# DECENTRALIZED WASTEWATER TREATMENT: AN INNOVATIVE APPROACH FOR RURAL AREAS

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ABSTRACT

This study provides a comparative analysis of conventional and innovative wastewater treatment technologies for small settlements of up to 2,000 equivalent inhabitants (EH). Conventional systems such as the Sequencing Batch Reactor (SBR), Membrane Bioreactor (MBR), and Moving Bed Bioreactor (MBBR) were evaluated based on treatment efficiency, energy consumption, sludge production, operational complexity, and spatial requirements. Additionally, the potential of phytoremediation, specifically constructed wetlands, as a sustainable and low-cost alternative was explored. The study concludes that phytoremediation systems are a viable option for decentralized wastewater treatment in rural or ecologically sensitive areas due to their low operational costs and minimal energy needs. It recommends wider adoption of these systems, supported by further research and educational programs to optimize their design across different climates.

## Introduction

In 2022, the global rural population constituted approximately 43.10% of the total population, equating to 3.43 billion people (UN DESA, 2022). According to World Bank data, the proportion of people living in rural areas has been steadily declining, dropping from 44.81% in 2018 to 43.10% in 2022 (Macrotrends, 2024). This trend is expected to

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continue as urbanization progresses, with projections from the United Nations estimating that the rural population will decline to 3.1 billion by 2050, representing only 22% of the global population (UN DESA, 2022). The highest concentration of rural populations is found in developing countries, particularly in Africa and Asia. For example, in Southeast Europe, rural populations remain significant. In 2022, countries like Moldova (57%), Romania (46%), Serbia (43.13%), Croatia (43%), North Macedonia (42%), and Georgia (41%) had considerably higher rural population percentages than the EU average of 24.53% (OECD, 2022; Trading Economics, 2024). These figures highlight the importance of rural populations in this region, with more than twice as many people residing in rural areas compared to the average in OECD countries.

However, rural populations face significant challenges, particularly regarding access to basic services like sanitation. According to Eurostat (2022), population decline in rural areas is more prevalent than in urban regions, and the lack of access to essential services, such as sanitation, contributes to this trend. A report by UNICEF and the World Health Organization (WHO/UNICEF, 2021) revealed that 4.2 billion people globally, or 46% of the world's population, do not have safely managed sanitation services. In rural areas, access to adequate sanitation is even more limited. In Southeast Europe, for instance, only 43% of rural populations have access to proper sanitation services (OECD, 2022). This situation poses severe health risks and adversely affects the well-being of rural communities. The World Health Organization promotes the Sanitation Safety Plan (SSP) approach to support countries in achieving Sustainable Development Goal (SDG) 6.2, which aims to provide access to adequate and equitable sanitation and hygiene for all by 2030 (WHO, 2024). However, constructing and managing large-scale, centralized wastewater collection and treatment systems is often economically unfeasible for rural areas, particularly in developing regions with declining populations and limited financial resources (Hoffmann, 2020).

As Capodaglio et al. (2017) have noted, centralized wastewater treatment in low-income countries can be prohibitively expensive, often leading to long-term debt burdens. In contrast, decentralized wastewater treatment systems (DWTS) offer a more sustainable, ecologically sound, and cost-effective solution for managing wastewater in rural areas (Muzioreva et al., 2022, Paraušić et al., 2025). DWTS reduce the need for long-distance transport of wastewater, lowering energy consumption and greenhouse gas emissions, and they are particularly suitable for areas with low population densities and dispersed households (Massoud et al., 2009). Additionally, decentralized systems present opportunities for resource recovery, such as the reuse of treated wastewater and byproducts like nutrients, sludge, and energy (Garcia et al., 2022; Đaković et al., 2024; Bernal et al., 2021; Eggimann et al., 2018; Luković et al., 2024). Decentralized systems focus primarily on treatment and disposal, minimizing the collection component, which can account for up to 60% of the total cost of centralized systems (Massoud et al., 2009; Eggimann et al., 2016; Bernal et al., 2021). This cost reduction makes decentralized solutions an attractive option for small settlements.

