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PROCESS STABILITY IN LIVESTOCK WASTEWATER TREATMENT: A COMPARATIVE REVIEW OF CONVENTIONAL SYSTEMS AND MEMBRANE BIOREACTORS FOR DECENTRALIZED APPLICATIONS

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Abstract

Livestock wastewater, particularly from pig farming, represents a major environmental challenge due to its high organic load, nutrient content, and strong hydraulic variability. Conventional treatment approaches such as lagoons or activated sludge systems frequently exhibit unstable performance under fluctuating agricultural conditions, resulting in inconsistent effluent quality. This study presents a structured literature review and comparative technological analysis of wastewater treatment systems applicable to livestock farms, focusing on process stability in decentralized environments. The analysis shows that instability in conventional systems originates primarily from biomass washout associated with gravity-based sludge separation. Membrane bioreactors overcome this limitation by physically retaining biomass and decoupling sludge retention time from hydraulic retention time, ensuring stable nitrification and consistent treatment performance. Consequently, MBR technology represents a promising solution for decentralized and mobile livestock wastewater treatment systems.

Key words*: decentralized wastewater treatment, livestock wastewater, membrane bioreactor (MBR), pig farming.*

INTRODUCTION

Growing pressure on freshwater resources and stricter environmental regulations are accelerating the development of decentralized wastewater treatment systems for agricultural environments (European Commission, 2020). Pig farming represents one of the major sources of agricultural pollution, generating large volumes of wastewater rich in organic matter, nutrients and microbial contaminants (Chen et al., 2024). Despite this pollution load, wastewater management in many farms still relies on lagoon storage or simple digestion processes that provide only partial treatment (Ivanciu Popa et al., 2019; Chen et al., 2024).

Conventional biological treatment systems, particularly activated sludge, require stable hydraulic conditions to maintain biomass retention and treatment efficiency (Surdu et al., 2021). However, livestock wastewater is characterized by intermittent flows, high ammonia concentrations and strong seasonal variability, leading to biomass washout and unstable effluent quality (Burton et al., 2003; FAO, 2018).

Membrane bioreactor (MBR) systems overcome this structural limitation by physically retaining biomass through membrane filtration, decoupling sludge retention time from hydraulic residence time and enabling stable treatment under variable loading conditions (Capodaglio, 2017). Consequently, MBR technology represents a promising solution for decentralized and mobile livestock wastewater treatment systems.

Unlike most studies that focus primarily on pollutant removal efficiencies, this paper analyses wastewater treatment technologies from the perspective of process stability under variable hydraulic conditions, identifying biomass retention mechanisms as the key determinant for decentralized livestock wastewater treatment. The relationship between variable agricultural wastewater loading, process instability in conventional activated sludge systems, and the stabilizing role of membrane biomass retention is illustrated in Figure 1.

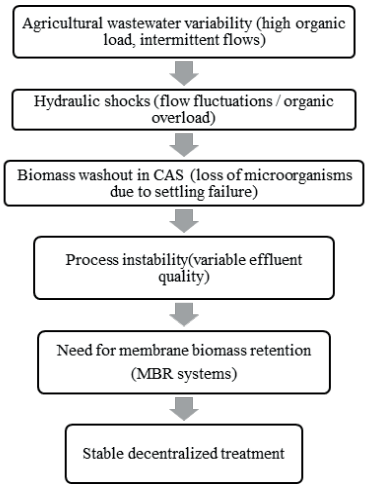


Figure 1. Conceptual framework illustrating the instability of conventional activated sludge systems under variable agricultural wastewater loading and the role of membrane biomass retention in stabilizing decentralized treatment processes.

The technological evolution of livestock wastewater treatment systems from conventional lagoon storage to modern mobile membrane-based systems is illustrated in Figure 2.

