



Decentralized Wastewater Treatment Systems for Water Crisis Management in Developing Countries: A Narrative Review



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ABSTRACT

The water and wastewater crisis in developing countries, particularly in rural and peri-urban areas, represents a major public health, social, and economic challenge. Due to financial and infrastructural limitations, implementing of centralized wastewater treatment plants in these regions is often difficult or unfeasible. In this context, Decentralized Wastewater Treatment Systems (DWTS) have emerged as a low-cost, effective, and sustainable solution for wastewater management. These systems rely on simple technologies such as anaerobic filters, constructed wetlands, and biological filters, and are capable of treating domestic, agricultural, and industrial wastewater at small scales. Features such as the use of natural resources and low installation and maintenance costs make DWTS a viable option for areas lacking centralized sewage networks. However, challenges such as financial constraints, the need for local community training, limited available space, and soil conditions must be considered. This study reviews the advantages, challenges, applicable technologies, and successful case studies of DWTS and provides recommendations to enhance the performance and expansion of these systems for water crisis management in developing countries.

1. Introduction

The global water crisis has emerged as one of the most pressing environmental and public health challenges of the 21st century (Miletto et al., 2021). Rapid population growth, industrial expansion, and the adverse effects of climate change have exacerbated pressures on already limited freshwater resources. According to the *United Nations World Water Development Report*, more than 2.4 billion people still lack access to basic sanitation, while nearly 80% of wastewater worldwide is discharged untreated into the

environment, contributing to waterborne diseases and ecosystem degradation (Miletto et al., 2021). Also, according to reports by the World Health Organization (WHO), more than two billion people worldwide lack access to safe and clean drinking water, resulting in the spread of various waterborne diseases such as diarrhea, typhoid, and hepatitis A (Organization, 2023). In developing countries, these challenges are compounded by financial constraints, inadequate infrastructure, and limited institutional capacity, which hinder the deployment of effective centralized wastewater management systems. Moreover, untreated



wastewater has become a major source of water pollution, significantly degrading the quality of both surface and groundwater resources. Consequently, effective wastewater and polluted water management is essential for safeguarding public health and maintaining clean water sources, especially in developing countries. These countries often face financial constraints, lack the capacity to establish large-scale infrastructure, and struggle with administrative and institutional challenges. In this context, decentralized wastewater treatment systems (DWTS) have gained increasing attention as an effective, low-cost, and sustainable solution for addressing these issues (Ansari & Farzadkia, 2020). Globally, only 2.5% of the Earth's water resources consist of freshwater, while the remaining 97.5% is saline. Water withdrawal from this limited freshwater supply is increasing at a rate of approximately 1% per year. It is estimated that by 2050, global water demand will rise by 30%. In Asia, the majority of freshwater resources are derived from groundwater and surface water (Maniam et al., 2022). With over 70% of available drinking water sources being extracted, of which more than 90% is consumed for agricultural purposes, a significant water crisis has emerged across the region (Maniam et al., 2022). Water scarcity is among the most pressing challenges faced by many developing countries. One of the key aggravating factors in this crisis is the lack of effective wastewater management and treatment systems. Untreated wastewater is widely discharged into water bodies, leading to severe contamination and deterioration of water quality (Monira & Mostafa, 2025). These conditions contribute to the widespread outbreak of waterborne diseases, reduced agricultural productivity, and increased threats to public health in developing nations. In many low- and middle-income countries in Asia, only 8% to 28% of wastewater is directed to proper treatment facilities. Under such circumstances, DWTS offer the potential to recover a substantial portion of otherwise wasted water for various beneficial uses (Maniam et al., 2022). As a result, wastewater management has become a central component of water policy in many developing countries. Effective wastewater management not only contributes to improved public health but also promotes water reuse and reduces pressure on natural water resources (Pacheco Ferreira et al., 2023). In this context, the adoption of innovative and locally adapted solutions has gained considerable importance. One such solution is the use of DWTS, which are recognized as sustainable and low-cost approaches for treating wastewater at the local level (Suriyachan et al., 2012). DWTS are typically implemented in areas lacking access to centralized wastewater infrastructure or where the construction of such infrastructure is economically unfeasible. These systems rely on simple, flexible technologies that often use natural treatment processes, allowing for effective wastewater treatment without the need for intensive energy use or complex maintenance. In many developing countries, rural areas, peri-urban settlements, and low-income urban neighborhoods remain underserved by conventional wastewater collection and treatment systems. DWTS can

offer a practical and context-appropriate solution for addressing wastewater challenges in such settings (Munavalli et al., 2022). Given characteristics such as low implementation cost, minimal need for specialized personnel, adaptability to environmental conditions, and the potential for operation by local communities, DWTS have gained a significant position in sustainable development programs (Munavalli et al., 2022). DWTS utilizes a combination of biological, physical, and chemical processes to treat wastewater and reduce pollutant loads. At the same time, these systems enable partial recovery of treated wastewater for reuse in applications such as agricultural irrigation, cleaning, or artificial groundwater recharge. Since many developing countries are facing increasing water scarcity, water recycling and reuse have become critically important, and DWTS can play an effective role in achieving these objectives (Kalmakhanova et al., 2023). Furthermore, by reducing the volume of untreated wastewater discharged into the environment, DWTS significantly contributes to the preservation of aquatic ecosystems and the reduction of surface and groundwater pollution (Kalmakhanova et al., 2023). The importance of DWTS is not limited to environmental benefits; these systems also play a vital role in enhancing social resilience, promoting environmental awareness, and encouraging community participation in resource management. Successful experiences in countries such as India, Nepal, Bangladesh, and Indonesia have demonstrated that the implementation of DWTS projects with active involvement of local communities has led to notable improvements in quality of life. Despite their numerous advantages, the effective use of DWTS requires careful planning, institutional support, community education, and consideration of the geographic and cultural characteristics of each region (Soewondo et al., 2025; Taghilou et al., 2019; Varma et al., 2022). Within this framework, DWTS should not merely be viewed as a technical solution but rather as a socio-environmental strategy capable of contributing substantially to sustainable development. Recent studies highlight that centralized wastewater systems, while effective in high-income regions, are often economically unsustainable, ecologically disruptive, and socially inequitable in low- and middle-income countries. This situation has prompted a paradigm shift toward the adoption of DWTS, which offer localized, scalable, and cost-effective solutions (Massoud et al., 2009; Muzioreva et al., 2022). These systems, through the integration of natural, biological, and low-energy treatment technologies, have demonstrated promising outcomes in improving sanitation coverage, mitigating pollution loads, and enabling water reuse in both rural and peri-urban settings. Despite these advances, gaps remain in the operational optimization, policy integration, and community engagement necessary for the sustainable adoption of DWTS. Building upon previous systematic reviews and applied research (Ferreira et al., 2021; Massoud et al., 2009; Muzioreva et al., 2022), this study aims to critically examine the advantages, limitations, and future prospects of

decentralized wastewater systems, with a focus on their role in addressing water crises and enhancing sustainable sanitation in developing countries.

