



Review of sanitation with a single-treatment approach of septic wastewater produced in decentralised areas

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Abstract

The proper management of septic wastewater in rural and peri-urban areas is vital for ensuring both environmental sustainability and public health. This review examines the composition of septic wastewater and the challenges associated with treatment through a single-treatment approach, evaluating different processes, and providing a comparative analysis to guide their selection. Different technologies have been investigated in the literature, namely sequencing batch reactors with floccular or granular sludge, membrane bioreactors in aerobic or anaerobic conditions, and up-flow anaerobic sludge blanket reactors, focusing on their mechanisms, operational efficiencies, and applicability. This paper highlights advantages, limitations, and design considerations for each technology, emphasizing their suitability for different wastewater compositions and flow rates. The results highlight that sequencing batch reactors are ideal for direct decentralised applications due to their flexibility and versatility, while membrane bioreactors and up-flow anaerobic sludge blanket reactors can be seen as an upgrade of wastewater treatment plants that have reached the full capacity, to allow the treatment of additional septic wastewater brought from decentralised areas. This review provides a valuable resource for researchers and engineers seeking sustainable solutions for decentralised wastewater treatment.

Keywords Aerobic granular sludge · Membrane bioreactor · Septage · Sequencing batch reactor · Up-flow anaerobic sludge blanket

Introduction

The treatment of septic wastewater (SWW) is a critical aspect of modern sanitation systems, particularly in decentralised and rural areas where centralized sewer systems are impractical or unavailable. SWW, characterized by high organic content, pathogens, and nutrients (Singh et al. 2023), poses significant environmental and public health risks if not properly managed. Traditional on-site systems are widely used but often fall short in meeting stringent effluent quality standards, especially for nitrogen and phosphorus

removal. This has stimulated the development and adoption of advanced treatment technologies capable of achieving higher efficiency, reliability, and sustainability.

In addition to treatment efficiency, the size of the population connected to sewers compared to on-site systems determines how much septage requires collection and treatment. Worldwide, more people use on-site sanitation than sewer connections—a trend the WHO/UNICEF Joint Monitoring Programme (JMP) describes as increasing more rapidly than does the extension of sewers, emphasising the persistent need for septage emptying, transport, and treatment (Mills et al. 2022; UNICEF 2025). The most updated JMP report further indicates that 2 out of 5 people still lack safely managed sanitation (2024 data), reinforcing that large volumes of faecal waste are generated outside of centralised sewers (UNICEF 2025).

In the European Union, connectivity is higher but remains uneven; in 2022, ~81% of the EU population was connected to secondary or higher wastewater (WW) treatment, with increasing coverage since 2000 (EEA 2025a; EU 2025). However, gaps still prevail in several Member

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States; for example, only 59.2% of Romania's population remained connected to wastewater collecting systems in 2022, revealing the high non-sewered portion still present in selected regions of the EU and why managing faecal sludge remains relevant (EEA 2025a).

Connectivity in Czechia is higher than the EU average but a significant off-network population remains. In 2023, 86.7% of residents were connected to the sewerage system and 84.5% were connected to sewerage terminating at a wastewater treatment plant (WWTP). On the other hand, the remaining population was not connected to sewerage with a centralised treatment system. National guidance explicitly anticipates households off sewers to employ drainless cesspools or septic tanks (or small domestic WWTPs) with professional export to municipal WWTPs, i.e., traditional septage routes (Mertl et al. 2024).

Untreated SWW has negative effects on nature when is poorly stored, dumped, infiltrated, or land-applied without control. In Europe, discharges of nutrients from small rural wastewater sources—like septic tanks—are an identified pressure on surface waters and can encourage eutrophication in sensitive receiving waters (UKEA 2019). Across the EU, faecal pollution continues to drive bathing-water downgrades in hotspots, with short-term pollution episodes after rain highlighting the vulnerability of near-shore ecosystems to untreated releases (EEA 2025b). In Central and Eastern Europe, leaking cesspools are regularly involved in the contamination of private wells by faecal bacteria and ammonia, indicating the need for controlled emptying and proper treatment of septage (Istenič et al. 2021). Septic systems also represent point pathways of pharmaceuticals to rivers, which further makes the case for pre-treatment and nature-based polishing before any discharge (Wilschnack et al. 2024). Apart from these environmental effects, methane emissions from long-stored septage in tanks are not negligible, adding a climate dimension to septage management (Huynh et al. 2021).

Traditional on-site systems—septic tanks and cesspools—were designed for primary treatment and storage: septic tanks settle solids and float fat, oils, and grease, and depend on the soil absorption system to provide the majority of polishing, whereas cesspools are percolation pits that dispose of rather than treat wastewater (EPA 2002, 2025; Tayler 2018). Accordingly, conventional septic effluent tends to have high organic and nutrient concentrations, and a high pathogen load, making it a challenge to ensure surface- and groundwater-protection without additional treatment (EPA 2002; Tayler 2018). Persistent maintenance gaps further degrade performance and increase illegal or uncontrolled septage disposal, while many jurisdictions now restrict or phase out cesspools outright because they do not provide treatment (EPA 2025; Tayler 2018).

Despite the relevance of the problem, a coordinated approach to its management is currently lacking. To the authors' knowledge, to date, there is no critical analysis of the literature demonstrating the advantages and disadvantages of adopting different technologies to manage SWW with a single-treatment approach after its extraction from septic tanks in decentralised areas. The aim of this paper is to provide a critical analysis of the effectiveness of the main treatments and discuss a possible approach to managing this WW in contexts that, due to low levels of urbanisation or low population density, do not have a centralised sewer system. The results of this discussion may be useful both to the scientific community, by highlighting areas to focus attention on in future studies, and to industry professionals, by providing useful guidance on approaches to implement for the management and treatment of SWW.

