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MOBILE WASTEWATER TREATMENT SYSTEMS FOR CIRCULAR WATER REUSE: TECHNOLOGIES, APPLICATIONS AND THE ROMANIAN GAP IN THE EUROPEAN CONTEXT

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Abstract

This study investigates the transition from conventional wastewater treatment toward circular water management within the European Union, with a particular focus on the role of mobile and decentralized treatment systems. Despite considerable progress at EU level, major disparities persist in infrastructure coverage, wastewater reuse and resource recovery performance among Member States. A structured literature review and comparative analytical framework were applied to evaluate wastewater treatment technologies, circular economy pathways and implementation indicators, integrating data from Eurostat, the European Environment Agency and national Romanian statistics. The results show that 80–81% of the EU population is connected to at least secondary wastewater treatment, while Romania remains significantly below this level (60.7%), with over 150 non-compliant agglomerations. The analysis indicates that three dominant circular wastewater valorisation pathways can be identified in the EU context: water reuse, agricultural sludge valorisation and thermal nutrient recovery. In contrast, Romania remains in a transitional stage, characterized by limited reuse, low sludge valorisation (21.3% vs. EU average 37.3%) and limited deployment of advanced nutrient recovery systems. The study demonstrates that mobile wastewater treatment systems can function as transitional circular infrastructure, enabling localized treatment, resource recovery and reuse. Their flexibility and rapid deployment capacity position them as potentially strategic solutions for bridging infrastructure gaps and accelerating the implementation of circular water systems in emerging contexts.

Key words*: circular economy, resource recovery, mobile wastewater treatment systems, wastewater reuse.*

INTRODUCTION

Water scarcity and increasing pressure on freshwater resources represent major global challenges driven by population growth, industrialization and climate change. Although freshwater accounts for only approximately 2.5% of global water resources, demand is expected to increase significantly by 2050, particularly due to agriculture, which already accounts for 70% of global freshwater withdrawals (Maniam et al., 2022; Hamam et al., 2024). At the same time, up to 80% of wastewater worldwide is discharged without adequate treatment, leading to environmental pollution and loss of valuable resources (Yang et al., 2020).

In Europe, up to 30-32% of the population experiences seasonal water stress (EEA, 2023b), highlighting the urgency of more sustainable water management approaches. Traditional wastewater management follows a linear model focused on pollutant removal, without fully valorising wastewater as a source of water, nutrients and energy (Van Loosdrecht & Brdjanovic, 2014).

The circular economy framework promotes the transformation of wastewater treatment plants into Water Resource Recovery Facilities (WRRFs), enabling water reuse and resource recovery (Larsen et al., 2016; Smol, 2023). Wastewater reuse supports agricultural, industrial and urban applications, contributing to water security (EEA, 2023a).

In this context, decentralized and mobile wastewater treatment systems represent a key technological extension, enabling on-site treatment and local reuse while reducing

dependence on centralized infrastructure (Capodaglio & Olsson, 2020; Mannina et al., 2022). These systems also support resource recovery pathways, including energy generation and nutrient recycling, positioning them as flexible tools for circular water management.

However, the transition toward circular wastewater systems remains uneven across the European Union, particularly in emerging Member States where infrastructure deficits and limited resource recovery hinder implementation. Romania represents a relevant case study, characterized by gaps in connectivity, treatment performance and circular economy integration.

Against this background, this study analyses mobile wastewater treatment systems as transitional circular infrastructure, integrating technological performance, resource recovery pathways and system-level implementation. The study develops a multi-level analytical framework, compares EU and Romania indicators, and positions mobile systems as enabling solutions for bridging infrastructure gaps and accelerating circular water management.

Figure 1 presents the flow of wastewater from multiple sources (domestic, industrial and agricultural) through treatment processes, enabling water reuse and the recovery of valuable resources such as nutrients, biofuels and bio-based products. The framework highlights the role of wastewater treatment plants as resource recovery hubs within circular economy systems.

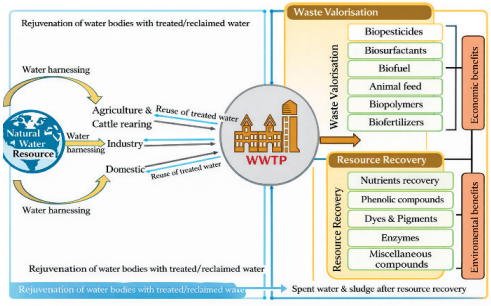


Figure 1. Integrated circular wastewater management framework: water reuse and resource recovery pathways (Singh et al., 2022)

Figure 2 illustrates the conceptual framework of circular wastewater management, emphasizing the integration of treatment technologies, resource recovery pathways, and water reuse applications, with mobile systems serving as a bridge toward circular economy implementation.