Furthermore, decentralized systems are flexible and scalable, making them adaptable to local conditions and capable of expanding as populations grow (Bernal et al., 2021; Eggimann et al., 2018; Ignjatijević et al., 2024; Capodaglio, 2017). These systems can be implemented in a variety of settings, from small communities to industrial sites, and can be easily modified to accommodate changing wastewater generation patterns. Their resilience to natural disasters and other disruptions also makes them a more reliable option than large, centralized systems, which are more vulnerable to system-wide failures (Fluence, 2024).

Decentralized wastewater treatment systems can also be designed to align with the social and cultural preferences of local communities, making them more socially acceptable (Massoud et al., 2009). However, despite these advantages, the widespread adoption of decentralized systems faces significant challenges, particularly in terms of regulatory frameworks and institutional support. In many countries, there is a lack of legal and institutional arrangements to incorporate these technologies into formal urban planning processes (Chirisa et al., 2017; Nansubuga et al., 2016; Petković et al., 2024; Muzioreva et al., 2022).

Given these factors, this article aims to present the most frequently used models of decentralized wastewater treatment systems in rural areas with populations of up to 2,000 inhabitants, with a particular focus on both classical technologies and new innovations based on phytoremediation.

## Materials and Methods

The methodological approach employed in this study is based on analytical methods, aimed at systematically evaluating and comparing wastewater treatment technologies. The research was conducted in two distinct phases.

The first phase of the study involved a detailed analysis of three widely used conventional wastewater treatment technologies: the Sequencing Batch Reactor (SBR), Membrane Bioreactor (MBR), and Moving Bed Bioreactor (MBBR). The primary objective was to evaluate the performance, operational efficiency, and sustainability of each system. The analysis considered several key parameters, including treatment efficiency, energy consumption, sludge production, and operational complexity. Data for the analysis were drawn from scientific literature, technical reports, and case studies focusing on the use of SBR, MBR, and MBBR technologies in small and medium-sized settlements. Performance metrics from existing wastewater treatment plants employing these systems were reviewed and compared.

In the second phase of the study, an innovative method based on phytoremediation was analyzed. This approach involves the use of constructed wetlands, which mimic the natural processes occurring in wetland ecosystems to treat wastewater. The following aspects were assessed: system design and components, treatment mechanisms, environmental integration,  and sustainability. Field data were collected from case studies of operational constructed wetlands, particularly in rural settings. These data were supplemented by information from technical reports and studies focused on the efficiency of phytoremediation for wastewater treatment.

A comparative analysis was conducted to evaluate the relative performance of the conventional technologies (SBR, MBR, MBBR) and the innovative phytoremediation approach. The following criteria were used for the comparison: treatment efficiency, economic viability, sustainability and scalability. The results of the comparative analysis were synthesized to determine the most appropriate wastewater treatment solutions for small settlements, considering both technical performance and ecological sustainability.

For the reasons mentioned above, this article presents the most frequently used models of decentralized water treatment systems in rural areas with populations of up to 2,000 inhabitants, with a special analysis of classical and new technologies based on phytoremediation.

## Results and discussion

Several biological wastewater treatment technologies, including the Sequencing Batch Reactor (SBR), Membrane Bioreactor (MBR), and Moving Bed Bioreactor (MBBR), and waste water treatment based on phytoremediation - constructed wetlands (CWs) have been employed effectively over the past decades for the treatment of wastewater (Rashid et al., 2021; Saidulu et al., 2022, as cited in Singh et al., 2022). These technologies have played a crucial role in managing wastewater, particularly in smaller settlements and rural areas.

**The Sequencing Batch Reactor (SBR)** has been in use since the 1920s and remains one of the most widely adopted wastewater treatment methods, especially in rural regions. The SBR system is a traditional biological treatment technology that employs activated sludge and deep aeration. Unlike conventional wastewater treatment systems, where each stage of treatment occurs in separate reactors, the SBR integrates all stages within a single reactor. This consolidation results in significant cost savings and reduces the spatial footprint required for installation and operation.