Methodology of the review

This paper is a review of the existing scientific literature focused on SWW treatment technologies. This work aims to (i) highlight the advantages and the disadvantages of each treatment, identifying potential recommendations for future research, and (ii) discuss the potential for managing SWW in decentralised areas using single-treatment approaches by investigating the feasibility of each technology.

Relevant and recent publications were collected using selected keywords such as “septic treatment”, “wastewater sanitation”, “wastewater treatment”, and “septage treatment”, including their combinations. The literature search was carried out using databases such as ResearchGate, Scopus, Google Scholar, and Elicit.

Only articles with high relevance and significant contributions to the field were selected and analysed from the retrieved records. Given the substantial number of publications, the literature has been screened, and the discussion has been limited to the treatments for which the largest number of publications was retrieved: sequencing batch reactors (SBR) with floccular or granular sludge, membrane bioreactors (MBR) in aerobic or anaerobic conditions, and upflow anaerobic sludge blanket (UASB) reactors.

Additional literature has been considered to provide deeper insights into topics such as (i) the characteristics of SWW, (ii) recommendations for future studies, and (iii) potential approaches to addressing the problem.

Septic wastewater (SWW)

Characteristics and differences with sewage

SWW, also known as septage or septic tank effluent, refers to the semi-aqueous waste material that accumulates in septic

tanks and other onsite sanitation systems, consisting of a complex mixture of human excreta, wastewater, and solid particles (Singh et al. 2023). Septage is pumped out from a septic tank or cesspool after it has accumulated over a period. A septic tank typically retains 60–70% of the solids, greases, and oils entering it. Scum forms on the surface, while sludge settles at the bottom, constituting approximately 20–50% of the tank volume (Rohilla et al. 2017). Generally, septage has an offensive odour appearance and high concentrations of BOD, COD and TSS (EPA 1999b).

Generally, septage differs from sewage because the former is a slurry and it's extracted during the emptying of the septic tanks (Rohilla et al. 2017) while the latter is defined as water whose quality has been degraded by human activity and is conveyed through a sewerage system (CZ 2001). The characteristics of SWW are highly variable (Table 1). The permissible pH values in the effluent range from 6 to 8.5. While the lower range aligns with typical wastewater, the upper limit (9.6) suggests that some septage samples were alkaline, likely due to biological activity or chemical inputs. Biological treatment processes typically perform optimally around neutral pH values (approximately 6.5 to 8) whereas extreme pH conditions can reduce microbial activity and treatment efficiency (Kang et al. 2009). In general, organic content and nutrients are more concentrated than in sewage due to the high content of faecal sludge (organic matter and nitrogen), detergents, and the biochemical transformations that occur in the septic tank (phosphorus) (Eliyan et al. 2022; Myszograj 2018).

Challenges in the treatment

The treatment of SWW faces significant challenges due to its high concentration of solids, organic matter and nutrients, making it difficult to treat using conventional methods. These high-strength levels are the result of prolonged retention times in septic tanks, where solids decompose and nutrients solubilised. Such concentrated wastewater can overwhelm conventional treatment plants, necessitating

advanced or specialised treatment to comply with regulations and minimise environmental harm (Wilschnack et al. 2024).

Generally, the composition of septage is highly variable and influenced by factors such as household habits, water usage patterns, and the presence of non-biodegradable materials. This variability presents significant challenges for the operation and design of treatment systems, which must be robust and flexible enough to accommodate fluctuating loads and contaminant patterns. Inconsistent influent characteristics can lead to process instability and reduce treatment performance (EPA 1999b). Moreover, many households lack properly designed septic tank. This can result in system failures, environmental contamination, and public health risks. These issues require investment in infrastructure enhancements, public education, and institutional maintenance programmes. Another challenge is the regularity of the emptying of septic tanks and cesspools (Bao et al. 2020).

Technologies for a single-treatment approach

This work investigates the main technologies for a single-treatment approach in the management of SWW, focusing on: SBR with floccular or granular sludge, MBR in aerobic or anaerobic conditions (AnMBR), and UASB. For each technology, a brief description is provided and the practical implications are discussed. Table 2 summarises selected case studies of various SBR, MBR, and UASB installations operating with floccular or granular sludge reported in the literature, highlighting their operational parameters, influent characteristics, and removal efficiencies for various wastewater types.

Sequencing batch reactor (SBR)

Description of the process

The SBR is a fill-and-draw activated sludge system for wastewater treatment. It involves a single complete-mix reactor where all stages of the activated sludge process—such as equalisation, aeration, and clarification—occur sequentially within the same tank. Unlike conventional activated sludge systems, which carry out these processes simultaneously in separate tanks, SBRs perform them consecutively in a single reactor (EPA 1999a; Gürtekin 2014).

In SBR systems, the operation consists of five phases (Fig. 1). Wastewater is introduced into a batch reactor, treated to remove unwanted components, and then discharged. To enhance performance and manage continuous inflow, multiple batch reactors often operate in coordinated sequence. This approach allows SBRs to handle both

Table 1 Characteristics of septage compared to sewage

Parameters [u.m.]	SWW*	Sewage**
pH [-]	6.42–9.6	6–8.5
N-NH ₄ ⁺ [mg L ⁻¹]	0.8–124.4	20–45
TN [mg L ⁻¹]	175–1240	30–70
TP [mg L ⁻¹]	10.2–120	5–15
COD [mg L ⁻¹]	754–13,970	250–800
BOD [mg L ⁻¹]	289–3000	150–400

*: data taken from (Petrušková 2023); **: data taken from (CZ 2001)

TN, total nitrogen; TP, total phosphorus; COD, chemical oxygen demand; BOD, Biochemical oxygen demand; u.m., unit of measure



Table 2 Case studies from several SBR, MBR, UASB installations operating with floccular or granular sludge