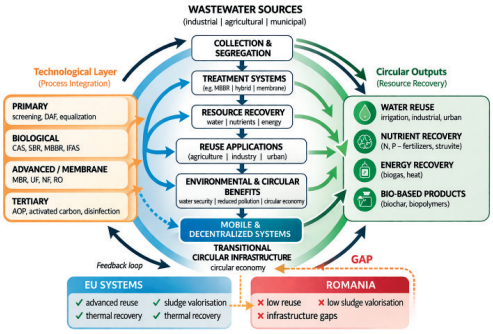


Figure 2. Conceptual framework of circular wastewater management integrating technological processes, resource recovery pathways, and reuse applications. The conceptual illustration was generated with the assistance of ChatGPT (OpenAI) based on the literature synthesized in this review and refined by the authors for visualization purposes

Unlike previous studies that primarily focus on either technological performance or circular economy pathways independently, this research develops a multi-level analytical framework that simultaneously integrates technological efficiency, resource recovery potential and system-level implementation gaps. In addition, the study offers one of the first structured comparative analyses between the European Union and Romania, highlighting the discrepancy between regulatory alignment and practical implementation.

MATERIALS AND METHODS

This study is based on a structured literature review combined with a comparative analytical framework. The literature review was conducted using major scientific databases, including Web of Science, Scopus and ScienceDirect, covering the period 2000-2025.

The search strategy included combinations of the following keywords: “wastewater reuse”, “circular economy”, “mobile wastewater treatment”, “decentralized systems”, “membrane bioreactor (MBR)”, “resource recovery”, and “nutrient recovery”. Only peer-

reviewed journal articles, official reports (European Commission, Eurostat, European Environment Agency) and highly cited review papers were considered.

The selection process followed three main criteria:

(i) relevance to circular wastewater management and reuse,

(ii) availability of quantitative performance data (removal efficiencies, energy, cost),

(iii) applicability to decentralized or mobile treatment systems.

Studies focusing exclusively on conventional treatment without relevance to circularity or reuse were excluded. In total, over 100 publications were screened, and approximately 70 sources were selected for detailed analysis.

Comparative tables and figures were developed through normalization of reported data ranges and semi-quantitative synthesis. The EU–Romania comparison was conducted using official datasets from Eurostat, the European Environment Agency and National Institute of Statistics (NIS), complemented by European Commission reports on directive implementation.

The reported values represent indicative ranges derived from heterogeneous sources and should be interpreted as comparative benchmarks rather than absolute values.

RESULTS AND DISCUSSIONS

Wastewater reuse and circular economy pathways

Wastewater reuse is a key strategy for increasing water availability and reducing environmental pollution, providing an alternative resource for agriculture, industry and urban applications (Angelakis & Snyder, 2015; Silva, 2023). Agriculture remains the dominant reuse sector due to its high-water demand and the additional benefit of nutrient supply, reducing the need for synthetic fertilizers (Yang et al., 2020). Industrial reuse further contributes to water savings through applications such as cooling and process water (Nydrioti & Grigoropoulou, 2025).

From a circular economy perspective, wastewater treatment enables resource recovery, including nutrients (nitrogen and phosphorus) and energy through anaerobic digestion, supporting renewable energy production (Kyllönen et al., 2021). Overall, these approaches reduce freshwater withdrawals, limit pollutant discharge and support the transition toward circular water management systems (Hamam et al., 2024).

Treatment technologies for circular and mobile systems

Wastewater treatment technologies for circular reuse and mobile applications must ensure high removal efficiency, operational flexibility and compact design. Biofilm-based systems such as moving bed biofilm reactors (MBBR) and integrated fixed-film activated sludge (IFAS) provide improved biomass retention and resilience under variable loading conditions, making them particularly suitable for decentralized systems (Ştefănescu et al., 2019; Surdu, et al., 2021).

Membrane technologies (MF, UF, NF, RO), particularly membrane bioreactors (MBR), enable the production of high-quality effluent suitable for reuse by ensuring efficient removal of suspended solids, pathogens and organic contaminants. However, membrane fouling and energy demand remain important operational challenges (Gkotsis et al., 2018; Yang et al., 2020). Hybrid treatment systems integrating biological processes, membrane filtration and advanced treatment steps (e.g., adsorption and advanced oxidation) can achieve removal efficiencies exceeding 90% for conventional pollutants and high removal rates for micropollutants, while maintaining compact configurations suitable for mobile applications (Luo et al., 2014; Meng et al., 2017).