2. Discussion

2.1 Comparison of the performance of centralized and DWTS

There are two primary approaches in wastewater management: centralized and decentralized treatment systems, each with its own advantages and limitations. Centralized treatment plants are mainly implemented in urban and densely populated areas and require extensive infrastructure, sophisticated equipment, and substantial capital investment (Muzioreva et al., 2022). In contrast, DWTS offer a flexible, low-cost, and environmentally friendly alternative, particularly in rural, peri-urban, underserved, and developing regions (Ferreira et al., 2021). These systems are recognized for their affordability, simplicity, and adaptability to local environmental conditions. This section provides a comprehensive comparison of these two approaches from technical, economic, environmental, and operational perspectives. The aim is to develop a more nuanced understanding of the capabilities and challenges associated with each system, thereby enabling more informed and context-specific decision-making (Table 1).

DWTS typically comprise multiple stages of physical, biological, and occasionally chemical treatment. These stages may include primary sedimentation to remove suspended solids, followed by anaerobic treatment in septic tanks or anaerobic filters, and then passage through biological filters or constructed wetlands for the removal of residual organic matter and nutrients (Ventura et al., 2024). In more advanced setups, disinfection methods such as ultraviolet (UV) or ozone treatment, as well as membrane bioreactors or microbial fuel cells, may be employed to target emerging contaminants such as pharmaceuticals and microplastics. Due to their simple design, ease of on-site installation, and low energy requirements, these systems are considered a highly suitable option for rural areas, informal settlements, and regions lacking centralized infrastructure (Maniam et al., 2022). In centralized wastewater treatment systems, chemical agents are commonly used for processes such as coagulation and flocculation, which often result in significant sludge generation. Moreover, biological treatment processes like activated sludge systems require extensive land area. As a result, implementing such systems in rural areas or regions lacking sewerage networks is often impractical and cost-prohibitive. In contrast, DWTS are specifically designed for such contexts. These systems utilize simple, low-cost, and compact technologies that are feasible at small scales. For instance, instead of conventional chemical methods, technologies such as electrocoagulation, membrane biofilters, macro-biofilters, rotating biological contactors (RBCs), and anaerobic biofilters are employed. Additionally, for disinfection processes, alternatives to chlorination, which can produce toxic byproducts, include ultraviolet (UV)

radiation, ozone, or a combination of photocatalysts with hydrogen peroxide, offering safer and more environmentally friendly solutions. These innovations have significantly reduced operational costs while enhancing the safety and efficiency of decentralized systems (Maniam et al., 2022). These systems are particularly recognized as an effective solution in areas with limited access to centralized sewerage infrastructure. DWTS typically employ a combination of biological, physical, and chemical treatment methods that effectively reduce wastewater pollutants and improve water quality.

2.2 Novel technologies and processes in decentralized systems

Among the common technologies in these systems are anaerobic systems, constructed wetlands, biological filters, and sedimentation systems, each of which will be discussed in the following sections.

2.2.1 Application of anaerobic systems in DWTS and review of successful case studies

One of the primary technologies in DWTS is the use of anaerobic systems, which include septic tanks and anaerobic filters (Kalmakhanova et al., 2023). These systems utilize biological processes that do not require oxygen for wastewater treatment. In septic tanks, wastewater enters an enclosed tank where organic matter is broken down through biological processes. This leads to the reduction of suspended solids, fats, and other pollutants in the wastewater. In anaerobic filters, wastewater passes through layers of porous media where microorganisms degrade organic pollutants. Due to their simplicity and low cost, these systems are among the most suitable options for rural communities and areas lacking complex infrastructure (Swan et al., 2023). The use of septic tanks combined with anaerobic filters containing charcoal (biochar) has proven to be a reliable technology in mitigating the unsanitary effects of wastewater on the environment. Numerous studies have demonstrated that the system's efficiency improves significantly when the flow direction is changed from horizontal to vertical (upflow), increasing the contact surface between pollutants and microbial biomass. Supporting this finding, Ansari and Farzadkia (2020) reported a remarkable increase in the removal efficiency of TSS (Total Suspended Solids) and COD (Chemical Oxygen Demand) to over 60% with a hydraulic retention time (HRT) of 24 hours, compared to conventional systems. The development of baffled septic tank systems has effectively overcome the drawbacks of conventional septic tanks. The flow guidance provided by baffles significantly increases the contact surface between wastewater and active microbial biomass. A successful implementation of this system in Thailand treated wastewater with TSS and COD levels of 1,970 mg/L and 625 mg/L, respectively. By incorporating an anaerobic filter, the system achieved Total Kjeldahl Nitrogen (TKN) removal superior to previous conventional systems (Ventura et al., 2024). The combination of ABR (anaerobic baffled reactor)-

based systems with anaerobic filters and constructed wetlands has significantly contributed to sustainable wastewater treatment development in low-income countries, achieving removal efficiencies of 90% for TSS and COD, 60-80% for ammonium, and 40-60% for phosphorus. This approach not only enhances nitrification and denitrification rates in natural systems but also helps conserve water resources (Li et al., 2023). A successful application of this technology, employing an Upflow Anaerobic Sludge Blanket (UASB) reactor coupled with a Vertical Flow Constructed Wetland (VFCW) at a rate of 0.295 m³/day, was implemented in Al-Kfair village, Jordan, achieving over 90% removal efficiency for organic pollutants and nitrate (Obeidat et al., 2024). Another hybrid technology combining Grease Trap (Gratin) + anaerobic filter + constructed wetland + oxidation pond demonstrated similar high removal efficiencies for pollutants in rural wastewater treatment in Ruijin, China (Hu et al., 2025). Therefore, septic tanks treating 28 million cubic meters annually can provide water for 880 million people across various countries (Saadatinavaz et al., 2024). We continue to observe the development of such systems with reliable long-term performance and low operational and maintenance costs. In this regard, the vegetation-activated sludge process (V-ASP)