Source	Country	Type of WW	Untreated WW	Operational parameters	Removal efficiency
<i>FaSBR</i>					
Prasanna et al. (2021)	India	Septic tank effluent (domestic septage)	COD = 80–232 mg/L BOD = 22–49 mg/L	Lab SBR, natural adsorbents added during the reaction phase	COD = 73–87% BOD = 27–50%
Sarvajith et al. (2024)	India	Domestic	COD = 104–356 mg/L BOD = 110–265 mg/L P-PO ₄ ³⁻ = 3.7–6.5 mg/L TN = 13–25 mg/L	Start-up ≈ 2 months, SVI > 100 mL/g, T = 30–35 °C	COD = 91–96% BOD = 88–95% P-PO ₄ ³⁻ = 35–57% TN = 57–92%
<i>GrSBR</i>					
Pronk et al. (2015)	Netherlands	Domestic	COD = 506 mg/L BOD ₅ = 224 mg/L TP = 6.7 mg/L TN = 49.4 mg/L	Start-up ≈ 5 months, robust granule bed > 8 g/L, > 80% of sludge > 0.2 mm and > 60% > 1 mm	COD = 87.4%* BOD ₅ = 95.7%* TP = 86.6%* TN = 86%*
Kratochvíl and Kuffa (2024)	Slovakia	Septic-tank	COD = 560 mg/L BOD ₅ = 283 mg/L N-NH ₄ ⁺ = 131 mg/L	Full scale AGS at 1,600 PE, rapid start/up with immediate treatment after seeding	COD = 93.5%* BOD ₅ = 98.1%* N-NH ₄ ⁺ = 96.1%*
Jagaba et al. (2024)	Saudi Arabia	High-strength domestic	COD = 1629.05 mg/L BOD = 765 mg/L	Bench-scale GrSBR, OLR and cycle time varied and optimised	COD ≈ 74%
Sarvajith et al. (2024)	India	Domestic	COD = 104–356 mg/L BOD = 110–265 mg/L P-PO ₄ ³⁻ = 3.7–6.5 mg/L TN = 13–25 mg/L	Start-up ≈ 2 months, SVI = 100 mL/g, T = 30–35 °C	COD = 89–99% BOD = 91–96% P-PO ₄ ³⁻ = 60–99% TN = 54–99%
<i>Aerobic MBR</i>					
Alresheedi et al. (2023)	Saudi Arabi	Septic-tank effluent (residential)	COD = 386 ± 14.62 mg/L BOD = 160 ± 12.31 mg/L NH ₃ -N = 34 ± 3.55 mg/L	Ceramic-filter MBR; tested flux 0.2–0.65 m/d; best at 0.4 m/d	COD = 95% BOD = 95–97% NH ₃ -N = 79–96%
Valderrama et al. (2012)	Spain	Winery (harvesting)	COD = 13 448 mg/L TP = 39.5 mg/L TN = 34 mg/L	Pilot MBR, compared with full scale CAS, continuous feed with winery WW	COD = 99.2%* TP = 87.6%* TN = 83.2%*
<i>Anaerobic MBR</i>					
Uman et al. (2021)	USA	Synthetic medium-strength	COD = 501 mg/L	Lab-scale with tubular, cross-flow, PVDF UF membrane, HRT = 0.8 d, flux = 4.5 L.m ⁻² .h ⁻¹	COD = 86.5 ± 6.4% TN = (20.6% TP = 49.3%
Shyu et al. (2021)	South Africa	Blackwater	COD = 250 mg/L	Field-scale, UF membranes, 534 days, 2 membrane cleanings	COD = 94.5 ± 5% TN = 82.1 ± 24.0% TP = 43 ± 22.1%
Rattier et al. (2022)	Australia	Domestic sewage	COD = 500–600 mg/L	Pilot AnMBR at ambient temperature, UF membranes, HRT = 9 h	COD = 85%
<i>UASB</i>					
De Graaff et al. (2010)	Netherlands	Concentrated blackwater	COD = 12–16 g/L NH ₄ -N = 0.8–1.4 g/L	average HRT 8.7 d (5.8–13 d), OLR = 1 kg COD/m ³ /d	COD = 78 ± 9%
Rattier et al. (2022)	Australia	Domestic	COD = 500–600 mg/L	sensitive to hydraulic loading, HRT = 15 h	COD = 50%
Ali et al. (2007)	Palestine	Domestic	COD = 267–888 mg/L BOD = 116–333 mg/L	UASB-septic tank, 0.4 m ³ , HRT = 14 d, up-flow = 0.13 m/h	COD = 80% Nutrients not well removed

*: calculated based on the inlet and outlet concentration reported in the literature source

WW, wastewater; SBR, sequencing batch reactor; COD, chemical oxygen demand; BOD, biochemical oxygen demand; TP, total phosphorus; TN, total nitrogen; N-NH₄⁺, ammonium; OLR, organic loading rate; MBR, membrane bioreactor; NH₃-N, ammonia nitrogen; CAS, conventional activated sludge; SVI, sludge volume index; PVDF, polyvinylidene fluoride; UF, ultrafiltration; HRT, hydraulic retention time

municipal and industrial wastewater effectively and makes them particularly well-suited for applications with low or intermittent flow conditions (Al-Rekabi et al. 2007; EPA 1999a; Gürtekin 2014; M. Singh and Srivastava 2011).

To enhance SBR's performance and manage continuous inflow, multiple batch reactors often operate in a coordinated sequence. This approach allows SBRs to handle both municipal and industrial wastewater effectively and makes them particularly well-suited for applications with low or intermittent flow conditions (EPA 1999a; Gürtekin 2014).