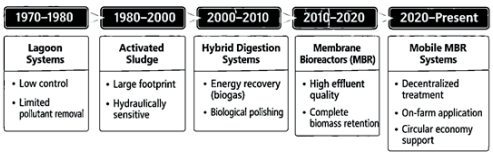


Figure 2. Evolution of wastewater treatment technologies applied in livestock farming, from conventional lagoon storage systems to modern mobile membrane bioreactor installations enabling decentralized treatment and resource recovery

MATERIALS AND METHODS

This study was conducted as a structured literature review and comparative technological analysis of wastewater treatment systems applicable to livestock farms, focusing on process stability and the suitability of decentralized and mobile treatment technologies.

Scientific publications were identified through systematic searches in the Scopus, Web of Science, and Google Scholar databases, covering the period 2000-2025. The search strategy included combinations of the following keywords: pig wastewater treatment, livestock wastewater, membrane bioreactor (MBR), decentralized wastewater treatment, mobile wastewater treatment systems, agricultural effluents, and nutrient removal technologies.

Selected studies were further analysed and categorized according to the type of treatment process. Studies were selected based on relevance, data availability and applicability for livestock wastewater systems.

For the comparative evaluation, the technologies were analysed based on several key operational parameters frequently reported in the literature.

The collected data were synthesized into comparative tables in order to highlight the technological limitations of conventional treatment approaches and the operational advantages of membrane-based systems in decentralized livestock wastewater management.

RESULTS AND DISCUSSIONS

Characteristics of livestock wastewater

Wastewater generated in animal husbandry contains high concentrations of organic matter, suspended solids, nutrients and pathogenic microorganisms originating from manure, feed residues and cleaning operations (Burton et al., 2003; FAO, 2018).

Mobile treatment technologies have emerged as an alternative approach for treating high-strength wastewater directly at source, reducing transport requirements and improving process control under variable loading conditions (Libralato et al., 2012; Capodaglio, 2017). These systems commonly integrate multi-stage filtration processes, including pre-filtration, membrane separation and disinfection, enabling the removal of suspended particles, microorganisms, and dissolved contaminants (Iorhemen et al., 2016; Meng et al., 2017).

In many regions, small livestock farms store wastewater in lagoons or reuse it for irrigation, whereas large farms increasingly implement anaerobic digestion to recover energy in the form of biogas (Burton et al., 2003; FAO, 2018).

A comprehensive treatment scheme for piggery wastewater typically includes solid-liquid

separation, anaerobic digestion, aerobic polishing and membrane filtration, followed by advanced polishing steps such as activated carbon or reverse osmosis (Metcalf & Eddy et al., 2014; Meng et al., 2017).

In Romania, most small livestock farms collect their wastewater in a storage basin, for further use as irrigation wastewater, or in aerated or non-aerated lagoons. The large farms, where significant financial investments have been made, have begun to build up their wastewater treatment plants with anaerobic digesters, and the biogas obtained can be used as a source of energy in the farm (Ivanciu Popa et al., 2019).

Historical livestock waste generation coefficients indicate that pigs produce approximately 6 kg total solids and 2 kg BOD_5 per 1,000 kg live weight per day. Although absolute values vary in modern intensive systems, the data demonstrate that livestock wastewater is generally characterized by high organic and nutrient loads. The current environmental challenge therefore results not from a change in manure composition but from the scale and hydraulic variability of modern production systems. The typical pollutant loads generated by swine livestock in Romania, compared with European reference ranges, are presented in Table 1.

Table 1. Typical pollutant load generated by swine livestock: Romania vs European reference values ($kg \cdot animal^{-1} \cdot day^{-1}$)

Parameter	Romania	European typical range
Total suspended solids (TSS)	4.48	3.0-5.5
Volatile suspended solids (VSS)	3.50	2.0-4.5
Chemical oxygen demand (COD)	3.94-5.78	3.0-8.0
Biochemical oxygen demand (BOD_5)	1.90-2.30	1.5-4.0
Total nitrogen (TN)	0.35	0.30-0.60
Total phosphorus (TP)	0.074	0.05-0.15

Romanian data: (Chiriac et al., 1977); European ranges: Burton et al., 2003; FAO, 2018; European Commission, 2020. Values are expressed per average pig live weight equivalent (livestock unit).

