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A COMPARATIVE ASSESSMENT OF CENTRALIZED AND DECENTRALIZED WASTEWATER TREATMENT SYSTEMS FOR SUSTAINABLE DEVELOPMENT

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Abstract

Water scarcity and inadequate sanitation continue to represent significant global concerns, driven by rapid population growth, urban expansion, and the limited availability of freshwater resources. Although the United Nations Sustainable Development in aims to achieve universal access to clean water and sanitation, global progress remains below the required pace. Currently, nearly half of the wastewater generated worldwide is discharged into natural ecosystems without sufficient treatment, highlighting the pressing need for effective wastewater management strategies. This study evaluates the socio-economic, environmental, and technical characteristics of centralized and decentralized wastewater treatment systems (DWTS), with particular emphasis on treatment efficiency, land requirements, environmental impacts, and energy consumption. The economic assessment demonstrates that decentralized wastewater treatment systems offer considerable cost benefits, particularly in low-density and rural communities where centralized infrastructure is often impractical. Furthermore, the modular and flexible configuration of DWTS supports sustainable water reuse while reducing environmental burdens and capital investment. The findings indicate that wider implementation of decentralized wastewater treatment systems can play a pivotal role in meeting SDG objectives by improving access to safe sanitation and promoting sustainable water resource management, particularly in newly developed and sparsely populated regions. Overall, this comprehensive assessment advances the understanding of sustainable wastewater treatment approaches and provides valuable insights for addressing the growing global challenges of water scarcity and sanitation.

Keywords: Water scarcity; Decentralized wastewater treatment systems (DWTS); Centralized wastewater treatment systems (CWTS); Water reuse; Sustainable water management; Environmental sustainability; Economic assessment

Introduction:

Water is one of the most valuable natural resources and serves as the foundation for human survival, economic development, and environmental sustainability. Rapid population growth, urbanization, and industrial expansion have significantly increased the demand for freshwater, intensifying concerns over global water scarcity. The Earth's total water volume is estimated to be approximately 1,350 million km^3, yet only about 3% of this amount consists of freshwater suitable for human consumption and other essential activities. Of this limited freshwater reserve, nearly 65% is stored in glaciers and polar ice caps, making it largely inaccessible. Consequently, rivers, lakes, and reservoirs collectively account for less than 1% of the planet's total water resources, supplying the freshwater needs of more than 8 billion people worldwide. [1] The increasing demand for freshwater has been accompanied by a substantial rise in wastewater generation.

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According to the World Health Organization (WHO), data collected from 231 countries indicate that approximately 269 billion m³ of wastewater are produced globally each year.[2] Despite this enormous volume, only around 53% of wastewater receives safe treatment through secondary or advanced treatment processes that comply with environmental discharge standards. This treatment is provided by nearly 58,500 wastewater treatment plants (WWTPs) operating worldwide. [3]
The remaining untreated or inadequately treated wastewater is discharged into natural water bodies, creating serious environmental and public health concerns. In addition to contaminating surface and groundwater resources, untreated wastewater contributes to greenhouse gas emissions and indirectly accelerates climate change. Insufficient sanitation infrastructure further increases the risk of water pollution, threatening already limited freshwater supplies. Wastewater containing high concentrations of nutrients such as nitrogen and phosphorus promotes excessive algal growth and eutrophication when released into aquatic ecosystems. The subsequent decomposition of organic matter consumes dissolved oxygen, leading to hypoxic conditions that disrupt ecological balance, degrade water quality, and cause extensive mortality of aquatic organisms. These adverse impacts emphasize the urgent need for effective wastewater treatment and sustainable water resource management to safeguard both human health and the environment.

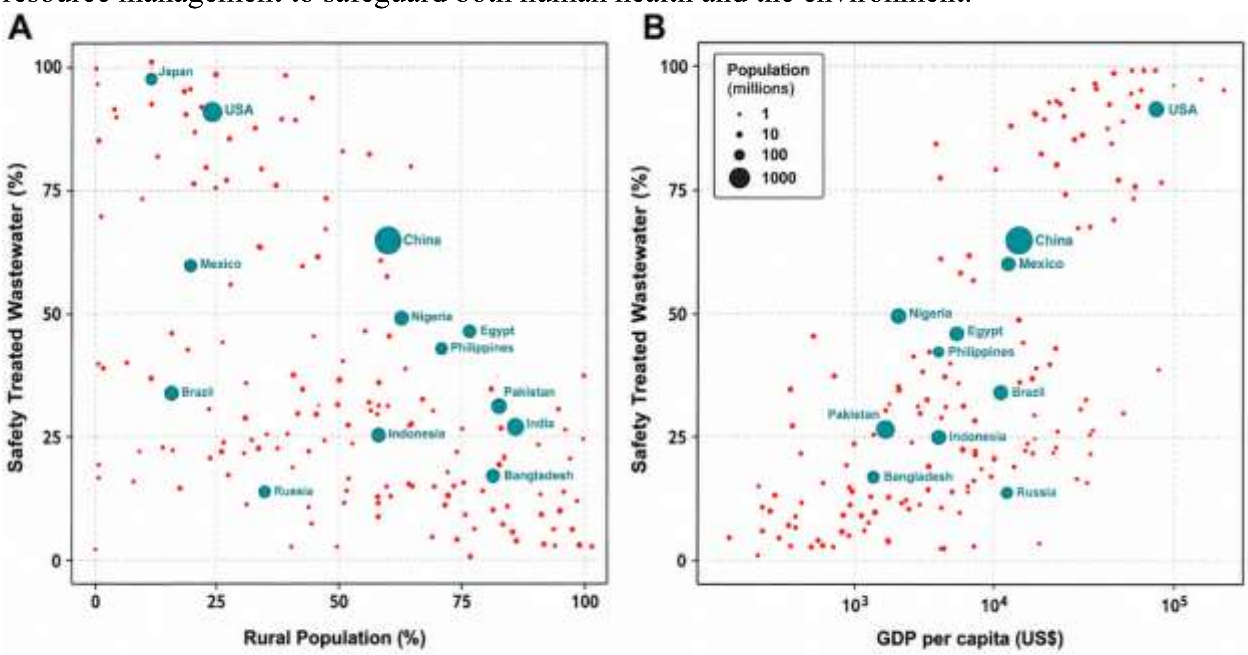

Figure 1. Percentage of safely treated wastewater by country based on (A) rural population and (B) GDP per capita. Countries with populations over 100 million are shown in green and labeled, while all others are represented by red markers. Data were adapted from the World Health Organization country profile database on safely treated wastewater.[2]

The degradation of aquatic ecosystems caused by untreated wastewater has become a major environmental concern. Excessive discharge of nutrient-rich effluents reduces dissolved oxygen concentrations, disrupts ecological balance, and results in significant losses of aquatic biodiversity.[4] In addition, inadequate sanitation infrastructure remains a persistent challenge in many parts of the world, particularly in rural regions of low- and middle-income countries where

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access to wastewater treatment facilities is limited.[5] More than 4 billion people still lack access to safely managed sanitation services, with the majority living in rural and sparsely populated communities.[2]

Figure 1A illustrates the relationship between the proportion of the rural population and the percentage of wastewater that is safely treated. The figure indicates that countries with larger rural populations generally exhibit lower levels of wastewater treatment, thereby increasing environmental pollution and public health risks. Similarly, Figure 1B demonstrates a positive relationship between gross domestic product (GDP) per capita and the proportion of safely treated wastewater, suggesting that economically developed countries are more capable of investing in effective wastewater treatment infrastructure and sanitation services.