In the SBR process, wastewater is treated in cycles using activated sludge, which comprises a complex mixture of microorganisms along with non-degradable organic and inorganic materials from the wastewater. A distinct advantage of the SBR system is its ability to support a diverse range of microorganisms due to the intermittent changes in environmental conditions within the reactor. These dynamic conditions enhance the overall quality of wastewater treatment by fostering the growth of microorganisms capable of efficiently degrading organic pollutants. The treatment cycle within the SBR reactor consists of four distinct phases: filling, aeration, settling, and decanting. After the decanting phase, the treated water is discharged into the receiving environment. These phases are carefully timed and sequenced to allow multiple treatment cycles to be completed in a single day, optimizing the efficiency of the process. By synchronizing these phases with the influent flow, SBR systems are capable of effectively treating wastewater in a compact and economical manner, making them particularly suitable for use in small settlements and rural communities where space and financial resources are limited.

**Table 1.** Values of treated wastewater using SBR systems (the data is for informational purposes and aims to illustrate the potential)

| Parameters | Permitted concentrations for discharge into Class II waters | Values of SBR systems | Minimum Treatment Efficiency Percentage |
|---|---|---|---|
| BPK5 (mg O2/l) | < 25 | < 25 | 70% |
| HPK (mg O2/l) | < 125 | < 125 | 75% |
| Suspended matter (mg/l) | < 35 | < 35 | 90% |
| Total P (mg/l) | < 1 | < 1 | Secondary treatment |
| Total N (mg/l) | < 21 | < 21 | Secondary treatment |
| Turbidity (NTU) | < 1 | < 5 | 99% |
| Removal of bacteria (%) | | No | - |

*Source*: Authors' calculations

The advantages of these systems include their ability to accommodate significant fluctuations in both flow rate and wastewater composition, making them particularly well-suited for smaller communities where such variability is common. Furthermore, these systems offer automated remote operation, enabling efficient monitoring and control with minimal on-site supervision. They deliver high-quality wastewater treatment, facilitate rapid equipment installation, and require a minimal spatial footprint, which is critical in space-constrained settings.

However, there are notable disadvantages. These systems necessitate the involvement of highly skilled personnel for maintenance and monitoring, due to the complexity of the fully automated processes. Additionally, they have relatively high specific energy consumption, which can increase operational costs. Another limitation is the need for regular sludge disposal, which requires further handling and treatment to ensure environmental compliance.

**Membrane Bioreactor (MBR) technology** integrates conventional biological treatment processes with membrane filtration, providing an advanced solution for wastewater management. In this system, the biological treatment, which utilizes activated sludge, is coupled with membrane ultrafiltration, resulting in highly efficient wastewater purification. The MBR process is typically carried out in a compact, containerized facility, making it suitable for use in areas where space is limited. The treatment procedure is usually divided into three distinct phases: biological degradation of organic matter, membrane filtration to separate solids from liquids, and the discharge of treated water.

**Table 2.** Values of Treated Wastewater Using MBR Technology (The data is for informational purposes and aims to illustrate the potential)

| Parameters | Permitted concentrations for discharge into Class II waters | Values of MBR systems | Minimum Treatment Efficiency Percentage |
|---|---|---|---|
| BPK5 (mg O2/l) | < 25 | < 2 | 95% |
| HPK (mg O2/l) | < 125 | <50 | 90% |
| Suspended matter (mg/l) | < 35 | <5 | 97% |
| Total P (mg/l) | < 1 | <1 | 95% |
| Total N (mg/l) | < 21 | <15 | 90% |
| Turbidity (NTU) | < 1 | <5 | 99.9 % |
| Removal of bacteria (%) | | Yes | 99.9% |

*Source*: Authors' calculations

The advantages of Membrane Bioreactor (MBR) systems include their ability to achieve a high level of removal of organic pollutants, nitrogen, bacteria, and viruses, which allows for the discharge of treated water directly into groundwater in the absence of nearby recipients. Moreover, the treated water can be immediately reused for non-potable purposes such as irrigation and toilet flushing, making MBR technology particularly suitable for application in environmentally sensitive areas. These systems occupy a small spatial footprint, feature a high degree of automation, and generate no unpleasant odors or noise, further enhancing their suitability for use in populated or restricted spaces. Maintenance costs for MBR systems are generally lower than those of conventional biological treatment systems, and they produce minimal waste sludge, thereby reducing the costs associated with sludge disposal.

However, there are also notable disadvantages to MBR systems. They require a continuous inflow of wastewater for optimal operation, and in the event of extended downtime, a full system restart is necessary. The maintenance of these systems requires highly qualified personnel, particularly for tasks such as draining and cleaning, which must be carried out by authorized staff. Additionally, MBR systems have relatively high specific energy consumption and require membrane replacement approximately every five years, contributing to ongoing operational costs.