Energy consumption remains a critical constraint, with aeration representing a significant share of total energy demand. Process intensification strategies such as partial nitrification–Anammox can reduce oxygen requirements and improve overall efficiency.

From a circular economy perspective, these technologies enable resource recovery through nutrient reuse and energy production via anaerobic digestion, supporting renewable energy generation and reducing sludge volumes.

Mobile systems are designed as compact, modular units integrating multiple treatment stages, including biological reactors, membrane filtration and disinfection, with the possibility of

advanced reuse (Meng et al., 2017). Their main advantages include rapid deployment, operational flexibility and local water reuse, particularly in industrial, agricultural and remote applications (Capodaglio & Olsson, 2020).

However, their treatment capacity is lower than that of centralized systems, and performance may be affected by influent variability and operational complexity (Mannina et al., 2022). Overall, mobile systems represent flexible and scalable solutions supporting localized circular water management and improved resource efficiency (Larsen et al., 2016).

Table 1 summarizes the main technological limitations in livestock wastewater treatment, together with their operational causes, proposed technological solutions, and potential performance improvements.

Figure 3 presents a qualitative technology–wastewater compatibility matrix, illustrating the applicability of different treatment technologies to various wastewater types based on published literature.

Table 1. Comparison of Technological Limitations and Technological Integrations

Technological Limitation	Measurable Indicator / Effect	Operational Cause	Proposed Emerging Technologies	Quantified Potential Improvement
High energy consumption	Aeration accounts for 40-60% of total plant energy use	Continuous aeration for biomass maintenance	Energy-efficient aeration systems, real-time DO control, membrane aeration	15-30% energy reduction (DO optimization & pulsed aeration)
High sludge production	Increased MLSS & MLVSS	Excess aerobic biomass with limited valorisation	Advanced anaerobic digestion, enzymatic hydrolysis, pyrolysis	20-50% sludge reduction, conversion to biogas
Sensitivity to flow variations	Unstable DO, non-compliant BOD/COD	Variable hydraulic and organic loading	Equalization tanks + AnSBR + adaptive control systems	10-25% improvement in effluent stability
Inefficient nutrient removal	NO_3^- > 10 mg/L, TP > 1 mg/L	Incomplete nitrification–denitrification	Anammox processes, biofilm systems (IFAS), MBBR	30–50% total nitrogen reduction without additional aeration
Large footprint	Space requirement > 5–10 m^3/PE	Conventional large-scale tank processes	MBR, SBR, IFAS, modular systems	40-70% footprint reduction (MBR systems)
Membrane fouling (in MBR)	Reduced flux, increased TMP	Membrane surface deposition	Automatic backwash, CIP cleaning, advanced hydrodynamic modules	2-3× increase in cleaning intervals
Poor micropollutant removal	Presence of compounds > µg/L	Conventional biological processes not adapted	Advanced oxidation processes (AOP), activated carbon adsorption, UV-H_2O_2	70-95% micropollutant removal
Biological instability (toxic shocks)	DO fluctuations, non-compliant BOD	Industrial toxic loads	Adaptive AnSBR systems, IFAS hybrid biofilm systems	2-4× improved performance under shock loads
High maintenance costs	High OPEX	Traditional mechanical equipment	SCADA/IoT automation, online sensors	10-25% OPEX reduction
Limitations in advanced water reuse	Residual N/P/salts concentrations	Lack of tertiary treatment processes	UF/NF/RO + AOP + biofilters	Effluent suitable for potable or industrial reuse

Source: author's synthesis based on literature review.

Technology	Municipal	Domestic	Industrial	Oily	Nutrient-rich	Secondary treated	Saline	Septic sludge	Organic-rich
Activated Sludge (CAS)	1	0	0	0	0	0	0	0	0
Sequencing Batch Reactor (SBR)	0	1	0	0	0	0	0	0	0
(MBBR)	1	0	1	0	0	0	0	0	0
Membrane Bioreactor (MBR)	1	0	1	0	0	0	0	0	0
Anaerobic MBR (AnMBR)	0	0	1	0	0	0	0	0	0
Ultrafiltration (UF)	0	0	0	0	0	1	0	0	0
Nanofiltration (NF)	0	0	1	0	0	0	0	0	0
Reverse Osmosis (RO)	0	0	1	0	0	0	1	0	0
Electrocoagulation (EC)	0	0	1	0	0	0	0	0	0
Coagulation–Flocculation	1	0	1	0	0	0	0	0	0
Dissolved Air Flotation (DAF)	0	0	1	1	0	0	0	0	0
Constructed Wetlands	1	0	0	0	0	0	0	0	0
High Rate Algal Ponds (HRAP)	1	0	0	0	0	0	0	0	0
systems)	0	0	0	0	1	0	0	0	0
(ABR)	0	1	0	0	0	0	0	0	0
Denitrifying Biofilter	0	0	0	0	0	1	0	0	0
Membrane contactor (nutrient recovery)	0	0	0	0	1	0	0	0	0
Hybrid membrane systems (MBR + RO)	0	0	1	0	0	0	0	0	0
Microbial Fuel Cells (MFC)	0	0	0	0	0	0	0	0	1
systems	0	0	1	0	0	0	0	1	0