To overcome sludge-water separation issues typical of floccular activated sludge SBR (FaSBR), aerobic granular sludge can be utilised (GrSBR) (Nancharaiah and Sarvajith 2019). It operates with dense microbial aggregates composed of bacteria, protozoa and fungi, among others, embedded in an extracellular polymeric substance (EPS) matrix that confers a compact structure and excellent settling properties (Beun et al. 1999; J.-H. et al. 2001; Nancharaiah and Sarvajith 2019; Rosa-Masegosa et al. 2021).

Granulation is promoted by the SBR regime. Aeration-induced hydrodynamic shear is bacterially aggregatory and EPS-promotive, compacting cells into round, dense granules, with short settling times (Nancharaiah and Kiran Kumar Reddy 2018). Regarding mechanisms, EPS with a high content of proteins and β -polysaccharides, plays a central role in microbial gluing, stabilising, and binding cells together (McSwain et al. 2005). Community formation, according to the SBR mode, results in slow-growing, functionally specialised microbial sub-communities, such as PAOs (phosphorus accumulating organisms), GAOs (glycogen accumulating organisms), and nitrifying microorganisms (Y. V. Nancharaiah and Kiran Kumar Reddy 2018).

The architecture of the granules creates internal redox gradients—an aerobic outer layer and an anoxic/anaerobic core—enabling the simultaneous removal of carbon,

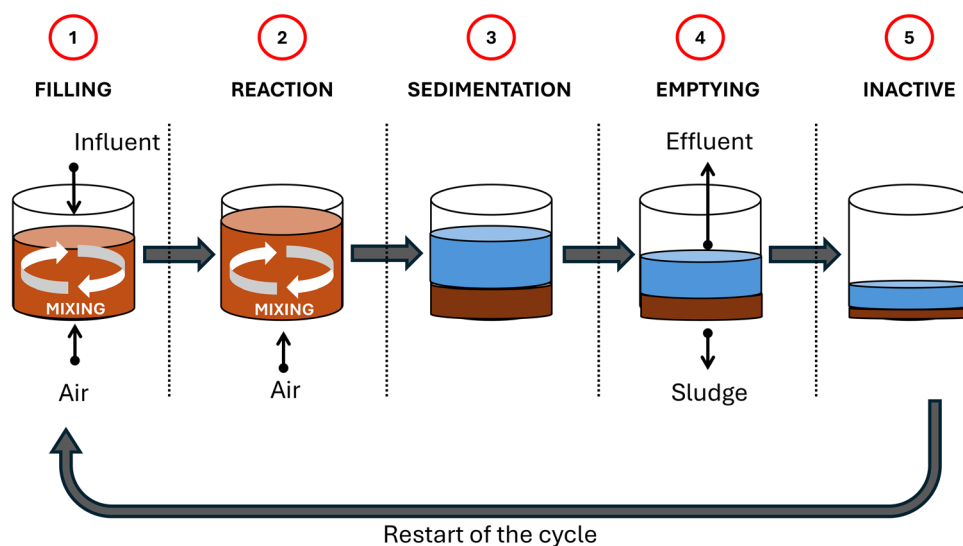
nitrogen, and phosphorus within a single reactor, while supporting high biomass concentrations (exceeding 8 g/L) (Nancharaiah and Sarvajith 2019; Nancharaiah and Kiran Kumar Reddy 2018; Rosa-Masegosa et al. 2021). This reduces plant footprint and energy demand with respect to FaSBRs (Nancharaiah and Sarvajith 2019).

GrSBR are typically operated with anaerobic feeding, feast-famine cycling and short settling periods that impose selection pressure for fast settling and dense biomass. During operation, a plug-flow process in the granular bed enables the withdrawal of the clarified effluent from the top, avoiding the need for external mechanical recirculation. Some designs, such as Nereda®, makes the hydraulics even simpler by utilising both filling and withdrawal simultaneously, eliminating the need for the moving decanters found in FaSBRs (Pronk et al. 2015).

Practical implications

These case studies demonstrate the adaptability of the SBR process under different loading and operational regimes, reinforcing its suitability for decentralised treatment systems (Petrušková and Hlušík 2025). SBRs are generally applied to wastewater flowrates of 220 L/s or less. While SBR technology is very effective for smaller wastewater flows, its application to larger flows is less frequent because of the more complex operation at larger sizes. Most SBR plants have been designed to treat flowrates below 22 L/s, and while the technology remains economical at up to 440 L/s, its use at larger flowrates is generally limited (Gürtekin 2014). From the perspective of a single treatment approach for the in-situ management of SWW in decentralised areas, the application of this technology is therefore cost-effective given the small flow rates to be treated, with a high impact on organic and inorganic pollutants. For instance, GrSBR

Fig. 1 Phases of SBR operation during one cycle



was tested to treat domestic sewage under tropical climate conditions and achieved over 70% and 80% of COD and ammonia removal rates, respectively (Sales et al. 2026). (Peng et al. 2025) combined SBR with UASB technology to treat real domestic sewage and optimise nitrogen removal performance (more than 85%). In another study, GrSBR enabled removal efficiencies of up to 89.7% for COD and 76.7% for BOD, with 74.2% and 96.3% for ammonia and phosphorus, respectively (Kassim et al. 2022).

SBR systems also possess a variety of practical advantages that make them particularly suitable for sites with limited land space. Because all the treatment processes occur in a single reactor, SBRs usually require a smaller footprint and occupy a smaller area compared with conventional systems, thus potentially generating cost savings on a capital basis by eliminating separate clarifiers and other specialised equipment (EPA 1999a; Mace and Mata-Alvarez 2002). The reported reduction in land footprint is approximately 50–75% (Nancharaiah and Sarvajith 2019). The systems also have flexibility in their operating cycles, allowing for the easy manipulation of aeration and phase timing, and can adapt to variations in the incoming wastewater loading and composition while maintaining stable performance (Gürtekin 2014). In addition, the ability to maximise energy use and operating efficiency relative to the influent load helps minimise operating costs (Gürtekin 2014).