Recognizing these global challenges, the United Nations General Assembly introduced Sustainable Development 6 (SDG 6) in 2015 to promote universal access to clean water and adequate sanitation. This initiative emphasizes equitable sanitation services (Target 6.2) together with improved wastewater treatment and reuse (Target 6.3). Its objectives include reducing water pollution, preventing the discharge of hazardous substances, minimizing untreated wastewater, and substantially increasing wastewater recycling and safe reuse by the year 2030.[6] Despite these ambitious commitments, current progress indicates that many countries remain behind schedule in achieving these targets.[7]

In densely populated urban areas, centralized wastewater treatment systems (CWTS**)** have traditionally served as the primary solution for wastewater collection and treatment. However, recent research suggests that implementing sanitation infrastructure in phased stages is often more economical than constructing large centralized facilities at once, particularly in newly developed urban regions. [8] This approach encourages the deployment of smaller decentralized wastewater treatment systems (DWTS) that can be expanded as demand increases.

The situation is considerably different in rural and low-density areas, particularly in developing nations, where financial limitations, inadequate technical expertise, and dispersed populations often make centralized wastewater systems difficult to construct, operate, and maintain.[9,10] Consequently, decentralized wastewater treatment systems (DWTS**)** and on-site wastewater treatment systems (OWTS) have emerged as practical and sustainable alternatives. Designed for small communities and isolated settlements, these systems provide affordable sanitation while reducing infrastructure costs associated with extensive sewer networks and long-distance wastewater transportation.[11] Moreover, their lower energy requirements, operational simplicity, and cost-effectiveness make them particularly suitable for developing countries where economic considerations strongly influence infrastructure planning.[12]

Selecting wastewater treatment technologies that reflect local environmental, economic, and demographic conditions is therefore essential for improving sanitation coverage in rural and peri-urban regions. Such localized approaches not only enhance affordability and operational efficiency but also encourage wastewater reuse and sustainable water resource management. Although numerous studies have investigated OWTS**,** DWTS**,** and CWTS**,** most have focused on specific case studies, individual treatment technologies, or particular wastewater streams such as greywater or domestic wastewater.[8,13,14] Comparatively fewer investigations have comprehensively evaluated the trade-offs between centralized and decentralized systems from a global perspective to support universal sanitation access and achieve the objectives of SDG 6**.**

In this context, the present review provides a comprehensive evaluation of the economic feasibility, operational performance, advantages, and limitations of OWTS**,** DWTS**,** and CWTS**,** with particular emphasis on rural and community-scale applications. By systematically comparing these wastewater management approaches, the review offers valuable insights for policymakers, engineers, researchers,

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and practitioners involved in sustainable sanitation planning. Furthermore, the study assesses the capability of these treatment systems to support the objectives of SDG 6.2 and SDG 6.3**,** including improved sanitation coverage, enhanced water quality, pollution reduction, and safe wastewater reuse. Ultimately, the review contributes to the development of sustainable wastewater management strategies that promote equitable access to clean water and sanitation regardless of geographical location or economic conditions.

2. Scale of Wastewater Treatment Systems

Wastewater treatment systems are generally classified into three major categories based on the scale of operation and the location where treatment is performed: on-site wastewater treatment systems (OWTS), decentralized wastewater treatment systems (DWTS), and centralized wastewater treatment systems (CWTS) (Figure 2). Each system differs in terms of treatment capacity, infrastructure requirements, operational complexity, and suitability for specific population densities and geographical conditions. The following sections provide an overview of these wastewater treatment approaches.

2.1. On-Site Wastewater Treatment Systems (OWTS)

On-site wastewater treatment systems (OWTS) are designed to collect, treat, and dispose of wastewater at or near the location where it is generated (Figure 2A). These systems play a crucial role in rural, peri-urban, and suburban areas where connection to centralized or decentralized sewer networks is either technically challenging or economically infeasible.[15] OWTS are particularly suitable for individual households, farms, and small communities with low population density.

Several technologies are employed within OWTS, including septic tanks, secondary treatment units, and constructed wetlands (CWs). Among these, septic tanks remain the most widely adopted technology worldwide (Figure 2A). They primarily provide physical treatment through sedimentation, while simultaneously facilitating limited biological treatment under anaerobic conditions.[14a] During treatment, heavier suspended solids settle to the bottom of the tank, forming sludge, whereas oils, fats, and grease accumulate at the surface as a scum layer. The partially clarified wastewater is then discharged to a soil treatment unit (STU) or drain field, where additional purification occurs as the effluent infiltrates through the surrounding soil and gravel matrix.

The soil treatment unit functions as a natural filtration and biological treatment system, removing remaining suspended solids, nutrients, and pathogenic microorganisms before the treated water reaches groundwater resources. The design and configuration of STUs vary according to local soil characteristics, groundwater levels, climatic conditions, and regulatory requirements.[14a] Consequently, proper system sizing, installation, and routine maintenance are essential to ensure reliable performance, protect public health, and minimize environmental contamination.[16]

Globally, septic tank systems treat approximately 28 billion m^3 of wastewater annually, providing sanitation services to nearly 880 million people, highlighting their significant contribution to wastewater management in regions lacking centralized infrastructure.[2]

To improve treatment performance beyond primary treatment, advanced packaged on-site treatment systems have been increasingly developed to provide secondary biological treatment before effluent is discharged to the soil treatment unit. These compact systems incorporate various biological treatment technologies, including coconut husk biofilters (e.g., Ecoflo Coco Filter), rotating biological contactors (RBCs) (e.g., Klargester BioDisc), and sequential batch reactors (SBRs) (e.g., Chieftain SBR). Such technologies are particularly advantageous where higher effluent quality is required or where site conditions limit the effectiveness of conventional septic tanks. [17]

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Secondary on-site treatment systems enhance wastewater purification by biologically degrading dissolved and suspended organic pollutants, substantially reducing biochemical oxygen demand (BOD), suspended solids, and pathogenic microorganisms before final discharge.[16] These systems offer improved environmental protection while maintaining the flexibility and cost-effectiveness associated with decentralized sanitation, making them an increasingly attractive option for sustainable wastewater management in rural and low-density communities.