Figure 3. Technology-wastewater compatibility matrix for circular water reuse systems (1 = the technology is suitable for that type of wastewater, 0 = not suitable)

The matrix was constructed using a binary classification approach (0-1), where each wastewater treatment technology was mapped to its most suitable wastewater types based on reported applications. Technologies were assigned to multiple categories where applicable. The heatmap represents a qualitative synthesis of technological applicability rather than a quantitative performance comparison.

The matrix highlights the heterogeneous applicability of wastewater treatment technologies across different wastewater types. Universally applicable systems such as MBR and MBBR contrast with more specialized technologies such as RO, DAF and membrane contactors, supporting the need for hybrid and modular configurations in mobile wastewater treatment systems.

Technologies were assigned to reuse categories based on keyword identification within the reuse target field (e.g., irrigation, industrial, urban, high-quality). Technologies could be included in multiple categories where applicable.

The reuse distribution was obtained through a qualitative classification of wastewater treatment technologies based on their reported reuse targets. A keyword-based approach was applied to categorize each technology into four reuse pathways (irrigation, industrial, urban and high-quality reuse), allowing multiple assignments per technology. The results represent a comparative synthesis of technological applicability rather than a quantitative performance assessment.

Figure 4 was constructed using a semi-quantitative scoring approach. Mobility levels were classified on a five-point scale (1 = low, 5 = very high) based on system transportability and deployment flexibility. Circular economy output was evaluated using a qualitative scoring system reflecting the potential for water reuse, nutrient recovery and energy generation. Bubble size represents the versatility of each technology, defined as the number of applicable wastewater types identified in the dataset.

To illustrate the versatility of mobile treatment systems, Table 2 presents the main wastewater streams, their characteristic pollutants, suitable treatment technologies, and potential reuse options.

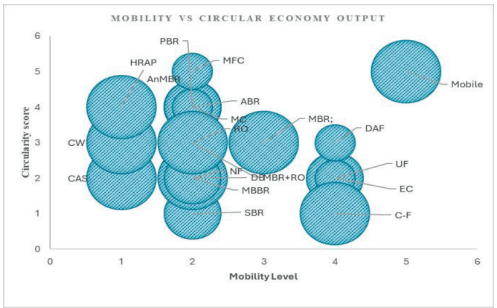


Figure 4. Mobility level versus circular economy output of wastewater treatment technologies

Table 2. Typology of Wastewater Streams Suitable for Mobile Treatment Systems

Wastewater source	Typical pollutants	Suitable mobile treatment technologies	Potential reuse applications	References
Petrochemical / refinery wastewater	hydrocarbons, oils, COD, suspended solids	oil separators, DAF, electrocoagulation, MBR, activated carbon, RO	industrial reuse, cooling water, process water	Meng et al., 2017; Yang et al., 2020
Food industry wastewater	high COD, BOD, fats, organic matter	DAF, SBR, MBBR, MBR, biological treatment + filtration	irrigation reuse, industrial cleaning water	Maniam et al., 2022; Khaki et al., 2026
Livestock wastewater	organic matter, nitrogen, phosphorus, pathogens	biological treatment, MBBR, MBR, anaerobic digestion	agricultural irrigation, nutrient recycling	Obijianya et al., 2025
Municipal wastewater (small communities)	COD, BOD, nutrients, pathogens	SBR, MBBR, compact activated sludge, membrane filtration	irrigation, landscape watering, groundwater recharge	Garrido-Baserba et al., 2024
Construction sites / temporary camps	suspended solids, organic matter	compact biological treatment, filtration, UV disinfection	local reuse, environmental discharge	Lakho et al., 2020
Emergency / humanitarian wastewater	pathogens, organic load	mobile modular treatment units, filtration + disinfection	sanitation reuse, emergency water management	Wolny et al., 2021

Resource recovery pathways

Wastewater streams contain multiple recoverable resources, including nutrients, energy, biomass-derived products and valuable metals, positioning wastewater treatment plants as resource recovery platforms rather than solely pollution control systems (Smol, 2023; Wada et al., 2026).

