

Policy Priority	Existing Specific Example	Recommended Implementation Action	Indicative Timeframe	Performance Indicators/Success Metrics
Harmonisation of Water Reuse Standards	South Korea Water Reuse Promotion and Support Act (2010) and purpose-specific reuse standards; Japan Technical Guideline for Reuse of Treated Wastewater (1981) and subsequent reclaimed-water criteria; India CPHEEO reuse guidelines (2013)	Develop harmonised, application-specific reclaimed-water standards with consistent parameters, risk criteria and monitoring protocols, including risk-based monitoring of priority emerging contaminants such as PFAS and pharmaceutical residues	Short term (1–3 years)	Number of reuse applications covered; water-quality compliance (%); common monitoring parameters adopted; priority emerging contaminants monitored
Financial Incentives and Investment	Singapore Water Efficiency Fund (WEF); Japan Shinjuku Water Recycling Project—national subsidy covered about half of construction cost; reclaimed-water users paid lower tariffs than potable-water users; South Korea local incentives including installation-cost support and fee/tax reductions	Introduce grants, preferential tariffs, tax incentives and targeted subsidies while maintaining adequate cost recovery	Short–medium term (1–5 years)	Number/value of projects financed; private investment mobilised; cost-recovery ratio; reclaimed-water uptake (m^3/year)
Industrial Symbiosis and Eco-Industrial Development	Ulsan Eco-Industrial Park, South Korea; China National Eco-Industrial Park Programme; Tianjin TEDA wastewater-reuse system	Establish shared treatment/reclamation infrastructure and wastewater, energy and by-product exchange networks within industrial clusters	Medium term (3–5 years)	Participating industries; wastewater exchanged/reused (m^3/year); freshwater-use reduction (%)
Resource Recovery and Waste Valorisation	Japan struvite-based phosphorus recovery and sewage-sludge co-digestion for biogas generation; Ulsan Eco-Industrial Park resource exchanges	Support nutrient, energy and material recovery where wastewater characteristics and market demand justify recovery	Medium term (3–5 years)	Nutrients/materials recovered (kg/year); renewable energy generated (kWh/year); resource-recovery rate (%)
Public–Private Partnerships (PPPs)	India NMCG–Indian Oil Corporation, Mathura—20 MLD treated-sewage reuse; Chennai Metro Water PPP reuse plant—45 MLD; Thailand government–private reuse initiatives	Establish PPP mechanisms defining financing, risk allocation, treatment responsibility, reclaimed-water purchase and performance requirements	Medium term (2–5 years)	Operational PPP projects; private capital mobilised; additional reuse capacity (m^3/day)

Table 4. *Cont.*

Policy Priority	Existing Specific Example	Recommended Implementation Action	Indicative Timeframe	Performance Indicators/Success Metrics
Capacity Building and Public Engagement	India CPHEEO Manual (2013); Singapore NEWater public-engagement programme; South Korea local water-reuse management plans and user-support measures	Combine operator training, technical guidance and public education with stakeholder engagement and user-support programmes	Short term and continuous (1–3 years onward)	Personnel trained/certified; public acceptance (%); facilities adopting guidance; stakeholder participation
Digitalisation and Smart Water Management	K-water Smart Water Networks, South Korea—real-time monitoring, leak detection and operational optimisation	Expand sensors, automated monitoring, predictive control and data analytics in treatment and reuse systems	Medium term (2–5 years)	Facilities with real-time monitoring (%); reduction in water/energy consumption (%); compliance incidents detected/resolved
Policy Harmonisation and Institutional Coordination	South Korea—water reuse management plans established for 167 local governments and mandatory review of wastewater reuse before new water-supply development in water-shortage areas; Beijing- binding responsibilities for reclaimed-water producers/users; Indonesia—fragmented local implementation	Define agency responsibilities, integrate reuse into water-resource planning and enforce clear reuse obligations and targets	Short term (1–3 years)	Local jurisdictions with reuse plans; reuse targets achieved (%); regulatory gaps resolved; compliance rate (%)
Regional Cooperation and Knowledge Exchange	ASEAN Circular Economy Framework (2021); Asia Wastewater Management Partnership (AWaP)	Establish common regional indicators, policy exchanges, technical guidance and demonstration-project networks	Medium–long term (3–10 years)	Participating countries/agencies; common indicators adopted; joint demonstration projects; knowledge-transfer activities

4. Conclusions

In conclusion, the shift towards circular economy (CE)-based industrial wastewater management in Asia varies according to regulatory advancement, institutional capacity, technical readiness, financing, and stakeholder involvement. This study shows that Singapore, Japan, South Korea, and China have progressed beyond conventional wastewater management through water reuse, resource recovery, industrial symbiosis, and smart water management. In contrast, Malaysia, India, Thailand, Vietnam, and Indonesia remain at different stages of transition, with a stronger emphasis on discharge control and regulatory compliance.

These differences indicate that a uniform policy approach to water reuse and reclamation would be inappropriate across Asia. Country-specific priorities are therefore required. Singapore should focus on improving the energy and cost efficiency of advanced reclamation systems; Japan should expand reclaimed-water applications beyond their currently limited scale; South Korea should further integrate smart monitoring with industrial reuse; and China should address regional differences in implementation and strengthen performance monitoring of eco-industrial parks. Malaysia should strengthen coordination between environmental and water-related authorities and link IER 2009 with clearer reuse and resource-recovery mechanisms. India should address the cost and energy constraints associated with ZLD while scaling successful industrial reuse models. Thailand and Vietnam should prioritise application-specific reclaimed-water quality standards, while Indonesia should first strengthen wastewater infrastructure and reduce regional disparities in regulatory implementation.

The Asian experience demonstrates that industrial wastewater can be reclaimed and utilised as a source of water, energy, nutrients, and other valuable resources when appropriate institutional and economic conditions are established. Future policy development should therefore adopt a staged and context-specific approach that reflects existing national capacities rather than applying uniform regional solutions. Such an approach can support a more economically viable, resource-efficient, and sustainable transition towards circular industrial wastewater management across Asia.

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