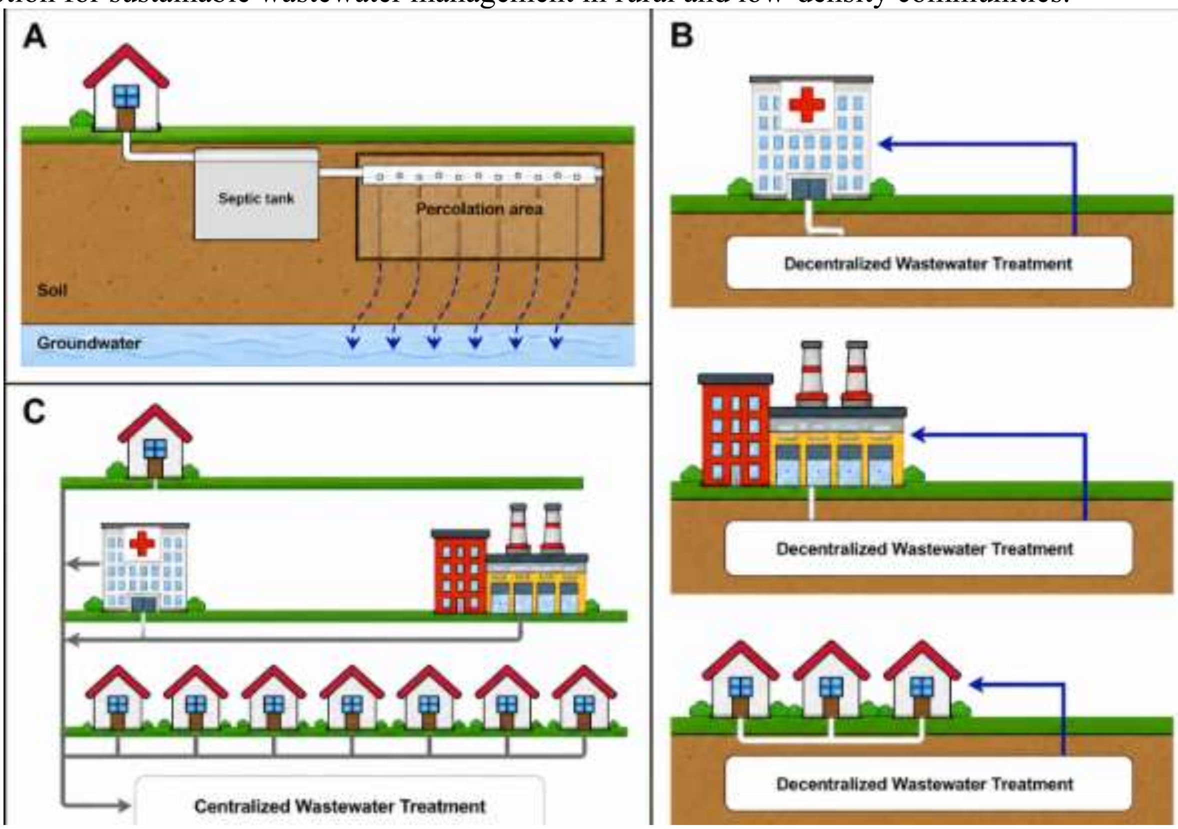

Figure 2. Schematic illustration of the major categories of sanitation systems: **(A)** Onsite Wastewater Treatment Systems (OWTS), **(B)** Decentralized Wastewater Treatment Systems (DWTS), and **(C)** Centralized Wastewater Treatment Systems (CWTS).

2.2. Decentralized Wastewater Treatment Systems (DWTS)

Decentralized Wastewater Treatment Systems (DWTS) are developed to provide wastewater treatment at an intermediate scale, serving small towns, residential clusters, institutions, and local communities (Figure 2B). These treatment facilities are intended for populations that are too large for individual onsite systems but too small to justify centralized treatment infrastructure. In Europe, approximately 62% of wastewater treatment plants (WWTPs) are small and remotely located, serving communities with capacities ranging from 2,000 to 10,000 population equivalents (PE). Consequently, the incorporation of digital technologies, including remote monitoring, automation, and intelligent process control, has become increasingly important for improving the operational performance and reliability of these decentralized facilities while addressing their unique management challenges.[18] Moreover, DWTS contribute to sustainable water resource management by facilitating the local reuse or safe discharge of treated wastewater within its originating watershed, thereby reducing environmental impacts and conserving freshwater resources.[19] Compared with centralized systems, decentralized treatment facilities generally require lower capital investment and reduced conveyance infrastructure, making them particularly

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suitable for regions with low population densities where centralized sewerage networks are economically impractical.[9]

2.3. Centralized Wastewater Treatment Systems (CWTS)

Centralized Wastewater Treatment Systems (CWTS) are widely implemented in developed countries, where wastewater generated from residential, commercial, and industrial sectors is collected through extensive sewer networks and conveyed to a centralized treatment facility for processing (Figure 2C). These systems are particularly effective in densely populated urban environments because they benefit from economies of scale and efficiently manage large wastewater volumes through integrated collection networks.[20] Nevertheless, centralized systems present several operational limitations. Transporting wastewater over long distances requires extensive pumping infrastructure, resulting in higher energy consumption and increased operational costs. During periods of heavy rainfall, infiltration and inflow substantially increase the hydraulic load as stormwater enters sewer networks through damaged joints, manholes, roof drains, and other structural connections. Furthermore, the combined collection of municipal and industrial wastewater often complicates resource recovery, wastewater recycling, and nutrient reuse. Therefore, selecting between decentralized and centralized wastewater treatment systems requires a comprehensive assessment that considers sustainability, environmental impacts, socioeconomic conditions, population density, and local geographical characteristics.[21] In addition, national political priorities, institutional capacity, and economic development significantly influence the selection of appropriate wastewater treatment strategies.[22] Consequently, the decision between DWTS and CWTS should be based on achieving an optimal balance between technical performance, economic feasibility, environmental sustainability, and long-term community development.

3. Economics of Wastewater Collection Systems

The collection and conveyance of wastewater represent one of the most significant cost components in wastewater management and constitute a major distinction between decentralized and centralized sanitation systems. Variations in collection infrastructure directly influence both capital expenditure and long-term operational costs. Previous studies have estimated that sewer collection systems account for nearly 60% of the total capital investment and approximately 70% of annual operating expenditures associated with pumping, sewer maintenance, and network management. [8,12b]

Centralized wastewater treatment systems are designed to handle large wastewater volumes generated in densely populated urban regions, where wastewater must be transported over considerable distances to centralized treatment facilities.[23] Conversely, decentralized systems treat wastewater close to its source of generation, thereby minimizing the need for extensive sewer networks and pumping infrastructure while maintaining satisfactory treatment performance and enabling local disposal or reuse of treated effluent.[24]

Figure 3 illustrates the relationship between population density and the specific sewer length required per population equivalent (PE). As population density increases from 100 PE km^{-2} to 5,000 PE km^{-2}, the required sewer length per PE decreases substantially from approximately 84 m to only 3 m. Based on previously reported average construction and operating costs for gravity sewer systems of approximately US$150 per meter and US$0.17 per meter, respectively,[8,25] both construction and maintenance costs decrease considerably with increasing population density. Specifically, construction costs decline from approximately US$12,557 to US$400 per PE, while annual operating costs decrease from nearly US$14 to only US$0.5 per PE (Figure 3). These findings indicate that in sparsely populated regions with population densities below 1,000 PE km^{-2},

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sewer construction costs frequently exceed US$1,500 per PE, making centralized sanitation systems economically unattractive.