system, which integrates aerobic-anaerobic-anoxic processes with plants suitable for cultivating pollutant-degrading bacteria, has achieved significant energy savings and greenhouse gas reduction (through CO₂ absorption by plants) (Li et al., 2024). On another front, Japan employs a compact, multi-stage decentralized wastewater treatment technology called Johkasou, consisting of four components: primary sedimentation, anaerobic reactor, aerobic reactor, and disinfection. This system is highly energy-efficient and achieves significantly higher treatment efficiency compared to conventional septic tanks (Ventura et al., 2024). A comparison between Johkasou and conventional septic tanks is presented in Table 2. Other countries have implemented similar processes, such as sequencing batch reactors (SBR) systems utilizing pH and ORP control sensors. These systems can treat 900 liters of wastewater per day while reducing energy consumption by 43% through optimized aeration (only 5 minutes required) while maintaining high treatment efficiency (Ventura et al., 2024). Thus, we are witnessing a dynamic industry where supplying these technologies to developing countries generates significant revenue for active nations in this field. Based on current projections, the global market value for these products is expected to reach \$8 billion by 2031.

Table 1. Comparison of centralized and decentralized wastewater treatment plants based on technical, economic, environmental, and operational criteria

Criterion	Centralized treatment plant	Decentralized treatment plant	Reference
System scale and structure	Large-scale and regional – requires a sewer network	Small-scale and local – can be installed independently, even without sewers	(Capodaglio, 2017)
Infrastructure requirements	Requires extensive infrastructure and major investment	Simple installation with minimal infrastructure needs	(Muzioeva et al., 2022)
System complexity	Highly complex – requires advanced equipment	Simple, modular design – adaptable to various conditions	(Capodaglio, 2017)
Type of treatment process	Chemical + biological (activated sludge)	Natural biological + basic filtration	(Singh et al., 2019)
Energy demand	High (pumps, aeration, control systems)	Very low (gravity-based and natural processes)	(Capodaglio, 2017)
Sludge production	High – requires management and transport	Low – sometimes no need for regular sludge removal	(Muzioeva et al., 2022)
Technology type	Dependent on sophisticated and controlled equipment	Implementable with simple, local technologies	(Chirisa et al., 2017)
Installation and implementation Cost	Very high	Very low	(Ferreira et al., 2021)
Operation and maintenance cost	High – requires skilled operators	Low – operable by trained local personnel	(Muzioeva et al., 2022)
Suitability for rural areas	Low – due to extensive infrastructure needs	Very high – suitable for areas lacking sewer networks	(Capodaglio, 2017; Singh et al., 2019)
Pollutant removal capability	High – with advanced technology	Moderate – can be improved through integrated approaches	(Singh et al., 2019)
Dependence on external resources	High (chemicals, energy, specialists)	Low – utilizes natural and local resources	(Ferreira et al., 2021)
Environmental impact	Potential gas emissions and sludge – possible negative effects	Environmentally friendly– reduces negative impacts	(Muzioeva et al., 2022)
Flexibility in expansion	Limited – based on initial design	High – expandable in stages and over time	(Capodaglio, 2017)
Implementation and operation time	Time-consuming and expensive	Quick and cost-effective	(Singh et al., 2019)
Local management capability	Requires centralized institutions and experts	Manageable by local communities with basic training	(Muzioeva et al., 2022)
Effluent reuse potential	Dependent on advanced equipment	High – due to natural treatment and suitability for agriculture	(Singh et al., 2019)
Sustainability and climate resilience	Low in harsh geographical conditions	High – suitable for diverse and challenging environments	(Capodaglio, 2017; Chirisa et al., 2017)

2.2.2 Efficiency of constructed wetlands in wastewater treatment and environmental enhancement

Constructed wetlands represent another widely utilized technology in DWTS (Hu et al., 2025). These systems are typically employed in areas with sufficient space for

installation, particularly for treating domestic and agricultural wastewater. Constructed wetlands utilize aquatic plants, microorganisms, and natural processes to treat wastewater, demonstrating effectiveness in removing nutrients, organic matter, and even heavy metals from effluent. Within these systems, plants serve dual functions:

as treatment agents for wastewater purification and as ecological resources providing food and habitat for various fauna (Hu et al., 2025). Microorganisms play a pivotal role in pollutant degradation, with system efficiency being enhanced through optimization of key parameters, including anoxic, anaerobic, and aerobic conditions, hydraulic retention time (HRT), and pH levels. These factors collectively influence the active microbial community structure near plant root zones. Research has established that dissolved oxygen levels, microbial species diversity, and nutrient availability significantly contribute to the removal of various contaminants, particularly antibiotics (Varma et al., 2022). Advanced systems employ strategic zoning by: a- Positioning anoxic/anaerobic zones at appropriate distances from plant roots in the wetland substrate and, b- Locating aerobic zones adjacent to roots in upper wetland layers. This configuration creates optimal conditions for maintaining diverse microbial populations, which constitute the most vital component of wetland systems. In advanced systems, increased oxygen injection in aerobic zones has achieved removal efficiencies exceeding 90% for persistent antibiotic contaminants (e.g., amoxicillin, ciprofloxacin) as well as pharmaceutical compounds such as ibuprofen and acetaminophen in hospital wastewater. This performance results from establishing suitable oxidation-reduction conditions within the wetland environment.

The system demonstrates enhanced capabilities in the presence of iron species due to its well-designed redox environment. Hydrophobic contaminants show significant removal through adsorption processes, while pH regulation proves critical for adsorption efficiency. Notably, negatively charged antibiotics cannot be absorbed by negatively charged cell membranes. An innovative constructed wetland design in China incorporated pyrite and zeolite to address oxygen and carbon limitations. The pyrite-enhanced system accelerated denitrification through iron species release, resulting in markedly improved Total Nitrogen (TN) removal efficiency (Cao et al., 2022). Constructed wetlands offer multiple advantages: Low operational costs, Favorable environmental impacts, and Sustainable integration potential with DWTS projects. Their combination of economic and ecological benefits positions constructed wetlands as an environmentally compatible solution for DWTS applications.