Nutrient recovery represents one of the most established pathways. Wastewater and sewage sludge are significant secondary sources of phosphorus and nitrogen, with phosphorus recovery potential estimated at up to 22% of global demand.

Phosphorus is commonly recovered as struvite, while nitrogen can be extracted via membrane processes or converted into ammonium-based fertilizers. In addition, biosolids can be reused as soil amendments, while thermochemical processes such as pyrolysis enable biochar production and carbon sequestration (Kyllönen et al., 2021; Udu & Okpala, 2025; Wada et al., 2026).

Energy recovery is another key component, with anaerobic digestion converting organic matter into biogas that can be valorized for electricity and heat generation (Sevillano et al., 2021). Advanced processes, including thermal pretreatment and hydrothermal carbonization, further enhance energy recovery by producing energy-rich products such as synthesis gas, while emerging technologies such as microbial fuel cells enable simultaneous treatment and electricity generation (Udu & Okpala, 2025; Wada et al., 2026).

Beyond nutrients and energy, wastewater can support the production of bio-based materials and chemicals. Microalgae systems enable the recovery of nutrients and carbon while generating biomass for biofuels and bioproducts, while agro-industrial wastewater can be used for producing biodegradable polymers such as polyhydroxyalkanoates (Udu & Okpala, 2025; Wada et al., 2026).

Wastewater streams may also contain recoverable metals, particularly in industrial effluents, which can be extracted using biosorption, electrochemical processes, ion exchange or membrane technologies (Udu & Okpala, 2025; Wada et al., 2026).

The integration of these pathways underpins the transition from conventional treatment plants to Water Resource Recovery Facilities (WRRFs), enabling simultaneous pollutant removal, water reuse and resource valorisation (Neczaj & Grosser, 2018; Smol, 2023). In this context, decentralized and mobile systems extend the WRRF concept by enabling localized resource recovery and reuse, particularly in areas lacking centralized infrastructure.

Romania vs Europe: Implementation Gap

The analysis reveals significant structural gaps in wastewater management performance in Romania (Mosnegutu et al., 2025). Although approximately 66% of the population is connected to sewerage systems and 60.7% to wastewater treatment plants, only 12% of urban wastewater is treated in compliance with European Union requirements, compared to an EU average of approximately 76%. Wastewater treatment infrastructure remains underdeveloped, with 1,242 treatment plants in operation, of which 847 serve agglomerations larger than 2,000 population equivalents, yet important operational and performance limitations persist.

Resource recovery is also limited, with only around 24% of sewage sludge valorised through agricultural reuse or composting, indicating low circular integration. This aligns with broader circular economy indicators, where Romania records a circular material use rate of 1.3% compared to 12.8% at EU level, and a municipal waste recycling rate of 13.7% versus 48.6% in the EU, highlighting weak integration of circular principles across sectors.

At the European level, wastewater management is characterized by significant heterogeneity, shaped by water availability, climate and infrastructure development. Approximately 11% of the population is affected by water stress, while only around 1 billion m^3/year of treated wastewater is reused, compared to an estimated potential of 6 billion m^3/year (EEA, 2023b). Water reuse practices vary significantly across Member States, with high reuse rates in water-scarce countries such as Cyprus (>90%) and Malta (>60%), and moderate levels in Spain, Italy and Greece (5-12%), supported by tertiary treatment technologies in line with Regulation (EU) 2020/741.

Circular wastewater management in the EU is structured around three main valorisation pathways: water reuse, agricultural sludge reuse and thermal treatment systems enabling energy and phosphorus recovery. In 2020, the EU generated approximately 6.31 million tons of sewage sludge (dry matter), of which 37.3% was reused in agriculture, with significant national variations - from agricultural reuse-dominated systems (e.g., Estonia 85.9%, France 77.1%) to thermal recovery-oriented systems (e.g., Netherlands 95.6% incineration), where phosphorus recovery can reach 70-90%.

Despite these advancements, infrastructure disparities persist, with approximately 81% of the EU population connected to at least secondary wastewater treatment. The revised

Urban Wastewater Treatment Directive (UWWTD recast) further strengthens requirements by introducing stricter nutrient removal targets and advanced treatment for micropollutants.