Previous investigations have reported that decentralized sanitation systems can reduce implementation costs by approximately 40–45% compared with conventional centralized systems because they eliminate the need for extensive sewer connections, long conveyance pipelines, and pumping stations.[26] A case study conducted in South Africa further demonstrated that decentralized wastewater treatment systems offer substantially lower operational costs while producing reclaimed water suitable for agricultural irrigation and other non-potable applications. In contrast, centralized treatment would require expensive sewer network extensions to peripheral urban and agricultural areas, considerably increasing project costs.[27] Furthermore, decentralized systems provide greater flexibility for accommodating future urban expansion and population growth because treatment capacity can be expanded incrementally, thereby avoiding unnecessary investments associated with oversized infrastructure, idle treatment capacity, and uncertainties in future land-use planning and demographic changes.[26]

4. Footprint and Energy Usage of Different Treatment Technologies

The evolution of wastewater treatment technologies has been closely associated with growing environmental awareness, industrial development, and rapid urbanization. During the Industrial Revolution, deteriorating sanitation conditions and frequent outbreaks of waterborne diseases highlighted the urgent need for effective wastewater management solutions. These challenges ultimately led to the development of the Conventional Activated Sludge (CAS) process in 1914, which became the foundation of modern biological wastewater treatment.[28]

Since its introduction, the CAS process has undergone continuous improvements and has remained the most widely adopted biological treatment technology worldwide. Initially, CAS systems were primarily implemented in large metropolitan areas to address increasing wastewater generation. However, the need for more flexible treatment solutions in smaller communities led to the development of the Sequential Batch Reactor (SBR) during the 1980s, offering efficient treatment within a single reactor configuration.[29]

As urban populations continued to grow, the treatment capacity of conventional activated sludge plants became increasingly inadequate, prompting the introduction of the Moving Bed Biofilm Reactor (MBBR) during the 1990s. MBBR technology significantly enhanced biological treatment efficiency by increasing the available surface area for microbial growth without requiring substantial expansion of existing infrastructure.[30] Subsequently, the Membrane Bioreactor (MBR) was developed by integrating biological treatment with membrane filtration, producing superior effluent quality while substantially reducing plant footprint. However, these advantages were accompanied by increased energy requirements associated with membrane operation and aeration processes.[31]

A major technological advancement was achieved in 2006 with the development of the Aerobic Granular Sludge (AGS) process, which represented a significant breakthrough in biological wastewater treatment. Compared with previous technologies, AGS requires considerably less land area and lower energy consumption while maintaining excellent treatment efficiency. The emergence of AGS marks the culmination of nearly a century of technological innovation, reflecting the continuous progression from conventional activated sludge systems toward highly efficient, compact, and sustainable wastewater treatment technologies. [32]

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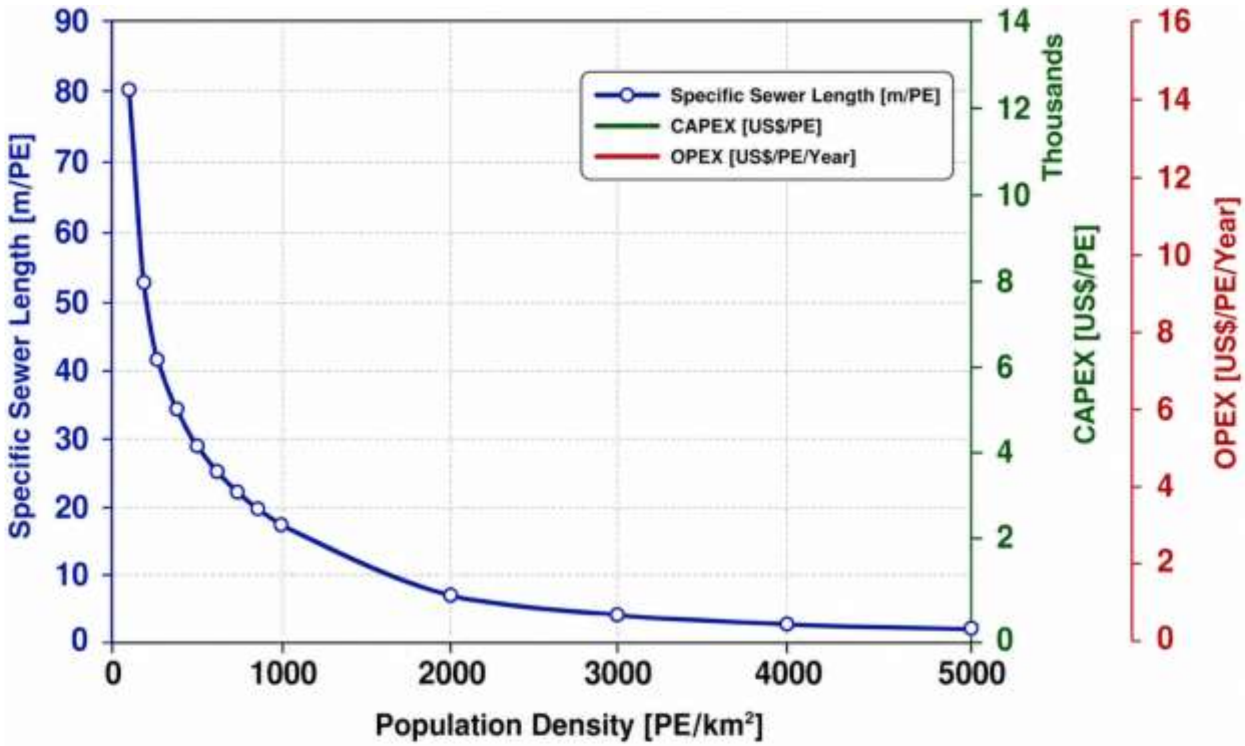

Figure 3. Variation in specific sewer length (m/PE) as a function of population density (PE/km²). The secondary y-axis illustrates the corresponding capital expenditure (CAPEX) for sewer network installation and the annual operating expenditure (OPEX) incurred for the operation and maintenance of the sewer system.