However, SBR systems demand a higher level of sophistication and accurate control, especially in larger applications, which also raises maintenance requirements due to the utilisation of advanced automated devices (Li et al. 2024). In some configurations, there is a risk of discharging floating solids or settled sludge during the draw or decant phases. Furthermore, aeration devices may experience clogging under certain conditions and, depending on downstream needs, post-SBR equalisation may remain necessary (EPA 1999a).

Internally stratified redox zones allow simultaneous C–N–P removal and facilitate short-cut nitrogen routes, while high amounts of retained biomass enable flexible and high-strength substrate treatment (Rosa-Masegosa et al. 2021). In combination with reduced internal recirculation, this has led to full-scale energy savings of approximately 50% (Nancharaiah and Sarvajith 2019).

These benefits require strict SBR operation to maintain selection pressure and granule integrity. Start-up and granulation can take weeks to months, particularly with low-strength wastewater, and granules are vulnerable to instability under toxic shocks or excessive organic loading resulting in biomass loss and elevated effluent solids. Maintaining influent quality control and monitoring for signs of EPS degradation or overgrowth remains important for long-term stability (Kratochvíl and Kuffa 2024; Rosa-Masegosa et al. 2021).

Membrane bioreactors (MBR)

Description of the process

Membrane bioreactors (MBRs) combine biological degradation with membrane filtration (microfiltration or ultrafiltration), thereby replacing secondary clarifiers in a single operation and producing a high-quality effluent. Since the membrane retains suspended solids as well as microorganisms, the permeate is often of sufficient quality to be reused (for irrigation, industrial utility water, or as a prerequisite feed stream for reverse osmosis) (Judd 2008; Melin et al. 2006). MBR use extends from small, decentralised modules to municipal-scale facilities, mostly due to stricter standards and water scarcity (Melin et al. 2006).

The bioreactor can be designed for operation in the presence or absence of oxygen (AeMBR and AnMBR, respectively) to facilitate carbon oxidation reactions, nitrification–denitrification reactions, and, if necessary, high-strength organic substance conversion. Although the prevalent type of MBR consists of suspended-growth type reactors, there could also be hybrid reactors comprising both suspended and attached growth layers (Judd 2010). The membrane stage offers the final solid–liquid separation. Both MF and UF membranes are employed, however, UF is often used when there is a need for improved colloidal and pathogen removal. The prevailing configurations of commercial modules consist of hollow fibre (HF), flat sheet (FS), or tubular or multi-tubular systems (PCIM 2025).

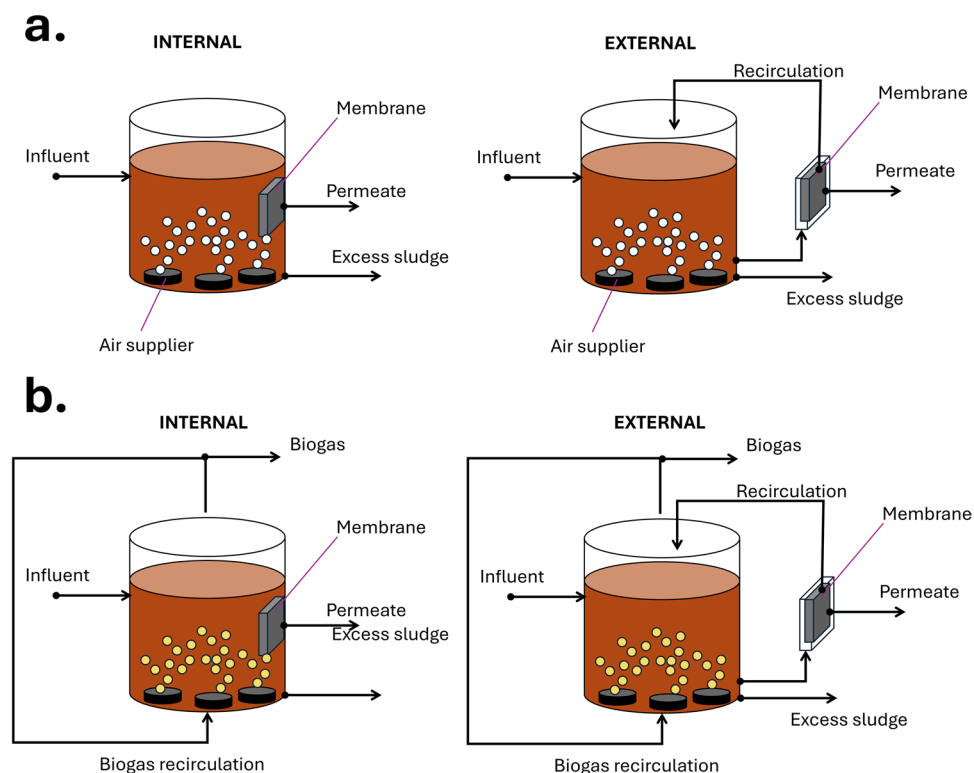
Two typical configurations of AeMBR are presented in Fig. 2a. For internal membranes, modules are situated directly inside the bioreactor. The primary mechanism of permeation is a result of forced suction. Bubble aeration is incorporated to induce shear forces at the membrane surface, thus preventing cake formation. At the same time, it mitigates fouling with relatively low energy demand. For side-stream membranes, modules can be mounted externally. High-velocity recirculation promotes turbulence to develop high flux rates. This is convenient for maintenance; however, it can be associated with high energy expenditure (Melin et al. 2006).

AnMBR combines anaerobic digestion with membrane filtration, treating wastewater without aeration, therefore saving energy. The membrane retains biomass and solids, producing high-quality effluent and methane-rich biogas for renewable energy. AnMBRs are compact, generate minimal sludge, and maintain stability under fluctuating loads, making them effective for both industrial and municipal wastewater (Lew et al. 2009; Osman and Hodaifa 2023).