The comparison between typical Romanian practice and controlled Western European treatment (Table 2) indicates that removal efficiency is not primarily determined by the treatment technology itself but by process controllability. Lagoon-based systems exhibit moderate organic matter removal (30–60% COD), yet nutrient removal remains below 40%, and effluent stability is highly seasonal. In contrast, controlled biological systems achieve >90% removal efficiency and consistent compliance.

This demonstrates that livestock wastewater treatment failure is associated with hydraulic and operational variability rather than insufficient biodegradability of the substrate.

Western European treatment systems achieve higher removal efficiencies not always due to superior technologies but because wastewater is treated as a controlled process rather than stored as an agricultural by-product, resulting in predictable effluent quality and enabling water reuse.

Table 2. Comparative performance of swine wastewater treatment (Romania vs Western European practice)

Parameter	Romania - typical practice (lagoons / storage / basic digestion)	Western Europe - controlled treatment (biological + advanced)
COD removal	30-60% in anaerobic lagoons; highly dependent on retention time	85-98% in biological reactors; >95% with MBR polishing
BOD_5 removal	40-70% (partial stabilization)	90-99% in activated sludge/MBR
TSS removal	50–80% sedimentation based	>99% membrane separation
Nitrogen removal	<20-40% (mostly volatilization and soil uptake)	70-95% nitrification–denitrification; >90% advanced systems
Phosphorus removal	<10-30% natural precipitation	80-95% EBPR / chemical / struvite recovery
Pathogen removal	inconsistent; dependent on storage time	near complete removal after membrane/disinfection
Effluent stability	highly variable; seasonal	stable compliance
Water reuse suitability	Unsuitable	irrigation reuse feasible
Nutrient recovery	indirect via land spreading	controlled recovery (fertilizer products)
Treatment philosophy	manure management	wastewater treatment & circular economy

Livestock wastewater is fundamentally different from municipal wastewater due to its extreme variability in organic loading, nutrient concentration and suspended solids content (Musa & Idrus, 2021; Rahman et al., 2023).

Limitations of conventional systems

Conventional activated sludge (CAS) systems are frequently considered an upgrade solution; however, their application in livestock wastewater treatment presents intrinsic limitations (Du et al., 2020).

The process stability of CAS depends on constant influent composition and controlled loading rates; conditions rarely encountered in agricultural effluents (Rahman et al., 2023).

Sudden variations in organic load or ammonia concentration may lead to biomass inhibition and process imbalance (Iorhemen et al., 2016).
Furthermore, gravity sedimentation used for biomass separation represents a structural weakness of the CAS process (Iorhemen et al., 2016).
The treatment process typically involves several stages to effectively treat pig wastewater, as shown in Figure 3.

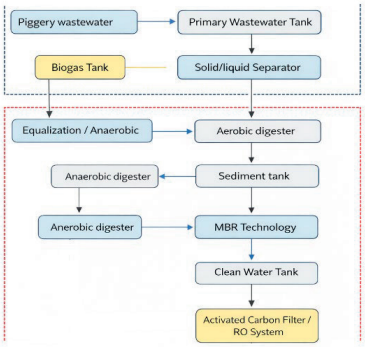


Figure 3. Treatment process of piggery wastewater (adapted and redrawn by the authors based on Hinada, n.d. and literature sources)

Poor sludge settling characteristics frequently observed in high-strength agricultural wastewater led to solids washout (Du et al., 2020). Therefore, achieving consistent compliance with discharge standards becomes difficult without tertiary treatment stages (Ezugbe & Rathilal, 2020).