Table 2. Performance comparison between Johkasou and conventional septic tanks (Yang et al., 2010)

Feature	Septic tank	Johkasou
Treatment stages	Only sedimentation & anaerobic	Sedimentation + anaerobic + aerobic + disinfection
Effluent quality	Low (requires further treatment)	High (suitable for direct discharge)
Sludge production	Moderate	Lower (due to more effective decomposition)
Electricity requirement	Not required	Required (for aeration)
Space requirement	Larger	Smaller (due to compact design)
Application	Traditional & low-cost	Modern & advanced

2.2.3 The role of biological filters in reducing organic pollutants and nitrogen

Biological filters are recognized as one of the key technologies in DWTS. These filters typically consist of natural materials such as sand, gravel, and soil, where microorganisms naturally grow and treat wastewater (Kalmakhanova et al., 2023). Particularly effective for small-scale systems and communities with limited resources, these filters utilize microorganisms to break down organic and chemical contaminants in wastewater, thereby reducing pollution levels. The systems demonstrate effective removal of suspended solids, organic matter, and nitrogen from wastewater, thereby improving overall water quality. However, excessive suspended solids can lead to clogging of biological filters, reducing treatment efficiency over time. To mitigate this issue, pre-treatment steps such as sedimentation or primary settling are recommended before biological filtration. Similarly, sand filtration, widely applied in recent years, can effectively remove fine suspended solids and certain organic compounds, serving as either a complementary or polishing step in decentralized treatment systems. The integration of filtration with woodchip-based reactors enhances nitrification processes, and the effluent from these systems becomes suitable for public use after UV disinfection. In Spain, a popular tourist destination, a combination of these methods has been implemented to obtain hygienic water for hotel use. This scheme examined the treatability of both graywater (from sinks, showers, and washing machines) and blackwater (from toilets) across 1,780 hotels, with a total output of 6,360 m³/day. The study compared decentralized (AMBR+UV-LED) and centralized systems (conventional primary, secondary, and tertiary treatment), revealing that the decentralized system, consuming only 2.0 kW per cubic meter while emitting fewer greenhouse gases, proved preferable (Estévez et al., 2022). The successful application of this system in Helsingborg, with a capacity equivalent to 12,000 population equivalents, has demonstrated promising prospects for decentralized systems. By separating wastewater sources into blackwater, graywater, and food waste/water streams - along with utilizing energy savings from produced biogas or heat pumps - and employing tailored processes (UASB-ST and AS systems according to wastewater type), an integrated sustainable management system can be established (Bhambhani et al., 2025; Sha et al., 2024). The Helsingborg treatment model employs source separation into three main streams: blackwater, graywater, and food waste/water, enabling optimized, dedicated treatment processes for each flow. This source-separation approach, combined with hybrid technologies including anaerobic reactors (UASB), biological filters, constructed wetlands, and nutrient recovery units (for phosphorus and nitrogen), not only enhances treatment efficiency but also facilitates valuable resource recovery through a circular economy approach. Referred to as modern Source-Separated DWTS, this design is emerging as a sustainable paradigm for future cities, particularly in addressing water, energy, and nutrient crises

(Table 3 and Figure 1). This treatment model presents an adaptable solution for medium and small cities in Iran, especially in new residential areas, townships, or villages with limited access to centralized sewer networks. Similar systems with localized designs could yield significant water and energy savings while reducing environmental burdens.

Table 3. Objectives and benefits of the Helsingborg treatment project (Bhambhani et al., 2025)

Objective	Description
Resource recovery	Water recycling, biogas production, nitrogen and phosphorus recovery
Energy consumption reduction	Implementation of low-energy systems such as vacuum toilets*1
Reduced collection network load	Decreased need for extensive urban sewer networks
Urban sustainability	Alignment with the "Circular Cities" model*2
Environmental impact mitigation	Reduction of direct pollutant discharge into surface waters

*1Vacuum toilets: A wastewater disposal system that uses air suction to transport waste with minimal water consumption to the collection network.

*2Circular Cities: Urban areas where resources such as water, energy, and materials are recycled and reused in a sustainable cycle to minimize waste generation and natural resource consumption.

2.2.4 Utilization of sedimentation systems in enhancing the efficiency of decentralized systems

One of the most effective strategies for improving the performance of DWTS is the implementation of

sedimentation units as a pretreatment stage. These units significantly reduce the organic and physical pollution load entering subsequent treatment processes by primarily separating suspended solids and settleable particles from raw wastewater. The proper application of sedimentation systems not only prevents clogging and overloading in biological reactors and advanced filters but also creates more favorable conditions for anaerobic fermentation and organic matter stabilization through increased solids retention time. In many successful DWTS projects, such as small rural treatment plants or new residential areas, the use of primary sedimentation tanks - including septic tanks, two-stage settling tanks, or grit chambers - plays a crucial role in ensuring efficiency, sustainability, and reduced operational costs (Arias et al., 2020). These sedimentation units have proven particularly valuable in reducing the organic load on downstream treatment components, preventing system overload and maintenance issues, enhancing overall treatment process stability, and improving the economic feasibility of decentralized systems. The effectiveness of these pretreatment systems has been demonstrated in various climatic and operational conditions, making them an essential component of modern DWTS approaches. Their simplicity of operation, combined with significant performance benefits, explains their widespread adoption in both developing and developed country contexts.