The selection of an appropriate wastewater treatment technology requires a comprehensive assessment of multiple technical, environmental, and economic factors, among which land requirement and energy consumption are particularly important. These parameters significantly influence the overall feasibility, sustainability, and long-term operational performance of wastewater treatment facilities, especially in regions experiencing rapid urbanization and limited land availability.

Figure 4A illustrates the relationship between the land area required by different wastewater treatment technologies and the population served. The comparison reveals considerable variation in footprint among the treatment processes. Constructed wetlands (CWs) exhibit the highest land demand, requiring approximately 4.5 m² per population equivalent (PE) due to their reliance on natural treatment mechanisms. Trickling filters (TFs) represent the second-largest footprint, occupying nearly 0.45 m²/PE. In comparison, membrane bioreactors (MBRs) require substantially less land, with an estimated footprint of approximately 0.05 m²/PE, reflecting their highly compact design and efficient reactor configuration. Other advanced biological treatment technologies, including aerobic granular sludge (AGS), conventional activated sludge (CAS) with chemical phosphorus removal, CAS with biological phosphorus removal, and integrated fixed-film activated sludge (IFAS), generally require between 0.06 and 0.125 m²/PE. Among these technologies, the AGS process demonstrates superior land-use efficiency because of its dense granular biomass and

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compact reactor design, making it one of the most space-efficient wastewater treatment technologies currently available.

Figure 4B compares the estimated daily energy consumption of various wastewater treatment technologies as a function of the population served. The results indicate noticeable differences in energy demand among the evaluated treatment systems. The AGS process exhibits the lowest daily energy consumption at approximately 70 kWh, followed closely by CAS with chemical phosphorus removal, which requires approximately 75 kWh. These comparatively low energy requirements contribute to reduced operational costs and improved overall energy efficiency. Nevertheless, although chemical phosphorus removal offers favorable energy performance, it depends on the continuous addition of chemical coagulants for phosphorus precipitation. This practice increases chemical consumption, produces larger quantities of sludge, and necessitates additional treatment and disposal processes, thereby increasing both operational complexity and environmental impacts. Consequently, the selection of an appropriate wastewater treatment technology should not rely solely on energy efficiency but should also consider land availability, chemical requirements, sludge generation, maintenance demands, operational costs, and long-term environmental sustainability to ensure optimal system performance under specific local conditions.

Figure 4. Comparison of land area requirement and energy consumption for different wastewater treatment technologies. (A) Land footprint required by various treatment processes as a function of the population served (m² per population equivalent, PE). (B) Estimated daily energy consumption (kWh/day) of different wastewater treatment technologies relative to the served population. The comparison highlights the trade-offs between spatial requirements and operational energy demand, providing a basis for selecting suitable technologies according to site-specific constraints and sustainability objectives.

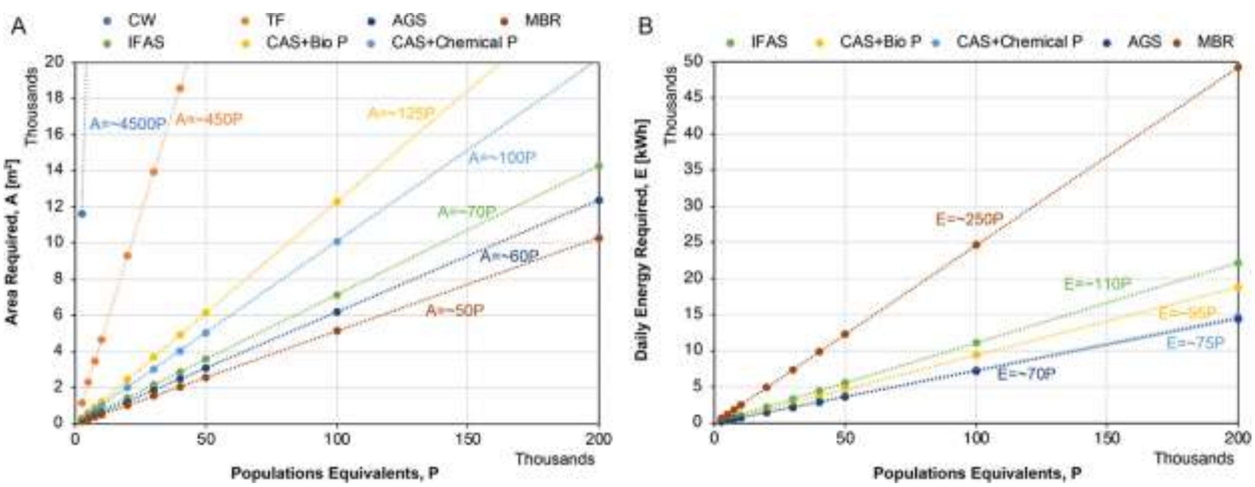

Figure 4. Comparison of land area and energy requirements for different wastewater treatment technologies. (A) Land area required as a function of the population served for various treatment systems. (B) Daily energy consumption relative to the population served. Data adapted from Ref. [51].

Although conventional activated sludge (CAS) with chemical phosphorus removal demonstrates relatively low energy consumption, its dependence on chemical additives for phosphorus precipitation results in the production of considerable quantities of chemical sludge. The handling, treatment, and disposal of this sludge increase operational complexity and overall treatment costs. In comparison, CAS with biological phosphorus removal and integrated fixed-film activated

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sludge (IFAS) systems require higher energy inputs because of their more intensive aeration and biological treatment processes.

Among the technologies evaluated, the membrane bioreactor (MBR) exhibits the highest specific energy demand, consuming approximately 0.25 kWh per population equivalent (PE). This elevated energy requirement is primarily attributed to membrane filtration, continuous aeration for fouling control, and periodic membrane cleaning, which also involves chemical consumption. Although MBR technology is widely recognized as one of the most advanced wastewater reuse processes due to its ability to produce high-quality effluent and reduce dependence on energy-intensive reverse osmosis desalination (typically 3–8 kWh m^{-3}) for freshwater production, its substantial energy demand remains a significant limitation.

An attractive alternative is the aerobic granular sludge (AGS) process, which can reduce the energy footprint by more than three times compared with MBR systems. Furthermore, integrating AGS with gravity-driven membrane filtration offers an innovative treatment strategy capable of producing high-quality reclaimed water while considerably lowering energy consumption. This hybrid configuration is suitable for both centralized and decentralized wastewater treatment applications, making it an attractive option for future sustainable treatment systems.

The growing emphasis on reducing greenhouse gas emissions, as outlined in the Paris Agreement, has further increased the importance of energy-efficient wastewater treatment technologies. Many European countries have committed to reducing carbon emissions by approximately 50% by 2030 and achieving carbon neutrality by 2050. Since electricity generation in many regions still relies heavily on fossil fuels, minimizing the energy demand of wastewater treatment plants plays a crucial role in reducing their overall carbon footprint.