Mechanistic origin of process instability

The instability of conventional activated sludge treatment under variable agricultural loading originates from the dependence of biomass retention on gravity settling.
Animal farms, particularly small and medium units, rarely have sufficient available land for aeration basins and clarifiers (Kesari et al., 2021). This structural difference between gravity-based biomass separation and membrane retention is illustrated in Figure 4.
Consequently, treatment infrastructure is often undersized, leading to chronic overloading conditions (Musa & Idrus, 2021).

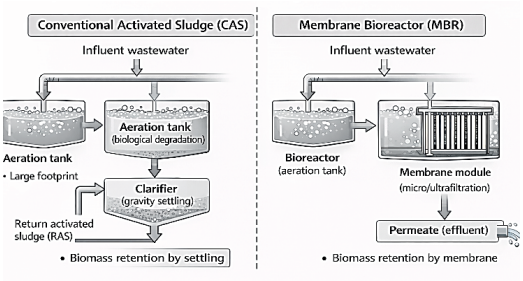


Figure 4. Mechanistic comparison between conventional activated sludge (CAS) and membrane bioreactor (MBR) systems highlighting biomass retention mechanisms and treatment stability under variable hydraulic loading

Cleaning operations, rainfall infiltration and manure removal cycles generate hydraulic shocks that conventional biological reactors cannot buffer effectively (Iorhemen et al., 2016). Additionally, nutrient removal in conventional systems remains limited without advanced process control (Ezugbe & Rathilal, 2020). High ammonia concentrations typical for livestock wastewater inhibit nitrification and reduce biological stability (Iorhemen et al., 2016).
Overall, the main limitation of conventional treatment is not insufficient pollutant removal capacity per se, but the incompatibility between system design philosophy and agricultural wastewater characteristics (Du et al., 2020). Systems optimized for stable municipal flows cannot maintain performance under decentralized, variable and high-strength effluents (Rahman et al., 2023). This structural mismatch explains the increasing interest in compact, modular and physically separated biomass systems such as membrane bioreactors (Iorhemen et al., 2016; Rahman et al., 2023). If manure is treated on-farm to reduce emissions of nitrogen, phosphorus, odours, and microbial pathogens to air and water, as well as to improve storage and land application, Best Available Techniques (BAT) require the application of specific processing methods (European Commission, 2017). These include mechanical separation of slurry, anaerobic digestion in biogas installations, external tunnel drying, aerobic digestion, and nitrification-denitrification of slurry (European Commission, 2017).

Comparative performance analysis

The pollutant removal efficiencies reported for several livestock wastewater treatment technologies are summarized in Table 3.

Table 3. Pollutant removal efficiencies of selected livestock wastewater treatment technologies in percentage (Kashyap, 2017)

Treatment Technology	BOD	COD	SS	TN	TKN	TP	Cu
Stabilization Pond	77.78	78.02	88.12	61.65	67.02	65.16	88.57
Cover Lagoon	85.18	83.06	85.43	47.61	51.88	66.42	89.28
Fixed Dome	85.06	70.97	80.63	51.98	52.16	67.27	82.72

Note: BOD – biochemical oxygen demand; COD – chemical oxygen demand; SS – suspended solids; TN – total nitrogen; TKN – total Kjeldahl nitrogen; TP – total phosphorus; Cu – copper.

The operational ranges presented in Table 4 show that conventional activated sludge systems require the sludge retention time (SRT) to be maintained through hydraulic stability, whereas membrane systems can maintain long sludge retention times (SRT) independently of the hydraulic retention time (HRT). Under variable loading, conventional systems operate outside the nitrification stability domain (<10-20 days effective SRT), whereas MBR systems maintain 15-40 days due to physical biomass retention. Therefore, process instability in agricultural wastewater treatment is a structural consequence of gravity separation rather than biological kinetics.

The comparative analysis illustrated in Figure 6 is based on a synthesis of representative literature data regarding livestock wastewater treatment technologies. Reported operational ranges and removal efficiencies were extracted from peer-reviewed studies and aggregated to obtain indicative average values for each technology group.