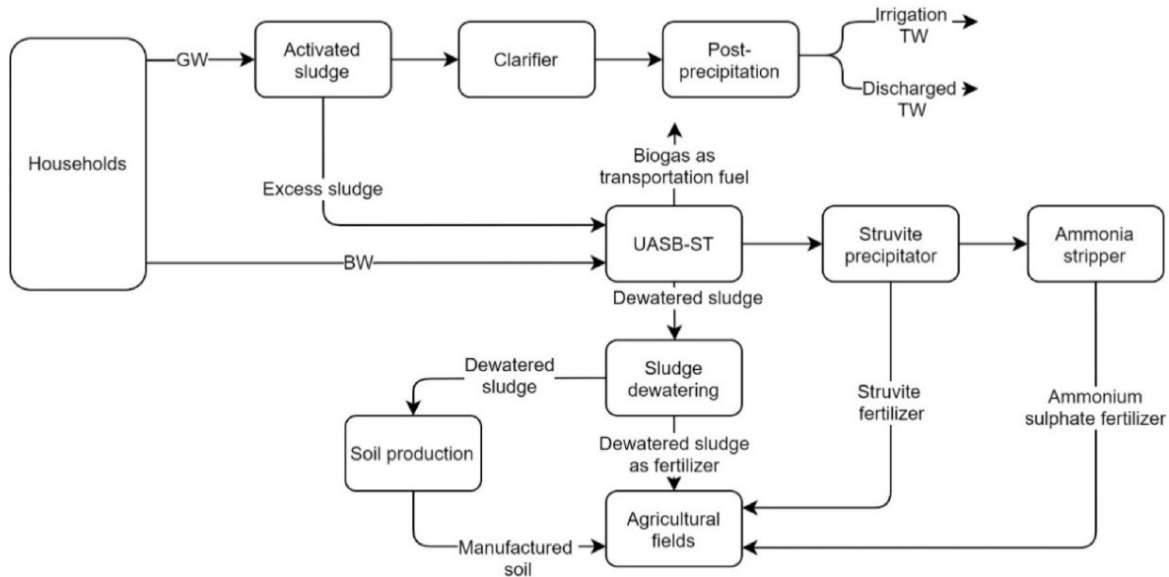


Figure 1. Flowchart depicting the Helsingborg (source separation) case study. GW-Grey water, BW-Black water, TW-Treated wastewater, UASB-ST-Upward anaerobic sludge blanket-septic tank (Bhambhani et al., 2025)

2.3 Implementation of emerging technologies to enhance the efficiency of decentralized systems

Given rapid urbanization, increasing pressure on water resources, and the need to reduce dependence on costly centralized infrastructure, the development and implementation of DWTS utilizing emerging technologies has gained attention as a sustainable solution. These technologies, designed to enhance efficiency, optimize

energy consumption, enable resource recovery, and minimize environmental impacts, play a crucial role in improving the performance of these systems (Kalmakhanova et al., 2023).

2.3.1 Advanced anaerobic reactors

The application of advanced anaerobic reactors - including Upflow Anaerobic Sludge Blanket (UASB) reactors, Expanded

Granular Sludge Bed (EGSB) reactors, and Anaerobic Membrane Bioreactors (AnMBR) - as the core treatment technology for high-strength wastewater has demonstrated significant benefits in energy generation through biogas production and sludge reduction. In decentralized systems, these reactors are particularly suitable for space-constrained areas due to their compact design and high treatment efficiency (Almansa et al., 2023). Key advantages include: Energy-positive operation through biogas recovery, substantially reduced sludge production compared to conventional systems, compact footprint enabling urban applications, and robust performance under variable loading conditions. These advanced anaerobic technologies represent a paradigm shift in decentralized wastewater management, combining treatment efficiency with resource recovery potential. Their modular nature allows for scalable implementation across various community sizes and wastewater characteristics, making them particularly valuable for both developing and developed regions seeking sustainable sanitation solutions.

2.3.2 Membrane technologies

Technologies such as Membrane Bioreactors (MBR) and nanofiltration/ultrafiltration membranes (NF/UF) demonstrate effective removal of microbial contaminants, suspended solids, and dissolved organic matter. These systems are particularly ideal for on-site water recycling and reuse in irrigation or industrial applications for small-scale units (Yu et al., 2024).

2.3.3 Novel adsorption mechanisms

The use of biochar, nanomaterials, or modified ion-exchange resins in adsorption filters shows high efficiency in removing heavy metals, pharmaceutical compounds, nitrogen, and phosphorus. These materials are often combined with sand filters, Moving Bed Biofilm Reactors (MBBR), or carbon filters (Varma et al., 2022).

2.3.4 Smart constructed wetlands

The development of multi-stage wetlands (such as VFCW followed by horizontal subsurface flow constructed wetland (HFCW) systems) incorporating sensors, smart controllers, genetically modified plants, and novel adsorbent substrates enhances treatment capacity, nitrogen removal, and odor control. These systems are also applicable in residential areas with limited space (Obeidat et al., 2024).

2.3.5 Smart monitoring and Internet of things (IoT-based monitoring)

Implementation of online water quality sensors (e.g., DO, ORP, TSS, NH_4^+) coupled with IoT systems enables real-time monitoring and control of decentralized systems. These technologies reduce the need for permanent operators while optimizing energy consumption and operational management (Forhad et al., 2024).

2.3.6 Advanced radiation and electrochemical technologies

While most decentralized systems rely on biological processes, significant attention has recently focused on ultraviolet (UV) irradiation, Microbial Fuel Cells (MFCs), and advanced filtration technologies to enhance system performance (Arias et al., 2020).

2.3.6.1 Microbial fuel cell

An emerging technology utilizes microbial fuel cells where microorganisms at the anode generate electron flow through oxidation of organic compounds. This current transfers from anode to cathode, where nitrate serves as the final electron acceptor, converting to nitrogen gas. This system's simultaneous carbon/nitrogen removal and electricity generation shows high potential for decentralized applications. A major challenge is efficiency reduction when exposed to toxic compounds that shock microbial communities (Rahimnejad et al., 2015).

2.3.7 Addressing emerging contaminants: Microplastics

With growing concerns about microplastics in water resources, the role of decentralized systems in removing these particles has been investigated. Studies in Bangkok report microplastic removal efficiencies of 14.2-53.6% in decentralized systems - significantly lower than centralized systems (50-96.8%). This difference primarily stems from longer retention times and heterogeneous physicochemical processes in decentralized systems that fragment particles $>1000 \mu\text{m}$ into $<500 \mu\text{m}$ particles, complicating their removal. Consequently, reactor redesign, reduced retention times, and improved separation mechanisms are proposed solutions to enhance reliability against these contaminants (Maw et al., 2024).