Compared with aerobic treatment systems, anaerobic processes require significantly less energy because they eliminate the need for aeration and simultaneously generate methane (CH_4), which can be recovered as a renewable energy source to partially offset operational energy requirements. The selection of aerobic, anaerobic, or hybrid treatment systems depends largely on wastewater characteristics, and integrated approaches are increasingly adopted to maximize treatment efficiency.

However, anaerobic treatment is generally unsuitable for low-strength domestic wastewater with biochemical oxygen demand (BOD) concentrations below 230 mg L^{-1}, whereas it performs effectively for high-strength industrial wastewater containing BOD concentrations exceeding 560 mg L^{-1}. One major limitation of anaerobic treatment is the release of dissolved methane, which often represents more than 50% of the total methane produced. Because methane possesses a global warming potential nearly 30 times greater than carbon dioxide, uncontrolled methane emissions can substantially increase environmental impacts. Additionally, anaerobic systems provide minimal removal of nutrients such as nitrogen and phosphorus, increasing the risk of eutrophication in receiving water bodies. Consequently, these systems generally cannot satisfy stringent discharge and water reuse standards requiring BOD concentrations below 10 mg L^{-1} and ammonium concentrations below 5 mg L^{-1} without additional post-treatment.

Historically, centralized wastewater treatment systems (CWTS) were developed to serve large populations by exploiting economies of scale, thereby reducing treatment costs through centralized infrastructure and operation. In contrast, decentralized wastewater treatment systems (DWTS) capitalize on economies of scope, offering greater operational flexibility, modularity, and multifunctionality. Their compact design allows treatment units to be distributed closer to wastewater generation points, reducing land requirements compared with a single centralized facility. Moreover, decentralized systems can be readily expanded or upgraded by adding modular

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treatment units without disrupting ongoing plant operation, making them highly adaptable to changing population demands and urban development.

Consequently, the selection between centralized and decentralized treatment strategies largely depends on population density and local infrastructure requirements. Centralized systems are generally more appropriate for densely populated urban regions, where economies of scale improve economic performance, whereas decentralized systems provide greater advantages in sparsely populated or peri-urban areas by offering flexibility, lower infrastructure requirements, and enhanced adaptability.

5. Economics of Wastewater Treatment Systems

Figure 5A demonstrates the influence of treatment plant size on the capital expenditure (CAPEX) of wastewater treatment facilities. As the population served increases, the CAPEX per population equivalent (PE) decreases substantially, reflecting the benefits of economies of scale. Specifically, the capital investment decreases from approximately US$1,084 per PE for a treatment capacity of 2,500 PE to approximately US$227 per PE for facilities serving 200,000 PE. Although the total capital investment increases from approximately US$2.68 million to US$60.34 million as plant capacity expands, the cost per individual served declines considerably, highlighting the improved economic efficiency associated with large-scale wastewater treatment facilities.

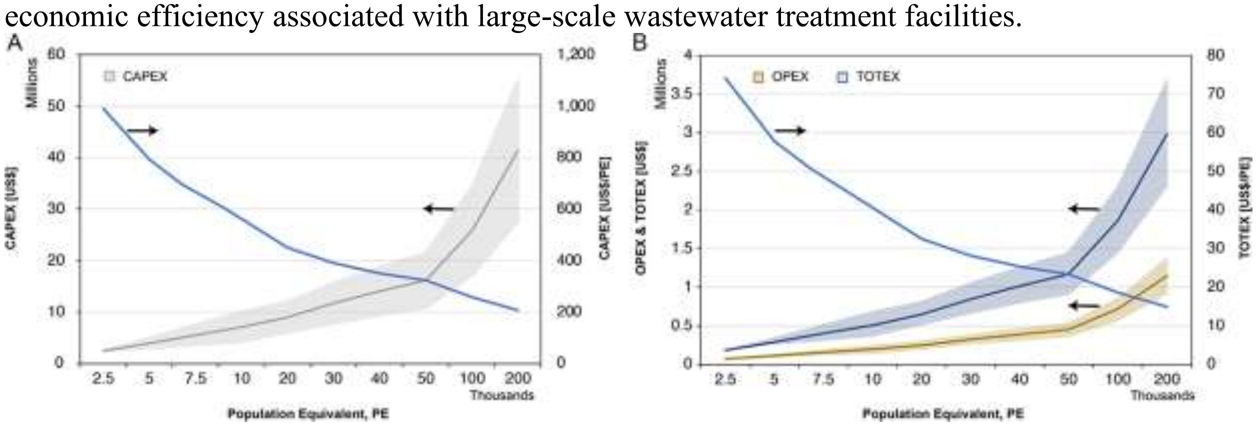

Figure 5. Population served versus (A) CAPEX and (B) OPEX and TOTEX for wastewater treatment systems. Shaded bands indicate value ranges, and solid lines represent average costs. Adapted from Refs. [8,25].

Large centralized wastewater treatment systems (CWTS) benefit from economies of scale by reducing both capital expenditure (CAPEX) and annual operating expenditure (OPEX). However, their overall economic feasibility should also consider the investment and maintenance costs of the associated sewer network. In densely populated regions with population densities exceeding 1500 PE km^{-2}, centralized systems generally provide the most economical solution for both CAPEX and OPEX. Conversely, in sparsely populated or rapidly developing areas, decentralized wastewater treatment systems (DWTS) employing modular and phased expansion strategies offer a more cost-effective alternative. Their modular configuration allows treatment capacity to be expanded progressively in response to population growth while minimizing initial investment costs.[8]

In addition, wastewater treatment technologies must be designed with future environmental regulations in mind. For example, the European Union (EU) requires secondary treatment for all urban wastewater treatment plants serving ≥1000 PE by 2035.[39] Furthermore, tertiary treatment for nitrogen and phosphorus removal will become mandatory for facilities serving ≥150 000 PE

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by 2039 and ≥10 000 PE by 2045, while quaternary treatment for micropollutant removal will be compulsory for plants serving ≥150 000 PE by 2045.[39] Consequently, modular wastewater treatment systems should be planned with sufficient flexibility to accommodate future regulatory requirements.

6. Challenges and Opportunities of DWTS

The implementation of decentralized wastewater treatment systems (DWTS) presents several technical, economic, regulatory, and social challenges while simultaneously offering significant opportunities for sustainable wastewater management.

6.1 Challenges

6.1.1 Operation and Maintenance Requirements

Reliable operation of DWTS depends on effective preventive, predictive, and corrective maintenance. Inadequate inspection and maintenance expose treatment units to environmental fluctuations such as changes in pH, temperature, and hydraulic or toxic shock loading, thereby reducing treatment efficiency. Compared with centralized systems, DWTS frequently experience shortages of skilled operators, resulting in operational deficiencies. An assessment of decentralized treatment facilities in Indonesia demonstrated that insufficient management practices and irregular maintenance significantly reduced the removal efficiencies of chemical oxygen demand (COD), ammonia, oil, and grease.[40]

Poor operational management may also create downstream environmental problems, particularly in water-scarce regions where reclaimed wastewater is extensively used for agricultural irrigation.[41] The integration of remote monitoring, automation, and digital control systems can substantially reduce dependence on on-site operators by enabling rapid fault detection and allowing skilled personnel to respond efficiently when required.