Two typical configurations of AnMBR are presented in Fig. 2b; the membrane material—either ceramic or polymeric—strongly affects fouling resistance, energy use, and maintenance. The configurations with internal membranes



Fig. 2 Scheme of **a** MBR with internal and external membrane and **b** AnMBR with internal and external membrane



are more compact and consume less energy for pumping but may pose cleaning challenges, whereas external configurations offer easier access for maintenance and better fouling control at the cost of higher energy input. Fouling remains the major operational challenge also in case of anaerobic conditions, and it can be minimised through backwashing, gas sparging, chemical cleaning, or additives (Lew et al. 2009; Osman and Hodaifa 2023; Ozgun et al. 2013).

Practical implications

For new installations, MBR systems offer the advantage of treating higher wastewater flows or achieving superior treatment performance within a smaller footprint compared to conventional designs that rely on secondary clarifiers and sand filters. While membranes were historically limited to smaller-scale applications due to higher capital costs, advancements in technology and cost efficiency have led to their increasing adoption in larger systems (Zhen et al. 2019). For example, MBRs have been successfully applied in high-strength wastewater treatment applications like landfill leachate and textile effluents with COD removal higher than 90% and almost total suspended solids removal (Fazal et al. 2015).

MBRs are also particularly well-suited for industrial and commercial uses, where their ability to produce high-quality effluent supports both water reuse and surface discharge applications requiring stringent nutrient removal, including

nitrogen and phosphorus (EPA 2007). This makes them equally promising for septage treatment, as they can address the high organic load, pathogens, and variable composition typical of septage.

AnMBRs are flexible in treating various waste streams, including industrial effluent, domestic sewage, and synthetic wastewater (Osman and Hodaifa 2023). The treatment of high-strength wastewater represents one of the most well-established applications of AnMBR technology. Septage, with its characteristic composition of concentrated organic matter, fats, and nutrients, shares significant similarities with industrial wastewaters from food processing and chemical industries where AnMBRs have demonstrated remarkable efficacy. Studies have shown that AnMBRs can achieve COD removal rates between 73 and 100% even at organic loading rates as high as 2.2 g COD/(L*d) (Hummel et al. 2025).

MBR systems can replace secondary clarifiers and tertiary filtration units and reduce the need for additional treatment steps. They can be configured as a single compact unit and can be easily integrated with digital control and monitoring systems (Crawford et al. 2000; EPA 2007; Golbabaei Kootenaei and Aminirad 2014). However, membrane fouling is the most serious problem affecting system performance. It occurs due to physicochemical interactions between foulants and the membrane material, and if not properly managed, it can compromise the system's ability to treat the intended design flows (Iorhemen et al. 2016). In the long term, fouling determines



the loss of performance of a membrane due to the deposition of suspended or dissolved substances on its external surfaces, at its pore openings, or within its pores (Koros et al. 1996).

Membrane cleaning in MBRs, both aerobic and anaerobic ones, is normally categorized as being in-situ or ex-situ: in-situ interventions are carried out much more frequently (from 10-min intervals to week or months), while ex-situ cleaning is much less frequent (around 1–3 times per year) (Wang et al. 2014). All physical methods like relaxation, backflushing, air scouring (Wang et al. 2014), along with newer options like ultrasonication (Kobayashi et al. 2003), mechanical scouring (van den Brink et al. 2013), and membrane vibration (Yang et al. 2013) tend to address reversible fouling with minimal chemical damage. More persistent fouling is addressed by chemical cleaning via maintenance and intensive recovery soaks, normally in combination with the physical steps as physicochemical regimes such as chemically enhanced backflushing (Buzatu et al. 2012; Wang et al. 2014). The biological/biochemical methods such as enzymes, energy-uncouplers, and quorum quenching agents are under active study, while biological predation remains largely experimental (Kim et al. 2013; Wang et al. 2014).

In practice, AnMBRs operate without the need for aeration and utilise methane produced for heating or electricity, thereby facilitating energy neutrality, especially under favorable conditions (Jain 2018). Furthermore, high solids separation results in an efficient, reusable final effluent, and complete system retention of biomass implies significantly low excess sludge production and a more enclosed system with reduced odour. All these advantages are beneficial, especially within small wastewater treatment facilities and rural applications (Dvořák et al. 2016). All these aspects have ensured efficient functionality, especially on high-strength industrial wastewater, and increasingly on municipal wastewater.

Against these advantages, there are technical limiting factors that influence design, operation and maintenance. Process stability depends on precise temperature, pH, and organic matter control, as any deviation can cause instability in the anaerobic microbial community and reduce treatment efficiency. Finally, while AnMBRs demonstrate high organic removal efficiencies, they have low inherent nutrient removal capabilities, and thus efficient nutrient removal is often required post AnMBR treatment (Dvořák et al. 2016; Jain 2018). The management of SWW in remote communities, emergency relief situations, or small-scale industrial processes often demands systems that are low-maintenance, compact, and require low operating skills; all qualities intrinsic to the MBR process.

Up-flow anaerobic sludge blanket reactor

Description of the process

The up-flow anaerobic sludge blanket (UASB) is a high-rate, single-tank anaerobic reactor in which wastewater flows upward through a dense granular sludge (Rattier et al. 2022; van Haandel and van der Lubbe 2019). The most characteristic feature of the UASB reactor is the phase separator, which is placed in the top part of the reactor (Fig. 3). This tool enables the separation of biogas produced during anaerobic reactions from the sludge and the treated effluent. Three distinct zones can be highlighted: (i) a lower anaerobic digestion zone filled with biomass, (ii) an intermediate transition zone, and an upper settling zone where the separators are located. The influent is distributed evenly over the base of the reactor and flows upwards sequentially through the digestion, transition and settling zones to the top of the reactor where the effluent is collected (van Haandel and van der Lubbe 2019).