The results highlight clear differences in treatment efficiency and operational stability among the evaluated technologies. Conventional biological systems, such as activated sludge and hybrid biological-physicochemical configurations, can achieve satisfactory pollutant removal under stable influent conditions, but their performance may decline under hydraulic variability typical of agricultural wastewater.

In contrast, membrane bioreactor (MBR) systems demonstrate higher operational robustness due to complete biomass retention and the decoupling of sludge retention time (SRT) from hydraulic retention time (HRT). This allows the maintenance of high mixed liquor suspended solids (MLSS) concentrations and stable nitrification even under variable loading conditions, resulting in consistently higher effluent quality.

Overall, the compact design and process stability of MBR systems make them particularly suitable for decentralized and mobile wastewater treatment applications in livestock farms.

Operational ranges and performance indicators presented in Table 4 were obtained through a synthesis of representative literature data on livestock wastewater treatment technologies. Reported values from peer-reviewed studies were aggregated to illustrate typical operational conditions and treatment efficiencies.

MBR is an efficient wastewater treatment technology that integrates a biological process with membrane filtration.

The membrane bioreactor configuration illustrated in Figure 5 integrates biological treatment with membrane separation, ensuring complete biomass retention and stable effluent quality under variable loading conditions. Aeration supports both microbial activity and membrane fouling control, while sludge recirculation maintains process stability. This configuration enables the decoupling of sludge retention time from hydraulic retention time, which is essential for reliable treatment of livestock wastewater.

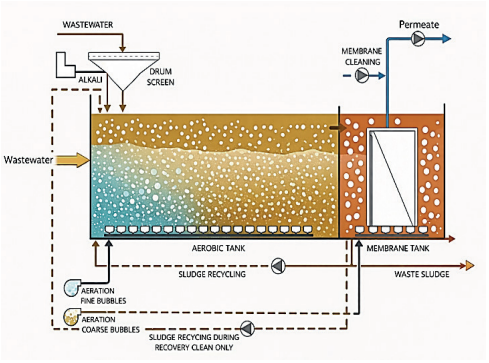


Figure 5. Containerized Membrane Bioreactor (MBR-C) Process Flow (adapted and redrawn by the authors based on literature sources)

Table 4. Comparative operational ranges and process stability of conventional activated sludge (CAS) and membrane bioreactor (MBR) systems for livestock wastewater treatment

Parameter (units)	Conventional systems (CAS / lagoons)	MBR systems (submerged / containerized)	Process stability mechanism
Influent COD (mg/L)	500-8000 (high variability typical of livestock wastewater)	Similar influent range; high-strength wastewater commonly treated up to 3000–5000 mg/L	Both systems depend on influent variability, but MBR tolerates higher load fluctuations
Influent BOD_5 (mg/L)	200-5000 depending on wastewater strength	Similar influent range; effluent BOD_5 typically <5–20 mg/L	Membrane barrier ensures consistent effluent quality
Influent TSS (mg/L)	200-3000	Similar influent range; permeate TSS typically <1–5 mg/L	Complete physical retention of suspended solids
SRT required for nitrification (days)	≥10-20 required for stable nitrification	Easily maintained at 15–40 due to membrane biomass retention	Decoupling of SRT from HRT stabilizes biological activity
HRT (hours / days)	CAS: 6-24 h; lagoons: several days–weeks	Typically 4-12 h; longer for high-strength wastewater	MBR allows shorter HRT with long SRT
MLSS (g/L)	2-5	8-15 typical; occasionally higher in pilot systems	High biomass concentration improves treatment robustness
Membrane flux (LMH)	Not applicable	10-30 typical operating range	Membrane filtration replaces gravity settling
Transmembrane pressure TMP (kPa)	Not applicable	~10-40 depending on fouling and operation	Fouling controlled through aeration and cleaning cycles
COD removal (%)	70-90 under stable operation	85-98	Higher stability due to retained biomass
BOD removal (%)	85-95	90-99	Membrane barrier prevents solids carryover
TSS removal (%)	80-95	>99	Membrane filtration ensures near-complete solids removal
Nitrogen removal (%)	40-80 depending on configuration	70-95 with nitrification–denitrification	Stable nitrification enabled by long sludge age
Phosphorus removal (%)	20-60 without advanced processes	60-90 depending on configuration	Enhanced biological or chemical removal possible
Energy consumption (kWh/m^3)	~0.2-0.6	~0.4-1.0	Higher aeration demand but compensated by smaller footprint