6.1.2 Policy and Regulatory Challenges

Environmental authorities worldwide are implementing increasingly stringent wastewater treatment regulations to improve environmental protection. However, compliance with these enhanced standards often requires technological upgrades that substantially increase treatment costs. Consequently, many decentralized systems, particularly those operating in low-income communities, encounter financial barriers that limit their ability to meet evolving regulatory requirements.[24a]

6.1.3 Public Acceptance and Social Challenges

Public perception remains a significant barrier to the implementation of DWTS. Concerns regarding pathogens, chemical contaminants, and potential environmental and public health risks frequently reduce community acceptance of decentralized wastewater treatment and water reuse projects.[41,42] Recent studies emphasize that successful implementation requires both public education and stakeholder engagement, particularly in regions experiencing water scarcity.[41,42] Increasing awareness of the environmental, economic, and water security benefits of wastewater reuse is essential for promoting a circular water economy and improving public confidence.[42,43] Furthermore, growing recognition of the flexibility, resilience, and economic advantages of decentralized treatment systems is contributing to their increasing acceptance worldwide.[43a,44]

6.2 Opportunities of DWTS

6.2.1 Water Reuse

Growing population pressures and increasing freshwater scarcity have made water reuse an essential component of sustainable wastewater management. Consequently, water reuse should be considered during the planning and design of wastewater treatment systems. Although

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implementation requires careful evaluation of investment costs and impacts on existing infrastructure, the long-term benefits often outweigh these challenges. A study conducted in Noida, India, reported that implementing wastewater reuse for toilet flushing and landscape irrigation reduced local freshwater consumption by approximately 48%.[42,45]

Treated wastewater provides a dependable alternative water source throughout the year, particularly when generated close to locations with high water demand. In centralized systems, reclaimed water often requires transportation through pipelines or tanker trucks from treatment plants to residential, agricultural, or industrial users, increasing operational costs. In contrast, DWTS produce reclaimed water directly at or near the point of demand, making them highly suitable for non-potable applications, including toilet flushing, landscape irrigation, agriculture, horticulture, and vehicle washing.[24b,42]

By minimizing water transportation requirements, decentralized systems reduce infrastructure costs, improve resource efficiency, and support localized water recycling. They also strengthen community resilience by narrowing the gap between wastewater generation and water reuse while reducing dependence on freshwater resources and energy-intensive distribution systems.[24] A case study from India, one of the world's most water-stressed countries, concluded that decentralized wastewater treatment represents an effective strategy for expanding water reuse and improving long-term water security.[24b] From an economic perspective, treating wastewater close to its source eliminates the need for extensive sewer networks and expensive centralized infrastructure, making decentralized systems a financially attractive solution.[23] Furthermore, industries are increasingly adopting DWTS to promote circular economy principles through on-site water recycling, resource recovery, and sustainable water management practices.[12b]

7. Conclusion

This perspective provides a quantitative comparison of centralized wastewater treatment systems (CWTS) and decentralized wastewater treatment systems (DWTS) by evaluating key economic indicators, including capital expenditure (CAPEX) and operating expenditure (OPEX) for both treatment facilities and associated sewer networks. The analysis indicates that CWTS are generally the most cost-effective option in densely populated regions with population densities exceeding 1500 PE km^{-2}**,** where economies of scale significantly reduce unit treatment costs. In contrast, DWTS are more advantageous in sparsely populated areas **(**<1500 PE km^{-2}**),** where economies of scope, modularity, and localized treatment improve economic and operational performance.

Compared with centralized systems, decentralized treatment offers additional benefits through reduced land requirements, localized infrastructure, and the ability to distribute treatment units closer to wastewater generation sources. The modular architecture of DWTS also enables straightforward expansion and technological upgrades without disrupting existing operations, thereby enhancing system flexibility and long-term adaptability. These characteristics make decentralized systems particularly suitable for rapidly developing communities and regions with dispersed populations.

References

[1] J. W. Moore, *Balancing the Needs of Water Use*, Springer Science & Business Media, Berlin 2013; b) B. H. Baker, C. A. Aldridge, A. R. Omer, *Water: Availability and Use*, Mississippi State University Extension, Starkville 2016.

[2] WHO, Country files for SDG 6.3.1: “Proportion of wastewater safely treated”, water-supply-sanitation-and-hygiene-monitoring/2021-country-files-for-sdg-6.3.1-proportion-of-water-safely-treated (accessed: July 2023).

[3] H. Ehalt Macedo, B. Lehner, J. Nicell, G. Grill, J. Li, A. Limtong,. Shakya, Earth Syst. Sci.