**The Moving Bed Bioreactor (MBBR)** is a biological wastewater treatment process that uses freely floating carriers to support the growth of biofilm, differentiating it from conventional activated sludge systems. These carriers, made from high-density polyethylene, provide a large specific surface area for microbial colonization, enhancing the efficiency of the treatment process. The carriers typically occupy about half of the reactor's volume, allowing for a substantial increase in the biomass concentration relative to the reactor's total volume.

A key distinction between the MBBR and traditional activated sludge systems lies in the lifecycle of the biomass. In conventional systems, the biomass in the form of activated sludge has a relatively short lifespan due to the regular removal of excess sludge. Conversely, in the MBBR process, microorganisms are immobilized on the biofilm carriers, allowing them to achieve significantly longer lifespans. This results in a more stable and consistent treatment process over time. Additionally, the amount of sludge produced in MBBR systems is notably lower than in conventional systems, largely due to biological efficiencies inherent in the immobilization process.

**Table 3.** Values of Treated Wastewater from MBBR System (data is for informational purposes and aims to demonstrate the potential)

| Parameter | Permissible Concentrations for Discharge into Class II Waters | MBBR System Values | Minimum Treatment Efficiency Percentage |
|---|---|---|---|
| BOD5 (mg O2/l) | < 25 | < 25 | 70% |
| COD (mg O2/l) | < 125 | < 125 | 75% |
| Suspended Solids (mg/l) | < 35 | < 35 | 90% |
| Total P (mg/l) | < 1 | < 1 | Secondary treatment |
| Total N (mg/l) | < 21 | < 21 | Secondary treatment |
| Turbidity (NTU) | < 1 | < 5 | 99% |
| Bacteria Removal (%) | - | No | - |

*Source*: Authors' calculations

The advantages of Moving Bed Bioreactor (MBBR) systems include high wastewater treatment efficiency, primarily attributed to the retention of sludge, which facilitates effective nitrification. These systems are capable of automatically adjusting to fluctuations in wastewater load without the need for operator intervention, and they exhibit strong resistance to toxic shocks, making them particularly robust in variable or challenging operating conditions. Additionally, MBBR systems produce minimal sludge, which reduces the costs and complexities associated with sludge management, and they require a relatively small installation footprint, making them ideal for space-constrained settings. However, there are certain disadvantages to these systems. Maintenance of MBBR systems requires a higher level of technical expertise due to the complexity of the process, particularly when managing fully automated operations. This can result in increased staffing requirements and associated costs. The complexity of the system's automation may also present operational challenges that necessitate specialized training for personnel to ensure smooth and efficient functioning.

## Wastewater treatment based on phytoremediation

In contrast to conventional technologies typically employed in decentralized wastewater treatment systems for settlements of up to 2,000 equivalent inhabitants (EH), this section explores an alternative approach leveraging the ecosystem services of wetland habitats for wastewater treatment. With growing interest in models that offer high efficiency alongside reduced construction costs, minimal or negligible energy consumption, low maintenance expenses, and easy environmental integration, phytoremediation—

specifically plant-based wastewater treatment systems—presents a promising solution. While this method has been practiced since ancient times, it has only gained significant attention in Western Europe over the last decade. In Eastern Europe, however, these systems are still underutilized.

Phytoremediation systems are multifunctional and can provide additional benefits beyond wastewater treatment, including the production of energy, food, and compost, as well as the reuse of treated water for irrigation, toilet flushing, and other purposes. This multifunctionality makes them economically viable solutions and attractive for investment. These systems mimic natural wetland processes, transforming polluted areas into ecological zones that serve as ecosystem processors. The treatment process begins with mechanical treatment, where solid materials settle in tanks, and the partially clarified water is directed to phytolagoons for further processing. In the biological treatment stage, specific plant species are employed to remove harmful substances from the wastewater, utilizing their natural filtration and absorption abilities. During physical treatment, the wastewater passes through a substrate composed of sand, gravel, and stones, which serves as a filter. Finally, chemical treatment transforms waste materials into harmless substances through processes such as the oxidation and reduction of phosphorus and nitrogen.