Note. Values were derived from reported ranges in peer-reviewed studies and validated against established wastewater engineering references (U.S. EPA, 2007; Judd, 2011; Metcalf & Eddy et al., 2014; Iorhemen et al., 2016; Meng et al., 2017; Nagarajan et al., 2019; Du et al., 2020; Rahman et al., 2023; Vaishnav et al., 2023; Chen et al., 2024).

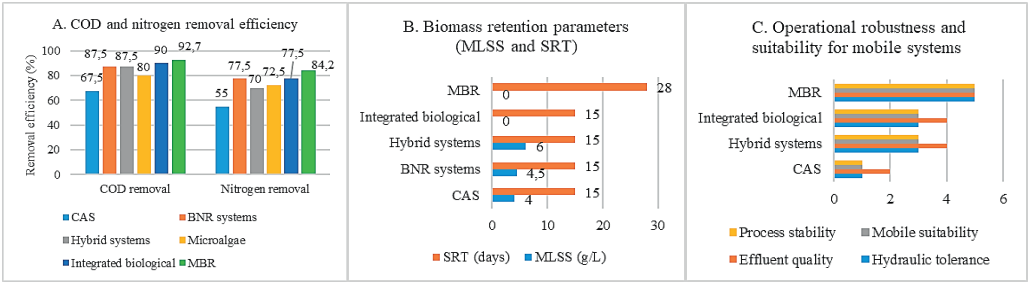


Figure 6. Comparative performance and operational stability of wastewater treatment technologies applied to livestock effluents

(A) Comparison of COD and nitrogen removal efficiencies reported in literature for conventional activated sludge (CAS), biological nutrient removal (BNR), hybrid biological–physicochemical systems, microalgae-based treatment, integrated biological treatment and membrane bioreactors (MBR). (B) Biomass retention characteristics expressed through mixed liquor suspended solids (MLSS) and sludge retention time (SRT). (C) Comparative operational robustness based on hydraulic variability tolerance, effluent quality and suitability for decentralized mobile systems

Membrane bioreactor (MBR) technology, which combines the activated sludge process with micro- or ultrafiltration membranes, is widely regarded as an effective tool for industrial water treatment and water reuse due to its high product water quality and low footprint (Hoinkis et al., 2012). In membrane bioreactor systems, biological degradation is coupled with physical separation through microfiltration or ultrafiltration membranes

(Ezugbe & Rathilal, 2020). The membrane barrier ensures near-complete suspended solids removal and significantly improved effluent quality (Iorhemen et al., 2016).

Consequently, the effluent quality becomes reproducible and independent of sludge settling characteristics (Rahman et al., 2023).

Another structural advantage is the possibility of operating at long sludge retention time and short hydraulic retention time simultaneously (Iorhemen et al., 2016). This condition favors slow-growing nitrifying microorganisms and improves nutrient removal stability (Du et al., 2020).

From a spatial perspective, eliminating secondary clarification significantly reduces the overall footprint of the treatment system, defined as the land area required for reactor installation and operation (Rahman et al., 2023).

The compact configuration of MBR systems makes them particularly suitable for decentralized and mobile installations where land availability is limited (Kesari et al., 2021).

This feature directly addresses one of the primary constraints of agricultural wastewater treatment infrastructure (Musa & Idrus, 2021).

The main drawback of MBR technology is membrane fouling, which reduces permeability and increases operational costs. However, fouling represents an operational challenge rather than a conceptual limitation, and extensive control strategies have been developed (Iorhemen et al., 2016; Du et al., 2020).