Romania remains in a transitional stage within this European framework, with only 60.7% of the population connected to wastewater systems (NIS, 2024) and over 150 agglomerations non-compliant with EU requirements (EEA, 2023a). Although the entire national territory is designated as a sensitive area - requiring enhanced nitrogen and phosphorus removal - circularity indicators remain underdeveloped, with only 21.3% of sewage sludge reused in agriculture compared to the EU average of 37.3%, and no consolidated national data on wastewater reuse.

These findings highlight a gap between legislative alignment and practical implementation, driven by infrastructure deficits, limited reuse deployment and weak resource recovery integration. At the same time, the limitations of conventional wastewater treatment systems - such as high energy consumption, sludge production, sensitivity to variability and incomplete removal of nutrients and micropollutants - further constrain progress toward EU targets. Addressing these challenges requires the integration of advanced technologies, including biofilm systems (IFAS/MBBR), optimized aeration, real-time monitoring and tertiary treatment processes such as filtration, granular activated carbon and advanced oxidation processes.

In this context, mobile systems represent a strategic opportunity due to their high treatment efficiency, flexibility and reuse potential, functioning as transitional circular infrastructure capable of enabling localized treatment, resource recovery and alignment with European wastewater management models.

The conceptual framework from Figure 5 illustrates the main circular wastewater valorisation pathways in the European Union - water reuse, agricultural sludge valorisation and thermal resource recovery - highlighting Romania's transitional position and the role of mobile and decentralized systems as enabling infrastructure for bridging implementation gaps. To provide a regulatory and technological context, Table 3 compares key EU and Romanian indicators related to wastewater treatment and summarizes their implications for WWTP modernization and the integration of advanced technologies.

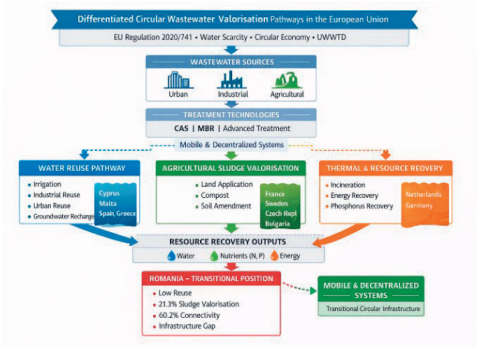


Figure 5. Differentiated Circular Wastewater Valorisation Pathways and the Role of Mobile Systems in the EU–Romania Context (The figure was generated with the assistance of a generative AI tool based on the authors' conceptual design and subsequently reviewed, edited, and scientifically validated by the authors)

Table 3. EU-Romania Indicators Relevant for WWTP Modernization and Integration of Advanced Technologies

Dimension	EU (Data / Requirements)	Romania (Data / Requirements)	Direct Technological Implication
Connection to treatment (minimum level)	~81% of the population connected to at least secondary treatment (2022) (Eurostat, 2023; EEA, 2022).	Significant disparities between agglomerations; major pressure on collection and treatment in large agglomerations (European Commission, 2023).	Need for network expansion and increased treatment capacity; shock load mitigation through equalization and operational control.
"Secondary" treatment performance (definition)	≥70% BOD and ≥75% COD removal required under the Urban Wastewater Treatment Directive (European Commission, 1991).	Uneven compliance; some agglomerations still lack adequate treatment (European Commission, 2023).	Biological process upgrades (IFAS/MBBR, DO control) and improved robustness.
Advanced treatment (nutrients / stricter require-ments)	Recast strengthens nutrient removal and introduces additional requirements for micropollutants (European Commission, 2022; EEA, 2022).	Application of the "sensitive area" concept → intense pressure on N and P removal (Romanian Government, 2002; European Commissio, 2023).	Integration of optimized nitrification/de nitrification, IFAS/MBBR; Anammox where feasible.

Dimension	EU (Data / Requirements)	Romania (Data / Requirements)	Direct Technological Implication
Non-compliance (large agglomerations)	—	150 (collection), 154 (inadequate treatment), 155 (lack of advanced treatment) (European Commissio, 2023).	Investment prioritization: collection systems + biological upgrades + nutrient removal.
Investments (EU context)	~€67 billion invested in environmental protection in 2023 (Eurostat, 2024).	Need for accelerated investments, especially in large agglomerations (EEA, 2023b; European Commissio, 2023).	Justification for OPEX/CAPEX optimization: smart control, energy efficiency, resource recovery.

Source: author's synthesis based on literature review.

Table 4 compares key indicators of wastewater valorisation across the EU, Romania, and selected Member States, highlighting differences in water reuse, sludge management, and nutrient recovery practices.