The vegetation plays a crucial role in these systems, with plants facilitating oxygen transfer to the root zone, absorbing waste materials, and providing nutrients through decaying organic matter. This supports the development of microorganisms essential for wastewater treatment. Some systems also incorporate energy crops to produce energy, further enhancing their sustainability. Commonly used native plant species include common reed (*Phragmites australis*), bulrush (*Typha latifolia*), yellow flag iris (*Iris pseudacorus*), and sedges (*Carex* spp.), as well as high-energy species like giant reed (*Miscanthus giganteus*) and willow (*Salix viminalis*). Phytoremediation systems offer several advantages, including low construction and maintenance costs, minimal or no energy requirements, and the potential for zero waste generation. They integrate easily into the natural environment without the use of chemicals, and they provide habitats for diverse flora and fauna. Additionally, these systems can rehabilitate degraded land, turning it into ecological zones, and they utilize natural, locally sourced materials for construction. Their flexibility allows for modular designs, making them adaptable for research and educational purposes. However, phytoremediation systems also have disadvantages. They require significantly larger land areas for construction compared to conventional systems and lack standardized design criteria for different climatic conditions, requiring customized designs for each specific case.

In Europe, there is a substantial body of research focusing on wastewater treatment through phytoremediation, with many studies concentrating on municipal wastewater from households. One such facility in Kirnberg, Austria, was analyzed to assess its efficiency. During a study visit in September 2017, in collaboration with representatives from the Faculty of Applied Ecology “Futura,” the facility, designed for 300 equivalent inhabitants (EH), was evaluated. The system consists of an aerated receiving shaft, a settling tank, a wave tank operated by a lever mechanism without energy consumption, and four phytoremediation lagoons with vertical water flow, planted with common reed (*Phragmites australis*). A control and inspection shaft is located at the end of the system, ensuring monitoring and maintenance. The Table 4 presents the results of wastewater treatment.

**Table 4.** Values of Treated Water from the Biological Wastewater Treatment Plant in Kirnberg, Austria

| Parameter | Permissible Concentrations for Discharge into Class II Waters | Average Values at the Outlet of the System in Kirnberg | Minimum Treatment Efficiency Percentage |
|---|---|---|---|
| BPK5 (mg O2/l) | < 25 | 2 | 80% |
| HPK (mg O2/l) | < 125 | 15 | 80% |
| Suspended Solids (mg/l) | < 35 | 1.70 | 90% |
| Total P (mg/l) | < 1 | 0.62 | Secondary treatment |
| Total N (mg/l) | < 21 | 10.5 | Secondary treatment |
| Turbidity (NTU) | < 1 | 0.6 | 99% |
| Removing bacteria (%) | | Partially | No |

*Source*: Authors' calculations

The following tables present a comparative overview of the financial requirements for the wastewater treatment models under consideration. The costs of construction, as well as the maintenance expenses, have been obtained from the company "Borplastika Eko" and are supplemented by personal experience in the design and construction of these systems.

**Table 5.** Overview and Comparative Analysis of Available Technologies for Wastewater Treatment

| Parameter | Minimum Percentage of TreatmentSBR | Minimum Percentage of Treatment MBBR | Minimum Percentage of Treatment MBR | Minimum Percentage of Treatment Fitoremedijacija |
|---|---|---|---|---|
| BPK5 (mg O2/l) | 70% | 70% | 95% | 75 % |
| HPK (mg O2/l) | 75% | 75% | 90% | 75% |
| Suspended Solids (mg/l) | 90% | 90% | 97% | 93% |
| Total P (mg/l) | Secondary Treatment | Secondary Treatment | 95% | Secondary Treatment |
| Total N (mg/l) | Secondary Treatment | Secondary Treatment | 90% | Secondary Treatment |
| Turbidity (NTU) | 99% | 99% | 99.9% | 95% |
| Bacteria Removal (%) | No | No | 99.9% | Partial |