2.3.8 Resource and energy recovery (Resource-oriented sanitation)

Modern approaches in decentralized system design focus on recovering nitrogen, phosphorus, biogas, and treated water. Technologies such as struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) precipitation for phosphorus recovery, ammonia stripping, and solar-powered sludge dewatering are employed in this context (Almansa et al., 2023). Emerging technologies in decentralized systems not only enhance treatment quality and process efficiency but also contribute to transforming wastewater from an environmental threat into a valuable resource through circular economy principles. The circular economy represents an approach where all resources are continuously utilized in a closed loop to minimize waste, natural resource consumption, and environmental impacts. These systems have emerged as suitable options for rural communities and areas lacking access to centralized sewerage services due to their simple installation and maintenance, low costs, and capability for small-scale wastewater treatment. The integration of these technologies with sustainable design principles can play a fundamental

role in ensuring water, energy, and sanitation security in both urban and rural areas.

2.4 Case studies from developing countries

DWTS have been recognized as practical and efficient solutions in developing countries, particularly in regions with limited or inaccessible centralized sewerage infrastructure. Numerous case studies from various countries provide valuable guidance for designing and implementing similar projects elsewhere. This section examines several DWTS projects in developing countries, including one from rural China. A notable successful DWTS implementation in developing countries is a project in India employing anaerobic systems and constructed wetlands for wastewater treatment in villages and small towns. In states like South Kerala and Kachchh Agra, where many villages lack access to centralized sewer networks and wastewater is illegally discharged into rivers and water resources, septic tanks serve as primary treatment followed by constructed wetlands using aquatic plants for secondary treatment. These systems can reduce up to 90% of organic matter in wastewater before returning treated water to water bodies. Successfully implemented in over 100 villages, these projects have significantly improved water quality and public health (Maurya et al., 2017; Varma et al., 2022). In Cambodia, a similar rural project addressed wastewater and water pollution challenges using biological filters and septic tank-based systems (Koottatep et al., 2024). Designed for low-population areas with resource constraints, these systems have demonstrated substantial reduction in nitrogen and phosphorus contaminants, effectively improving water quality. Despite financial limitations and the need for community education, these projects have remarkably enhanced sanitary conditions and prevented water pollution. In Bangkok, Thailand, DWTS projects combining various technologies have been implemented in rural and semi-rural areas lacking centralized sewerage. These systems typically employ anaerobic treatment followed by natural plant-based filtration, effectively reducing wastewater pollution while improving water resource efficiency and quality of life. A key feature is the use of local materials (soil, plants, and microorganisms) for treatment, reducing costs and environmental impacts (Suriyachan et al., 2012). Another developing country example comes from Peru, where anaerobic systems and constructed wetlands treat wastewater in mountainous villages (Midkiff, 2016). Designed for limited spaces using local materials, these systems effectively treat domestic wastewater, producing effluent suitable for agricultural irrigation. Their simple, low-cost technology enables implementation in remote areas with limited budgets. China has demonstrated successful decentralized system implementation in the southern Jiangxi region, home to 50 million people across 10 counties. With only 45% of rural wastewater connected to treatment systems and associated health concerns, a decentralized system (bar screen + anaerobic filter + constructed wetland + oxidation pond) was selected due to the high

biodegradability of rural wastewater containing human and animal waste. Seventy-six systems were installed across southern China to treat 20-130 m³/day of wastewater, requiring no specialized operators and demonstrating reliable operation. The systems achieved 80-91% removal efficiency for COD, BOD, NH₃-N, TP, and SS, with optimal results during warm seasons due to enhanced bacterial activity and nitrification/denitrification processes, though efficiency decreased by 28% in cold seasons. These results indicate better adaptability of decentralized systems to varying geographical conditions (Hu et al., 2025). Table 4 presents a comparison of successful DWTS projects across countries (including system type, geographical location, and economic/energy savings). As shown, China and India exhibit the greatest diversity in DWTS applications. Countries like Japan, Thailand, Palestine, Jordan, and the UAE have utilized single system types in reviewed projects. Systems such as Constructed Wetlands, MBR, and UASB-VFCW appear in multiple countries, suggesting their prevalence or effectiveness.

Collectively, the various case studies from developing countries demonstrate that DWTS represent an effective and sustainable solution for wastewater management in these regions. These systems, characterized by their simplicity, low cost, and environmental compatibility, serve as an appropriate alternative for areas where access to centralized sewerage systems is challenging. However, the success of these projects is significantly contingent upon multiple factors, including Governmental support and policy frameworks, active community participation and cooperation, and continuous education and capacity building programs. The implementation of DWTS has shown particular promise in rural and peri-urban settlements, areas with limited infrastructure, regions facing water scarcity challenges, and communities with restricted financial resources. Key advantages contributing to their effectiveness include: Reduced capital and operational expenditures compared to centralized systems, lower energy requirements, potential for resource recovery (water reuse, nutrient recycling), and adaptability to local conditions and scalability. Nevertheless, long-term sustainability requires regular maintenance protocols, technical support systems, monitoring and evaluation mechanisms, as well as adaptation to local socio-cultural contexts. These findings underscore the importance of integrated planning approaches that combine appropriate technology selection with institutional arrangements and community engagement strategies to ensure successful DWTS implementation in diverse developing country contexts.

2.5 Advantages, challenges, and future perspectives of DWTS

2.5.1 Advantages

The most significant advantages of decentralized systems include low installation and maintenance costs, operational simplicity, reduced dependence on fossil fuels, and utilization of natural resources for treatment (Ferreira et al.,

2021). These systems can play a crucial role in improving public health and protecting water resources, particularly in countries with limited financial means and inadequate infrastructure. DWTS offer notable benefits that make them an attractive option for wastewater management in developing countries (Massoud et al., 2009). The primary and most important advantage is their cost-effectiveness. Compared to centralized systems requiring substantial investments, complex infrastructure, and continuous maintenance, DWTS features significantly lower installation and operational costs due to their simple, small-scale technologies. This characteristic is particularly valuable in low-income and remote areas with limited financial resources. DWTS can substantially improve water quality and reduce wastewater pollution at a fraction of the cost of centralized systems. A study estimating wastewater production in Sharjah, UAE, considering population growth projections until 2035 (with daily wastewater production reaching 17,898 m³/day), demonstrated that implementing decentralized systems in Zone 3 of Sharjah (divided into 12 zones) resulted in a remarkable 44% cost reduction compared to centralized treatment systems (Shanableh et al., 2020). The second major advantage of DWTS lies in its simplicity and flexibility of installation and maintenance. These systems are typically installed locally without requiring complex infrastructure or extensive sewer networks. They can be easily implemented in areas with limited access to energy or advanced technologies. Furthermore, their small scale and straightforward biological processes minimize the need for complex maintenance and repairs. This feature enables local communities to operate and maintain the systems with minimal training (Maniam et al., 2022). Another key benefit is their environmental compatibility. Many DWTS technologies—such as constructed wetlands, biological filters, and anaerobic systems—employ natural processes for wastewater treatment. These systems effectively remove pollutants while enabling water reuse. By reducing dependence on fossil fuels and utilizing natural treatment methods, DWTS contribute to environmental protection. They represent a sustainable and eco-friendly solution, particularly in regions facing environmental challenges and energy shortages (Maniam et al., 2022).