Table 4. Comparative wastewater valorisation pathways in the EU and Romania

Indicator	EU Average	Romania	France	Estonia	Poland	Netherlands
Wastewater reuse (m^3/year)	~1 bn	n/a	low	low	low	low
Reuse potential	~6 bn	n/a	—	—	—	—
Population connected (%)	~81%	60.7%	>90%	>90%	~75–80%	>95%
Sludge production (t DM)	6.31 mil	254k	high	low	high	Moderate
Agricultural reuse (%)	37.3%	21.3%	77.1%	85.9%	38.0%	3.9%
Incineration (%)	Variable	low	low	low	18.5%	95.6%
Dominant model	Mixed	Transi-tional	Agricul-tural	Agricul-tural	mixed	Thermal
Nutrient recovery	Emerging	absent	limited	limited	emerging	Advanced

*Qualitative descriptors (low, moderate, high) are based on comparative analysis of Eurostat and EEA datasets.

Table 5 summarizes the main EU and Romanian legislative provisions governing wastewater management and highlights the key implementation gaps affecting the transition toward advanced and circular wastewater treatment systems.

The analysis indicates that Romania has largely achieved formal legislative alignment with EU wastewater policy, while significant gaps persist at the implementation level, particularly in infrastructure, compliance, water reuse and resource recovery. While the national regulatory framework is harmonized with European directives, significant gaps persist in infrastructure development, compliance, wastewater reuse deployment and nutrient recovery. These findings indicate that Romania is not primarily limited by regulatory deficiencies, but by implementation constraints, which delay the transition toward circular wastewater management.

Table 5. EU and Romanian wastewater legislation: key framework and implementation gaps (2026)

Compo-nent	EU frame-work	Romania – legislation	Implementation status and gap
Water policy	Directive 2000/60/EC	Law no. 107/1996	Objectives not fully achieved, gaps in reaching good ecological status
Urban wastewater	Directive 91/271/EEC; Directive (EU) 2024/3019	HG 188/2002; NTPA-011	Ongoing non-compliance confirmed by infringement procedure
Discharge	UWWTD require-ments	NTPA-001; NTPA-002	Legally implemented, compliance varies across agglomerations,operational gaps
Water reuse	Regula-tion (EU) 2020/741	Directly applicable	Limited documented implementation, lack of operational reuse systems
Sludge	Directive 86/278/EEC	Order 344/2004	Lower valorisation compared to EU average, limited nutrient recovery
Infrastructure	UWWTD obliga-tions	National implementation programs	~60.7% population connected, significant infrastructure deficit
Advanced / circular	Directive (EU) 2024/3019; EU CE policy	No dedicated framework	Limited deployment compared to EU requirements, technological and regulatory gaps

Source: Author's synthesis based on EU directives and Romanian legislation (Law 107/1996; HG 188/2002; NTPA-001/002/011; Order 344/2004; Directive (EU) 2024/3019; Regulation (EU) 2020/741); (EEA, 2024a), (EEA, 2024b) (EEA, 2024c), (EEA, 2024d) (EEA, 2024e), (EEA, 2024f).

Unlike many EU Member States, where circular wastewater management is driven by either water reuse, sludge valorisation or thermal recovery, Romania remains in a transitional stage where none of these pathways are fully developed at scale.

This gap creates a strategic opportunity for mobile and decentralized wastewater treatment systems, which can act as flexible, rapidly deployable solutions to bridge infrastructure deficits and accelerate circular economic implementation.

The comparative analysis shows that conventional wastewater treatment plants

remain economically efficient at large scale, due to lower operational costs and higher biogas recovery. In contrast, mobile and membrane-based systems outperform conventional processes in treatment efficiency, reuse readiness and operational flexibility. Despite higher energy demand and costs, they enable direct water reuse, improved nutrient recovery and stable performance under variable conditions, reflecting a shift from cost-driven to circularity-driven design.

Thus, conventional systems optimize cost and energy recovery at scale, while mobile systems prioritize flexibility, performance and circular economy integration. Table 6 compares the performance of conventional and mobile wastewater treatment systems in terms of treatment efficiency, resource recovery potential, energy demand, and economic indicators.