The technological barrier has shifted from demonstrating the feasibility of biological wastewater treatment to optimizing its operational stability, treatment efficiency, and adaptability under variable field conditions. In the decentralized agricultural context, where hydraulic loading fluctuates and wastewater characteristics are highly variable, stable biological treatment cannot be reliably maintained because sufficient biomass retention and settling cannot always be achieved. Membrane filtration is then more about securing the process stability than about increasing the performance of the wastewater treatment system. Thus, implementing membrane technology represents a completely new approach to wastewater treatment management in contrast to the incremental evolution from traditional to improved treatment systems.

The expected permeate quality of containerized MBR systems (Table 5) shows ammonium concentrations below 2 mg/L and BOD below 10 mg/L even at influent concentrations typical for agricultural wastewater.

Table 5. Typical influent and permeate water quality in containerized membrane bioreactor systems

Parameter	Feed Water Quality	Expected Permeate Quality	Removal Efficiency (%)
pH	6.5-7.5 S.U.	6.5 - 7.5 S.U.	-
Alkalinity (as $CaCO_3$)	125 mg/L	≥ 100 mg/L	20
Temperature Range	20-30°C	20-30°C	
Total Suspended Solids (TSS)	200 mg/L	< 5 mg/L	97.5
Biochemical Oxygen Demand (BOD)	250 mg/L	< 10 mg/L	96
Chemical Oxygen Demand (COD)	400 mg/L	< 50 mg/L	87.5
Ammonium-Nitrogen (NH_4)	30 mg/L	< 2 mg/L	93.33

*Values are indicative and may vary depending on influent characteristics and system configuration.

This indicates that stable nitrification is maintained despite high organic and nitrogen loads, confirming that decoupling SRT from HRT ensures biological robustness under intermittent inflow conditions.

In Romania, wastewater from farms has a biochemical oxygen demand (BOD) of up to 2000 mg/L, a total nitrogen content of less than 300 mg/L, and a dry matter content of less than 1% (Ministry of Environment, Waters and Forests & Ministry of Agriculture and Rural Development., 2021).

Wastewater passes through a drum screen to remove aggregates of hair and other debris, and to protect the membrane surface. The water then overflows to aeration tank, where air (fine bubbles) is injected to the tank to provide oxygen for microorganisms to decompose organic contents to CO_2, H_2O, and to convert ammonium/ammonia to nitrate. Membranes are periodically cleaned using chemical agents and air scouring with coarse bubbles in order to reduce fouling and keep the transmembrane pressure (TMP) within acceptable operating limits.

Despite the specific energy demand associated with membrane aeration and flux maintenance (0.4-0.8 kWh/m³), the MBR technology confers strategic benefits regarding compact footprint, high-quality effluent, and operational stability during load fluctuations.

MBR systems provide several advantages compared with conventional biological treatment processes, including improved effluent quality, reduced footprint, and easier process automation. They are typically operated with longer solids retention times (SRT), which contributes to lower sludge production. The treated effluent usually contains extremely low levels of bacteria, total suspended solids (TSS), biochemical oxygen demand (BOD), and phosphorus.

However, the main limitation of MBR technology is the higher investment and operational costs required to achieve treatment capacities comparable to those of conventional systems.

Energy costs are also higher because of the need for air scouring to control bacterial growth on the membranes (U.S. Environmental Protection Agency, 2007).

Suitability for decentralized systems

Mobile wastewater treatment systems for pig farms present significant potential, particularly for small and medium-sized farms needing flexible and sustainable solutions. However, addressing weaknesses such as limited capacity and high operational costs, while leveraging opportunities like renewable energy integration and rising regulatory demands, will be crucial for their widespread adoption and success.