10.48047/jocaaa.2026.35.07.06

Data 2022, 14, 559.
[4] a) V. H. Smith, D. W. Schindler, Trends Ecol. Evol. 2009, 24, 201; b)
[5] J. Yu, Y. Tian, H. Jing, T. Sun, X. Wang, C. B. Andrews, C. Zheng, ACS ES&T Water 2023, 3, 1314; c) S. Vergara-López, M. Domínguez,
[6] M. Conejo, Á. Pascual, J. Rodríguez-Ban˜o, Clin. Microbiol. Infect. 2013, 12, E490.
[7] D. Kone, Nat. Water 2023, 1, 752.
[8] WHO, Water,Sanitation and Hygiene strategy 2018-2025, World Health Organization 2019 https://www.who.int/publications/i/ item/WHO-CED-PHE-WSH-18.03 Geneva (accessed: August 2023).
[9] G. Alabaster, R. Johnston, F. Thevenon, A. Shantz, United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO) 2021, p. 544.
[10] I. Roefs, B. Meulman, J. H. G. Vreeburg, M. Spiller, Water Res. 2017,102, 274.
[11] M. A. Massoud, A. Tarhini, J. A. Nasr, J. Environ. Manag. 2009, 20, 652.
[12] P. Paraskevas, D. Giokas, T. Lekkas, Water Sci. Technol. 2002, 46, 177.
[13] K. Rabaey, T. Vandekerckhove, A. Van de Walle, D. L. Sedlak, Water Res. 2020, 185, 116276.
[14] a) J. Cardona, A. Lepilova, D. Gieseler, K. Kreter, Strategies and Tools for a Sustainable Rural Rio de Janeiro, Springer, Berlin 2019,
[15] pp. 277–293; b) M. Garrido-Baserba, S. Vinardell, M. Molinos-Senante, D. Rosso, M. Poch, Environ. Sci. Technol. 2018, 52, 8965.
[16] a) M. A. Badar, S. Venkatachalam, Z. A. Y. Sani, presented at Inter. Conf. on Industrial Engineering and Operations Management, Dubai, UAE, March 10–12, 2020; b) S. Boavida, M. Pinto, T. Salvador, Hind, S. Neto, New Water Policy Pract. 2016, 2, 54; c)
[17] M. Prihandrijanti, A. Malisie, R. Otterpohl, presented at Efffcient Management of Wastewater, Berlin, Heidelberg 2008.
[18] a) A. J. Criado Monleon, J. Knappe, C. Somlai, C. O. Betancourth,
[19] M. Ali, T. P. Curtis, L. W. Gill, Front. Microbiol. 2022, 13, 915856;
[20] b) M. Garrido-Baserba, I. Barnosell, M. Molinos-Senante, D. L. Sedlak,
[21] K. Rabaey, O. Schraa, M. Verdaguer, D. Rosso, M. Poch, Water Res., 218, 118408; c) J. Keller, Water Res. X 2023, 12, 100180; d)
[22] K. Rabaey, T. Vandekerckhove, A. V. de Walle, D. L. Sedlak, Water Res. 2020, 185, 116276.
[23] M. Yates, Encyclopedia of Environmental Health, Elsevier, Amsterdam 2011, pp. 256–263.
[24] E. Butler, Y.-T. Hung, M. Suleiman Al Ahmad, R. Y.-L. Yeh, R. L.-H. Liu, Y.-P. Fu, Appl. Water Sci. 2017, 7, 31.
[25] N. Tharavathy, M. Krishnamoorthy, B. Hosetti, J. Ecol. Environ. Sci. 2014, 2, 1.
[26] A. Soares, Environ. Sci. Ecotechnol. 2020, 2, 100030.
[27] S. Cook, G. Tjandraatmadja, A. Ho, A. Sharma, Deffnition of Decentralised Systems in the South East Queensland Context, Urban Water Security Research Alliance Brisbane, Australia 2008. J. Parkinson, K. Tayler, Environ. Urban. 2003, 15, 75.
[28] USEPA. Handbookfor Managing Onsite and Clustered (Decentralized) Wastewater

10.48047/jocaaa.2026.35.07.06

Treatment Systems, NSCEP, National Service Center for Environmental Publications, Cincinnati, OH45242, EPA-832/ B-05-001 2005.
[29] F. Pasciucco, I. Pecorini, R. Iannelli, J. Clean. Prod. 2022, 375, 134092.
[30] C. Zaharia, Process. Saf. Environ. Prot. 2017, 108, 74.
[31] a) N. Brunner, M. Starkl, A. A. Kazmi, A. Real, N. Jain, V. Mishra, Water 2018, 10, 1644;
[32] b) V. G. Varma, S. Jha, L. H. K. Raju,R. L. Kishore, V. Ranjith, Chemosphere 2022, 300, 134462.
[33] T. Dogot, Y. Xanthoulis, N. Fonder, D. Xanthoulis, Water Sci. Technol. 2010, 62, 640.
[34] Y. T. Jung, N. Narayanan, Y.-L. Cheng, J. Environ. Manag. 2018,213, 90.
[35] J. Späth, P. Arumugam, R. H. Lindberg, O. A. Abafe, S. Jansson, J. Fick, C. A. Buckley, Water SA 2021, 47, 396.
[36] E. Ardern, W. T. Lockett, J. Soc. Chem. Ind. 1914, 33, 523.
[37] M. L. Arora, E. F. Barth, M. B. Umphres, Water Pollut. Control Fed. 1985, 57, 867.
[38] H. Ødegaard, B. Rusten, T. Westrum, Water Sci. Technol. 1994, 22, 157.
[39] K. Yamamoto, M. Hiasa, T. Mahmood, T. Matsuo, Water Sci. Technol.1989, 21, 43.
[40] M. K. de Kreuk, N. Kishida, M. C. van Loosdrecht, Water Sci. Technol.2007, 55, 75.
[41] G. K. Matar, M. Ali, S. Bagchi, S. Nunes, W. T. Liu, P. E. Saikaly, Front.Microbiol. 2021, 12, 708531.
[42] M. W. Shahzad, M. Burhan, L. Ang, K. C. Ng, Desalination 2017,413, 52.
[43] M. Ali, Y. Singh, L. Fortunato, Z. U. Rehman, S. Manjunath,
[44] J. S. Vrouwenvelder, M. Pronk, M. C. M. van Loosdrecht P. E. Saikaly, ACS ES&T Water 2023, 3, 2681.
[45] Y. J. Chan, M. F. Chong, C. L. Law, D. Hassell, Chem. Eng. J. 2009, 155, 1.
[46] S. Chen, A. L. Smith, Environ. Sci.: Water Res. Technol. 2018, 4, 67.
[47] A. Helmrich, S. Markolf, R. Li, T. Carvalhaes, Y. Kim, E. Bondank, M. Natarajan, N. Ahmad, M. Chester, Environ. Res.: Infrastruct. Sustain. 2021, 1, 021001.
[48] New EU rules to improve urban wastewater treatment and reuse, European Parliament, 2024.
[49] S. Rahmawati, A. Yulianto, A. T. P. Wijayaningrat, MATEC Web. Conf. 2019, 280, 03006.
[50] K. I. Odoemena, K. M. D. Rowshon, C. M. Hasfalina Binti, Irrig. Drain.2020, 62, 149.
[51] A. Dev, T. C. Dilly, A. E. Bakhshipour, U. Dittmer, S. M. Bhallamudi, Water 2021, 13, 2004.a) C. Gómez-Román, L. Lima, S. Vila-Tojo, A. Correa-Chica, J. Lema, J.-M. Sabucedo, Int. J. Environ. Res. Public Health 2020, 17, 9060; b)N. Contzen, J. Kollmann, H.-J. Mosler, Nat. Water 2023, 1, 138.
[52] A. Mankad, S. Tapsuwan, J. Environ. Manag. 2011, 22, 380. a) J. Gerend, Cogent Soc. Sci. 2019, 5, 1589662; b) C. Yu, Y. Xiao, S. Ni, Sci. Bull. 2017, 62, 83.
[53] a) M. Ali, P.-Y. Hong, H. Mishra, J. Vrouwenvelder, P. E. Saikaly, Water Reuse 2022, 12, 346; b) A. Alkhudhiri, N. B. Darwish, N. Hilal, J. Water Process Eng. 2019, 32, 100915.
[54] JICA, Strategic Plan for sewerage development, Vol. 6, Japan International Cooperation

10.48047/jocaaa.2026.35.07.06

Agency, 2020.
[55] a) S. Bengtsson, M. de Blois, B. M. Wilen, D. Gustavsson, Environ. Technol. 2019, 40, 2769; b) GoP, Lahore 1986.