*Source*: Authors' calculations

**Table 6.** Electricity Requirements for 100, 500, 1000, and 2000 Equivalent Inhabitants (EH)

| Electricity Demand for the Entire Facility | SBR Value (kW) | MBR Value (kW) | MBBR Value (kW) | Phytoremediation |
|---|---|---|---|---|
| 100 ES | 5.66 | 19.16 | 5.66 | Negligible Value or None |
| 500 ES | 11.66 | 116.66 | 15.16 | Negligible Value or None |
| 1000 ES | 19.66 | 229.46 | 23.46 | Negligible Value or None |
| 2000 ES | 35.46 | 455.46 | 43.46 | Negligible Value or None |

*Source*: Authors' calculations

**Table 7.** Comparative Overview of the Financial Aspects for the Considered Wastewater Treatment Models

| Parameter | SBR | MBR | MBBR | Phytoremediation |
|---|---|---|---|---|
| Construction Cost (€/EH) (Excluding Land Area) | 210 - 370 | 350 - 700 | 330 - 520 | 130 - 240 |
| Annual Maintenance Costs (€/m$^3$) | 1.70 | 2.50 | 1.90 | 0.10 |
| Required Area (m$^2$/ES) | 0.5 – 0.9 | 0.5 – 0.9 | 0.5 – 0.9 | 2 - 5 |

*Source*: Authors' calculations

Despite the diversity of technological processes employed in wastewater treatment plants, the treated effluent must meet the maximum allowable discharge limits to comply with environmental standards. Among the various technologies, Membrane Bioreactor (MBR) systems offer the highest level of wastewater treatment. However, these systems are highly dependent on a continuous inflow of wastewater; any prolonged interruption necessitates a full system restart, which can complicate operations. In terms of operational complexity, MBR systems are the most intricate, requiring highly skilled personnel for both maintenance and operation, whereas phytoremediation-based systems are the simplest and can be managed without specialized training.

Regarding sludge production, MBR systems generate the highest amount of sludge due to their intensive treatment processes. However, they also provide the highest treatment efficiency, making them ideal for meeting stringent wastewater treatment requirements, particularly in sensitive or protected areas. From a financial standpoint, MBR systems are the most expensive to construct, followed by Moving Bed Bioreactor (MBBR) systems, Sequencing Batch Reactors (SBR), and finally, phytoremediation systems, which have the lowest construction costs.

In terms of land requirements, phytoremediation systems demand significantly more space compared to other treatment technologies. While this large spatial requirement may be a disadvantage in urban or densely populated areas, it is less of a concern in rural settings, where degraded or unused land is typically available and can be repurposed for such systems.

## Conclusion

Based on the results of this study, it can be concluded that phytoremediation-based wastewater treatment models represent a viable alternative to conventional systems, particularly for small settlements in rural areas. These models have demonstrated the ability to meet the wastewater treatment standards mandated by the European Union and the Republic of Serbia. Their low energy requirements, ease of maintenance, minimal operational costs, and seamless integration into the natural environment make them attractive for rural and ecologically sensitive areas. Additionally, these systems not only treat wastewater but also create habitats for wildlife, transforming treated areas into biotopes that contribute to biodiversity and support broader environmental sustainability.

One of the key advantages of phytoremediation systems is their reliance on natural processes that mimic the functions of wetland ecosystems. This ecological approach promotes sustainable development by utilizing locally available resources, such as native plant species, and minimizing the need for synthetic chemicals or energy-intensive processes. The ability of these systems to produce multifunctional benefits—such as providing treated water for irrigation, energy generation from biomass, and compost production—further enhances their economic viability and attractiveness for investment.

While the disposal of waste sludge remains a concern across all wastewater treatment systems, this issue is less pronounced in phytoremediation systems due to the minimal volume of sludge produced by small-scale plants. However, it is recommended that sludge from these systems be utilized for composting in conjunction with green waste, thereby contributing to a circular economy and achieving zero waste. If composting is not feasible, the sludge should be safely transported to the nearest central wastewater treatment facility equipped with a sludge management line or disposed of at a designated municipal landfill.

In conclusion, there is a strong case for promoting phytoremediation systems as ecologically and economically sustainable solutions for decentralized wastewater treatment in small settlements. It is crucial to encourage designers, planners, and decision-makers to prioritize the adoption of these innovative, environmentally justified approaches. Additionally, efforts should be made to implement educational programs for local residents and users of these systems, fostering greater community engagement and ensuring the long-term success and sustainability of these wastewater treatment models.

### Conflict of interests

The authors declare no conflict of interest.

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