Table 6. Conventional vs. mobile wastewater treatment systems: performance, resource recovery, energy and cost comparison

Indicator	Conventional WWTP (CAS)	Mobile / decentralized (MBR / advanced)	Resource recovery potential	Energy (kWh/m³)
Organic matter (BOD/COD)	BOD: 75-95%COD: 70-90%	BOD: 90-99%COD: 85-98%	20-40% (biogas)	0.3-0.6
Suspended solids (TSS)	80-95%	>99%	Sludge → energy	0.2-0.5
Nitrogen (TN)	40-70%	70-95%	Limited	0.4-0.8
Phosphorus (TP)	30-60%	60-90%	10–30% (struvite)	0.3-0.7
Pathogen removal	Moderate (needs disinfection)	Very high (membrane barrier)	≈100% safe reuse	0.1-0.3
Water reuse potential	Low–moderate	High	50–90% reuse	0.5-1.0
Energy recovery	High (anaerobic digestion)	Moderate	20–50%	-0.2 to 0.3*
Sludge production	High	20-50% lower	Reduced disposal	-
Hydraulic variability	Low tolerance	High tolerance	-	Stable
Footprint	Large	Compact (-50-70%)	-	-
CAPEX (€/PE)	300-800	500-1500	-	-
OPEX (€/m³)	0.2-0.6	0.4-1.2	-	-

*Negative values indicate energy recovery offset
Source: author's synthesis based on literature review.

At the European level, circular wastewater management is heterogeneous, structured around coexisting pathways including water reuse, sludge valorisation and thermal recovery (Larsen et al., 2016; Smol, 2023). In contrast, Romania remains in a transitional stage, characterized by infrastructure, compliance and circularity gaps. Low connectivity, limited sludge valorisation and the absence of large-scale reuse indicate that constraints are primarily systemic, driven by governance, investment and institutional capacity. While conventional systems remain suitable for centralized applications, their limitations - high energy consumption, sensitivity to variability and limited resource recovery - reduce their effectiveness in decentralized contexts. Mobile systems address these challenges through on-site treatment, operational flexibility and integration of advanced processes. However, they also involve higher costs, lower capacity and increased operational complexity, and should therefore be integrated as complementary components within hybrid systems. From a policy perspective, regulatory frameworks remain insufficiently adapted to decentralized solutions, limiting large-scale implementation, particularly in Romania. Systemic barriers - including weak policy implementation, low public acceptance, infrastructure deficits and limited awareness of resource valorisation - further constrain progress.

In this context, mobile wastewater treatment systems can be conceptualized as transitional circular infrastructure, enabling localized water reuse and resource recovery, particularly in agriculture, where they can reduce freshwater demand and support nutrient and energy recovery.

In contrast to the European examples shown in Table 7, the implementation of mobile wastewater treatment systems in Romania remains limited and fragmented.

Table 7. Examples of mobile wastewater treatment applications in Europe

Country	Application sector	Technology used	Key performance	Main purpose
Spain	Food industry	Mobile DAF + RO	80-85% TSS removal	Water reuse and compliance
Greece	Agro-industrial (fruit processing)	Mobile treatment unit (ULTIMATE project)	Water reuse in process	Resource recovery and reuse
Netherlands	Industrial / municipal support	Containerized MBR systems	High effluent quality (reuse standard)	Decentralized treatment and reuse
Germany	Industrial / emergency applications	Mobile modular systems	Rapid deployment	Temporary treatment and compliance

Sources: NSI Mobile Water Solutions (2023); ULTIMATE Project (2022); Water Europe (2023).

Existing applications are mainly restricted to temporary or industrial uses, with no systematic integration into wastewater management strategies. This indicates that, despite technological availability, decentralized and mobile treatment solutions are not yet widely adopted, and wastewater management remains predominantly centralized and treatment-oriented.

CONCLUSIONS

This study demonstrates a clear transition from linear wastewater treatment toward circular resource recovery systems. Although the European Union has made significant progress in wastewater reuse and valorisation, implementation remains uneven across Member States.

Romania exhibits a structural gap characterized by limited infrastructure coverage, low reuse rates and underdeveloped resource recovery. These challenges are primarily driven by implementation constraints rather than regulatory deficiencies.

Mobile wastewater treatment systems emerge as a viable solution, offering rapid deployment, operational flexibility and high treatment performance. They can be effectively positioned as transitional circular infrastructure.

Rather than replacing centralized systems, mobile technologies should be integrated into hybrid frameworks to support decentralized applications and accelerate infrastructure development, particularly in regions with limited capacity and increasing water stress.

Future research should prioritize improving energy efficiency, reducing operational costs and developing regulatory frameworks that support decentralized deployment. Their integration could significantly accelerate the transition toward circular water management.

Mobile wastewater treatment systems should therefore be considered strategic infrastructure components, enabling localized treatment, resource recovery and water reuse within emerging circular systems.

Despite their advantages, mobile wastewater treatment systems present several limitations that may constrain large-scale implementation. Their operational performance is highly dependent on influent variability and requires advanced monitoring and control systems.

Therefore, mobile systems should not be considered replacements for conventional infrastructure, but rather complementary solutions integrated within hybrid wastewater management frameworks.

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