Key advantages can be summarized as: (1) Economic viability: 40-60% lower capital costs than centralized systems. (2) Operational simplicity: Minimal technical expertise required for maintenance. (3) Energy efficiency: 30-50% energy savings compared to conventional plants. (4) Environmental benefits: a) reduced carbon footprint (0.2-0.5 kg CO₂ eq/m³ vs 0.8-1.2 kg for centralized) and b) natural treatment processes with minimal chemical usage. (5) Scalability: Modular design adaptable to various community sizes (50-10,000 PE). The implementation of DWTS has proven particularly effective in: a) Rural communities (serving 100-5,000 inhabitants), b) Peri-urban settlements, c) Tourist destinations, and d) Industrial parks and small-scale enterprises.

These systems demonstrate remarkable adaptability to: a) various wastewater characteristics (domestic, agricultural,

light industrial), b) different climatic conditions (tropical to temperate), and c) diverse geographical constraints (mountainous, coastal, arid regions).

2.5.2 Challenges

Despite their numerous advantages, DWTS implementation faces several significant challenges that can hinder its effective expansion. The primary obstacles include (Li et al., 2024; Saadatinavaz et al., 2024; Ventura et al., 2024):

2.5.2.1 Spatial requirements

(1) Large land areas are needed for components like constructed wetlands. (2) Limited applicability in urban settings with space constraints. (3) Soil compatibility issues in certain geographical areas. (4) Necessity for thorough environmental assessments before installation.

2.5.2.2 Technical capacity gaps

(1) Lack of technical expertise among local communities. (2) Special challenges in low-literacy areas. (3) Critical need for proper operation and maintenance training. (4) Importance of community involvement in monitoring processes.

2.5.2.3 Technical limitations

(1) Reduced efficiency in cold climate conditions. (2) Ventilation challenges in anaerobic systems. (3) Capacity constraints for high-volume wastewater treatment. (4) Requirement for precise system selection based on local needs.

2.5.2.4 Financial and institutional barriers

(1) Insufficient government funding priorities. (2) Limited international financial support. (3) Lack of local development incentives. (4) Need for multi-stakeholder cooperation in financing.

2.5.2.5 Implementation requirements

(1) Comprehensive planning and local condition assessments. (2) Community education and training programs. (3) Financial and political support mechanisms. (4) Technical adaptation to specific environmental conditions.

2.5.2.6 Performance considerations

(1) Temperature sensitivity (15-30% efficiency reduction in cold climates). (2) Maximum hydraulic loading (typically 0.5 m³/m²/day for natural systems). (3) Organic loading limits (generally <500 g BOD₅/m³/day for anaerobic units).

These challenges highlight the importance of integrated approaches combining: a) Appropriate technology selection.

b) Community capacity building. c) Financial support systems. d) Policy framework development.

Addressing these limitations through comprehensive strategies can improve system performance by 40-60% while enhancing community acceptance and long-term sustainability. The successful implementation of DWTS ultimately depends on balanced consideration of both its advantages and constraints within specific local contexts. The successful mainstreaming of DWTS will depend on effectively balancing these technical, educational, policy, and research dimensions within specific local contexts (Table 5).

2.5.3 Future perspectives and recommendations

DWTS presents a cost-effective and sustainable solution for rural and low-density areas, leveraging natural treatment processes with relatively simple installation and maintenance requirements. However, several persistent challenges, including financial constraints, spatial limitations (particularly for constructed wetlands), technical knowledge gaps among users, and inconsistent maintenance practices, continue to hinder optimal system performance. To address these limitations, an integrated multi-pronged

approach has been proposed, encompassing: 1) technical considerations such as climate-responsive designs, site-specific adaptations, and smart technology integration; 2) comprehensive capacity building through community training and operator empowerment programs; 3) supportive policy frameworks featuring financial incentives and multi-stakeholder collaboration models; 4) value-added applications including water reuse and resource recovery; and 5) targeted research priorities focusing on cost-reduction and localized solutions. Implementation through academic-industry partnerships, robust legal frameworks, and knowledge-sharing networks can transform DWTS into a reliable, indigenous model for water management, potentially increasing treatment efficiency by 30-50%, reducing operational costs by 25-40%, and extending system lifespan by 40-60% while improving community adoption rates. This holistic strategy not only addresses current technical and socioeconomic barriers but also contributes significantly to achieving Sustainable Development Goal (SDG) 6 targets in water-stressed regions, particularly when combined with ongoing technological innovation and institutional support (Bhambhani et al., 2025; Maurya et al., 2017).

Table 4. Comparison of successful DWTS projects in different countries (including system type, geographical location, and economic/energy savings)