Mobile treatment systems can be relocated to address wastewater issues at different farm sites, ensuring flexibility in operations, suitable for small-scale pig farms where permanent infrastructure may not be financially viable. They can incorporate multiple treatment stages (e.g., sedimentation, biological treatment, filtration) to meet specific water quality standards.

Increased regulations for agricultural wastewater management create demand for advanced treatment solutions. Biogas recovery from pig waste can power treatment units, reduce operational costs and create additional revenue streams (Sporea et al., 2023). Innovations in mobile treatment technologies (e.g., compact anaerobic digesters, advanced filtration) can improve efficiency and reliability. Maintenance, energy consumption, and operator training can be expensive. Performance can be affected by variations in wastewater characteristics, such as high solids or fat content from pig farming operations. High initial investment and operational costs may deter small-scale farmers from adopting the technology. Alternative wastewater treatment methods (e.g., centralized treatment plants, permanent lagoons) may be more appealing for certain farms.

The comparative operational characteristics shown in Table 6 demonstrate that the feasibility of decentralized treatment depends more on predictable effluent quality than on nominal removal efficiency. The compact footprint (0.1-0.3 m² per m³·d) and low hydraulic shock sensitivity enable treatment directly at source, transforming wastewater management from storage-based manure handling to a controlled treatment process.

Table 6. The differences between conventional activated sludge and membrane bioreactor systems in decentralized agricultural applications

Parameter	Conventional activated sludge	Membrane bioreactor (MBR)	Typical implication for mobile systems
Infrastructure requirement	Requires sewer network and storage	Operates directly at source	Suitable for decentralized farms
Specific energy demand	~0.3-0.6 kWh/m³	~0.5-1.0 kWh/m³	Comparable when transport energy included
Sludge retention time (SRT)	≥10-15 days for nitrification	20-40 days independent of hydraulics	Stable treatment under variable loads
Effluent suspended solids	10-40 mg/L (variable)	<1-5 mg/L (stable)	Reliable compliance
Total nitrogen removal	50-80% (load dependent)	80-95% (stable)	Better nutrient control
Sensitivity to hydraulic shocks	High	Low	Suitable for intermittent flows
Footprint	~0.5-1.5 m² per m³·d	~0.1-0.3 m² per m³·d	Compact mobile installations
Biomass retention	Settling dependent	Complete membrane retention	No washout risk
Operational stability	Less predictable performance	More predictable performance	Predictable effluent quality
Treatment philosophy	Dilution and discharge	Concentration and recovery	Compatible with circular economy

*Values represent typical operational ranges reported in literature.

This study is based on literature analysis and therefore does not include experimental pilot-scale validation. Future research should investigate the operational performance of mobile MBR systems under real farm conditions and evaluate economic feasibility for small and medium livestock operations.

CONCLUSIONS

Pollution generated by pig farms remains a major barrier to sustainable livestock production, not because of insufficient biological degradation capacity, but because centralized treatment concepts require hydraulic stability that livestock effluents inherently lack (Burton et al., 2003; Metcalf & Eddy et al., 2014). Membrane separation provides a different operational approach by decoupling sludge retention from hydraulics, transforming treatment reliability into a structural property of the process (Meng et al., 2017). For mobile and on-farm systems, environmental impact is determined by stability rather than nominal removal efficiency, making consistent effluent quality the primary performance indicator (WHO, 2006; Rahman et al., 2023).

Economic comparisons between conventional systems and membrane bioreactors are incomplete when transport, storage and dilution externalities are excluded from system boundaries (European Commission, 2020). Decentralized treatment preserves nutrients prior to dilution and therefore enables resource recovery and circular water management (Capodaglio & Olsson, 2020). Under this framework, performance must be evaluated by reuse safety and recoverability, not only pollutant removal (WHO, 2006; European Commission, 2020).

MBR systems should be considered a robust baseline technology for variable-load agricultural wastewater treatment rather than merely an advanced tertiary option.

The transition from activated sludge to MBR thus represents an infrastructural adaptation to circular economy requirements rather than a technological upgrade.

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