In the digestion zone, biomass converts organic components of SWW into biogas, which is captured by the phase separator above. Liquid passes into the settling zone, wherein an increasing cross-section reduces up-flow velocity and favours retention of carried solids. A deflector beneath the separator creates an inactive region. Biogas may entrain solids to form outlet blockage, with possible accumulation of fats and oils therein particularly at low temperatures. Sludge accumulates over time and needs to be removed either periodically or continuously, such as by centrifuges (Ahmed et al. 2015; van Haandel and van der Lubbe 2019).

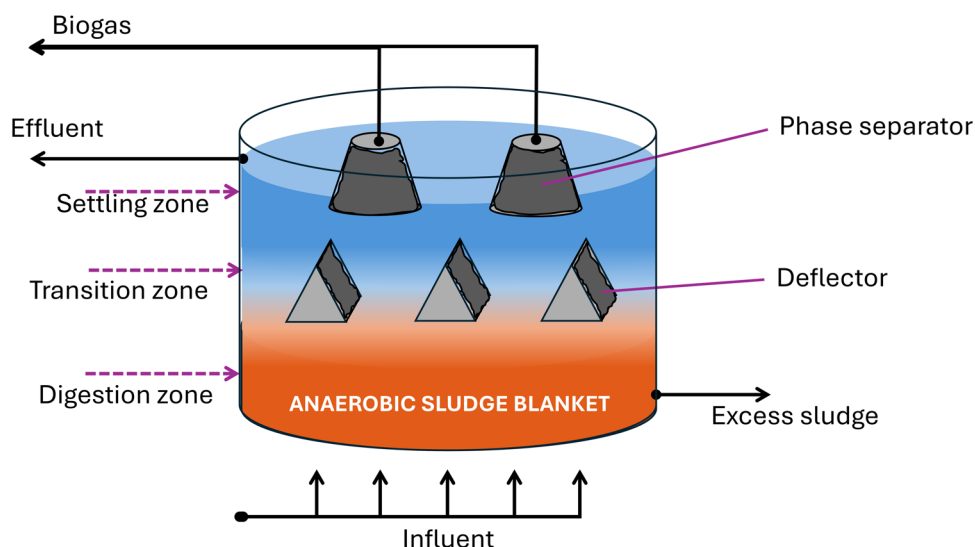
In some recent studies, UASB has been modified to overcome the main disadvantages of UASB and enhance the effectiveness in term of pollutants removal. Innovations include new techniques for granulation, the integration of complementary systems, and new configurations of reactors (Senadheera et al. 2025). For instance, (El Shahawy et al. 2024) upgraded a conventional UASB incorporating immobilised biochar with and without bioaugmentation of anaerobic bacteria. In some cases, improvements to the gas/solid/liquid separator or the deflectors have been made up to increase separation performance of the reactor (Mariraj Mohan and Swathi 2022).

Practical implications

The start-up of UASB is generally long and the reactor takes months to develop granular sludge (Ahmed et al. 2015). Compared to septic tanks, UASB units produce a higher-quality effluent at smaller volumes and are commonly used for high-strength industrial wastewater, such as those from breweries, distilleries, food processing, and pulp and paper facilities. Typical performance achieves approximately



Fig. 3 Schematic representation of a conventional UASB reactor



80–90% COD removal at organic loads of up to around 10 kg BOD/m³*d (Tilley et al. 2014). (El Shahawy et al. 2024) increased the performance of UASB incorporating immobilised biochar also with bioaugmentation of anaerobic bacteria *S. hydrogenans* S11. They increased the removal of COD, BOD₅, color and turbidity from 81%, 75%, 70%, and 70%, respectively, in case of conventional UASB to 93%, 91.5%, 85%, and 80%, respectively, in case of modified process. (Gutiérrez-Arzaluz et al. 2025) coupled a UASB reactor with a zeolite module improving the removal of organic matter and ammonium with removal efficiencies above 90%, a value higher than that obtained with a conventional reactor.

However, efficiency decreases with low-strength feeds or when there are high levels of fats, proteins, or solids, which poses challenges for septage treatment. Pathogens and nutrients are not sufficiently removed, so effluent generally requires post-treatment (Tilley et al. 2014).

The key advantages of UASB include their ability to achieve significant BOD and COD reductions even under high loading conditions (Tilley et al. 2014), alongside low and stable sludge production, which necessitates infrequent sludge extraction (van Haandel and van der Lubbe 2019). Generally, these systems have a low energy demand for operation (Stazi et al. 2022). UASB reactors facilitate biogas recovery while occupying a limited area, often situated underground, and feature enclosed digestion processes that minimise odours (van Haandel and van der Lubbe 2019). However, notable drawbacks include the necessity for specialised design expertise, limited standardisation, sensitivity to fluctuating loads and toxic substances, prolonged start-up periods, and the risk of methane or odour emissions if not adequately designed or managed (Tilley et al. 2014; van Haandel and van der Lubbe 2019). Another disadvantage of UASB reactors concerns the uncontrolled release of dissolved methane (45% and 88% of the total CH₄ produced in

UASB, depending on factors such as load, reactor type and operating conditions) in the effluent, which, if not properly recovered, can be released into the atmosphere (Stazi et al. 2022). Moreover, in colder climates, economic feasibility can be diminished due to the lower production of biogas and the reduced performances requiring effluent polishing (Tilley et al. 2014; van Haandel and van der Lubbe 2019).

Discussion and tips for future research

The treatment of SWW demands innovative and adaptable solutions to address the challenges of decentralised sanitation, environmental sustainability, and regulatory compliance. This work highlights the applicability of different technologies (FaSBR and GrSBR, AeMBR and AnMBR, and UASB) for a single-treatment approach to SWW in decentralised areas, each offering distinct advantages in efficiency, footprint, and operational flexibility (Table 3).