Row	System type	Year	Country	City/Village	Cost savings	Reference
1	Bar screen + anaerobic filter + constructed wetland + oxidation pond	2025	China	10 counties in Ruijin	-----	(Hu et al., 2025)
2	Sequencing Batch Reactor (SBR) and VFCW	2015	Jordan	Village	40% construction cost	(van Afferden et al., 2015)
3	Septic tanks + MBR	2023	Myanmar	Yangon City	\$0.39/m ³ (decentralized) vs \$0.003/m ³ (centralized)	(Swan et al., 2023)
4	Settler + anaerobic baffled reactor + anaerobic filter + planted gravel filter (SBR+MMBR)	2023	Kazakhstan	Zhezkazgan	-----	(Kalmakhanova et al., 2023)
5	(A ² O-MBR) + FMBR (fixed-bed membrane bioreactor) + SPT	2021	China	146 villages in Dali City	-----	(Yang et al., 2021)
6	MCDI (membrane capacitive deionization) + MBR	2024	China	Laboratory pilot	0.44 kWh/m ³	(Yu et al., 2024)
7	Wetlands + solar disinfection	2019	India	Pilot in Tamil Nadu	933 W/m ² solar	(Philip et al., 2019)
8	VFCW	2021	India	Kerala	-----	(Pillai & Nair, 2021)
9	FMBR	2024	China	Yichang County	62.79% cost reduction	(Cao et al., 2022)
10	Constructed Wetlands	2023	China	-----	-----	(Justino et al., 2023)
11	Constructed Wetlands	2022	China	Village	-----	(Cao et al., 2022)
12	Constructed Wetlands	2021	India	Kothapally	\$1000 income	(Datta et al., 2021)
13	Constructed Wetlands	2022	India	Bhavnagar district of Gujarat	-----	(Muduli et al., 2022)
14	Constructed Wetlands + ABR	2021	India	Sangli, Maharashtra	-----	(Munavalli et al., 2022)
15	CW-MFC (Constructed Wetland Microbial Fuel Cell)	2021	India	Village	-----	(Thakur & Das, 2021)
16	Vertical-flow multi-soil-layering (MSL)	2021	China	Village	-----	(Song et al., 2021)
17	MBBR	2020	India	-----	75% cost saving	(Rath et al., 2020)
18	Fabricated-Wastewater Treatment Plants (F-WWTPs)	2025	Indonesia	Pilot	-----	(Soewondo et al., 2025)
19	Aeration + filtration + disinfection	2023	Palestine	Kafr Qallil City	\$4 million cost saving	(Sallam et al., 2023)
20	ABR + wetland	2019	India	Pilot	0.131 MJ/m ³ energy consumption	(Singh et al., 2019)
21	Decentralized WWTP	2024	Thailand	Bangkok City	-----	(Maw et al., 2024)
22	Integrated Vegetation-Activated Sludge Process (V-ASP)	2024	China	Pilot	0.65 kW/m ³	(Li et al., 2024)
23	UASB-VFCW	2024	Jordan	Al-Kfair village	UASB = 40%, VFCW = 60% cost saving	(Obeidat et al., 2024)
24	Johkasou	2010	Japan	Pilot	60%	(Yang et al., 2010)

Table 5. Overcoming barriers to DWTS adoption: A multidimensional framework for sustainable wastewater management in developing regions

Category	Key aspects	Implementation strategies	Expected outcomes	Reference
DWTS advantages	- Low cost - Easy installation/maintenance - Natural treatment processes	- Suitable for rural/low-density areas	- Sustainable wastewater solution	(Capodaglio, 2017; Muzioreva et al., 2022)
Current challenges	a) Financial constraints b) Space limitations c) Technical knowledge gaps d) Inconsistent maintenance	- Needs addressing for wider adoption	- Impacts system performance	(Chirisa et al., 2017; Muzioreva et al., 2022)
Technical considerations	- Climate-responsive designs - Site-specific adaptations - Smart technology integration - Renewable energy use	- IoT monitoring - Membrane reactors	- 30-50% efficiency increase	(Capodaglio, 2017; Singh et al., 2019)
Capacity building	- Community training - Operator empowerment - Maintenance skills	- Local workshops - Hands-on training	- Improved system operation	(Chirisa et al., 2017; Muzioreva et al., 2022)
Policy framework	- Financial incentives - Land provision - Stakeholder collaboration	- Subsidies - Tax exemptions	- 25-40% cost reduction	(Capodaglio, 2017)
Value-added applications	- Water reuse - Groundwater recharge - Resource recovery	- Agricultural irrigation - Nutrient recycling	- Additional revenue streams	(Muzioreva et al., 2022; Singh et al., 2019)
Research priorities	- Cost reduction - Capacity enhancement - Localized solutions	- Academic-industry partnerships	- 40-60% lifespan extension	(Capodaglio, 2017; Muzioreva et al., 2022)
Implementation pathways	- Legal frameworks - Knowledge networks - Technology transfer	- Multi-sector collaboration	- Higher adoption rates	(Chirisa et al., 2017)
SDG contribution	- Clean water access - Sanitation improvement	- Integrated approach	- Achieving SDG 6 targets	(Capodaglio, 2017; Muzioreva et al., 2022)

3. Conclusion

DWTS have emerged as a transformative solution for addressing water and sanitation challenges in developing countries, particularly in rural and peri-urban areas with limited infrastructure. By leveraging cost-effective, low-energy technologies such as constructed wetlands, anaerobic filters, and biological treatment processes, DWTS demonstrate remarkable efficacy in pollutant removal, water reuse, and environmental protection. Case studies from diverse regions including India, China, and Jordan highlight their adaptability to local conditions, with removal efficiencies reaching 90% for organic matter and significant reductions in nitrogen and phosphorus. However, the full potential of DWTS hinges on overcoming persistent barriers, including financial constraints, spatial limitations, and the need for community capacity building. Strategic integration of smart technologies, policy support, and multi-stakeholder collaboration is essential to enhance system performance, ensure long-term sustainability, and align with Sustainable Development Goal (SDG) 6 targets. From a forward-looking perspective, DWTS represents not only a technical innovation but also a socio-environmental strategy that empowers communities, conserves resources, and fosters resilience against water scarcity. Future efforts must prioritize localized research, hybrid system designs, and institutional frameworks to scale these systems effectively. By addressing current challenges through a holistic approach combining technological advancement, education, and policy reinforcement, DWTS can evolve into a cornerstone of sustainable water management, offering a replicable model for global application in the face of growing water crises.

Authors' Contributions

Farshad Yaghoobian: Conceptualization; Data curation; Investigation; Writing original draft; Writing-review & editing. **Mohammad Reza Mehrasbi:** Conceptualization; Writing-review & editing. **Esrafil Asgari:** Supervision; Conceptualization; Visualization; Writing-review & editing. **Hossein Arabzade:** Investigation; Writing-original draft; **Mohammad Amin Abbasian:** Investigation; Data curation; Writing-original draft.

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Conflicts of Interest

The authors have declared no competing interests.

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Ethical Considerations

This study was conducted as part of a research project approved by the Ethics Committee of Zanjan University of Medical Sciences (Ethics Code: IR.ZUMS.BLC.1403.145).

Using Artificial Intelligence

No artificial intelligence was used.

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