The SBRs, particularly GrSBR, provide a compact and versatile solution for simultaneous carbon and nutrient removal, making them ideal for small-scale and variable-load applications. Their operational flexibility allows them to adapt to variable wastewater compositions, but they must be regulated by precise control systems. These technologies can potentially be applied directly in decentralised areas without the need for central infrastructure (e.g., structured WWTPs) (Fig. 4).

Other technologies have demonstrated feasible application for the treatment of septic wastewater, but given their complexity and, in some cases (i.e. UASB), the need for subsequent polishing treatments, their application in more structured WWTPs is suggested. In this context, these technologies can be seen as a valid solution when an existing WWTP has reached its full capacity, and a structural



Table 3 Comparison of the different technologies available for the management of SWW with a single-treatment approach in decentralised areas

Technology	SBR		MBR		UASB	
	FaSBR	GrSBR	AeMBR	AnMBR		
Oxygen condition	Aerobic	Aerobic	Aerobic	Anaerobic	Anaerobic	Anaerobic
Key mechanism	Time-based sequential treatment in single tank	Granular biomass with stratified microbial zones	Biological degradation + membrane filtration	Anaerobic digestion + membrane filtration	Up-flow sludge blanket with biogas production	Up-flow sludge blanket with biogas production
Effluent quality	Good	Excellent (simultaneous C, N, P removal)	Very high (suitable for reuse)	High (but limited N, P removal)	Moderate (requires post-treatment for pathogens/nutrients)	Moderate (requires post-treatment for pathogens/nutrients)
Nutrient removal	Yes (with phase control)	Yes (simultaneous)	Yes (with the adequate process dimensioning)	Limited (post-treatment required)	No (post-treatment required)	No (post-treatment required)
Regulatory suitability	Moderate limits	Stricter C, N, P limits	Stringent effluent standards	Requires nutrient polishing	Requires post-treatment for nutrients	Requires post-treatment for nutrients
Land footprint	Low	Very low	Moderate	Low	Low	Low
Energy demand	Moderate	Low to moderate	High (due to aeration and fouling control)	Low (no aeration, energy recovery via biogas)	Very low	Very low
Sludge production	Moderate	Low	Low	Very low	Very low	Very low
Fouling issues	Minimal	Minimal	Severe (needs cleaning)	Significant	None	None
Startup time	Short	Moderate (granulation period)	Moderate	Long	Long	Long
Resource recovery potential	Limited	Limited	Water reuse	Biogas and water reuse	Biogas	Biogas
Capital cost	Low to moderate	Moderate	High	High	Low	Low
Main operation and maintenance requirements	Cycle and aeration control	Granule stability control	Fouling and cleaning	Fouling and anaerobic control	Start-up and sludge blanket control	Start-up and sludge blanket control
Community acceptance	Good if operation is simple and odour is controlled	Good; requires skilled operation	Moderate; limited by cost and maintenance requirements	Moderate; limited by complexity, improved by energy recovery	Good for low-energy operation, odour must be managed	Good for low-energy operation, odour must be managed
Best application	Small to medium communities, variable flow	Advanced compact plants, nutrient-sensitive areas	Reuse applications, stringent effluent standards	High-strength wastewater, energy recovery	High-strength wastewater, warm climates	High-strength wastewater, warm climates



upgrade is necessary to treat additional SWW brought from decentralised areas.

UASB reactors, with low energy demand and high organic removal, are well suited for high-strength wastewater, like SWW. Application in geographical areas with cold climates could lead to drawbacks such as outlet blockage due to the possible accumulation of fats and oils. In any case, the low effectiveness of UASB in pathogen and nutrient removal necessitates post-treatment, limiting its possible application as a standalone treatment in decentralised areas. At the same time, such technologies provide significant potential for resource recovery, including biogas production from AnMBR/UASB (partially covering energy demands) and high-quality liquid effluents from MBR, enabling water reuse, thereby closing water-energy cycles and facilitating circular economy approaches. Future designs will need to aim for energy-neutral or energy-positive operation, particularly under conditions of limited resources.

The use of MBRs in aerobic and anaerobic conditions offers resilience to fluctuations in flow and allows to produce high-quality effluent that is reusable, but some major drawbacks remain. Among them, membrane fouling remains one of the key challenges for AeMBRs and AnMBRs, requiring innovative solutions like real-time monitoring, advanced cleaning protocols (e.g., physicochemical treatment), and improved membrane materials. In this sense, the evolution of materials (e.g., ceramic membranes) and anti-fouling technologies can help to increase their cost-effectiveness by reducing extra energy demand. AnMBRs represent a

promising alternative, as they integrate anaerobic digestion with membrane filtration, ensuring energy recovery through biogas production. However, to date, dissolved methane loss and inefficient nutrient removal represent the main limitations that need optimisation, possibly through hybrid system integration. For all these reasons, these systems could be considered more suitable as an upgrade to allow full capacity centralized plants to treat additional SWW.

In general, the selection of an appropriate SWW treatment system depends on site-specific needs, including wastewater characteristics, energy availability, regulatory requirements, and the option of recycling or using the treated water (Soni and Dikshit 2024). Technologies intended for direct discharge to surface waters or for reuse must meet site-specific requirements for organic pollution, suspended solids, nutrients, and pathogens. From this perspective, AeMBR and GrSBR appear more suitable for application requiring stringent effluent limits. They provide high effluent quality and potential for enhanced nutrient removal. In contrast, UASB and AnMBR systems are more appropriate as primary or core treatment steps for high-strength SWW. However, they cannot be used as single-treatment and usually need further polishing to remove nutrients, pathogens, or residual suspended solids. An effective approach is the intentional integration of two or more technologies in sequence to regulate efficiency unattainable by any single process.

For instance, a UASB reactor followed by a constructed wetland could offer a low-energy solution for communities

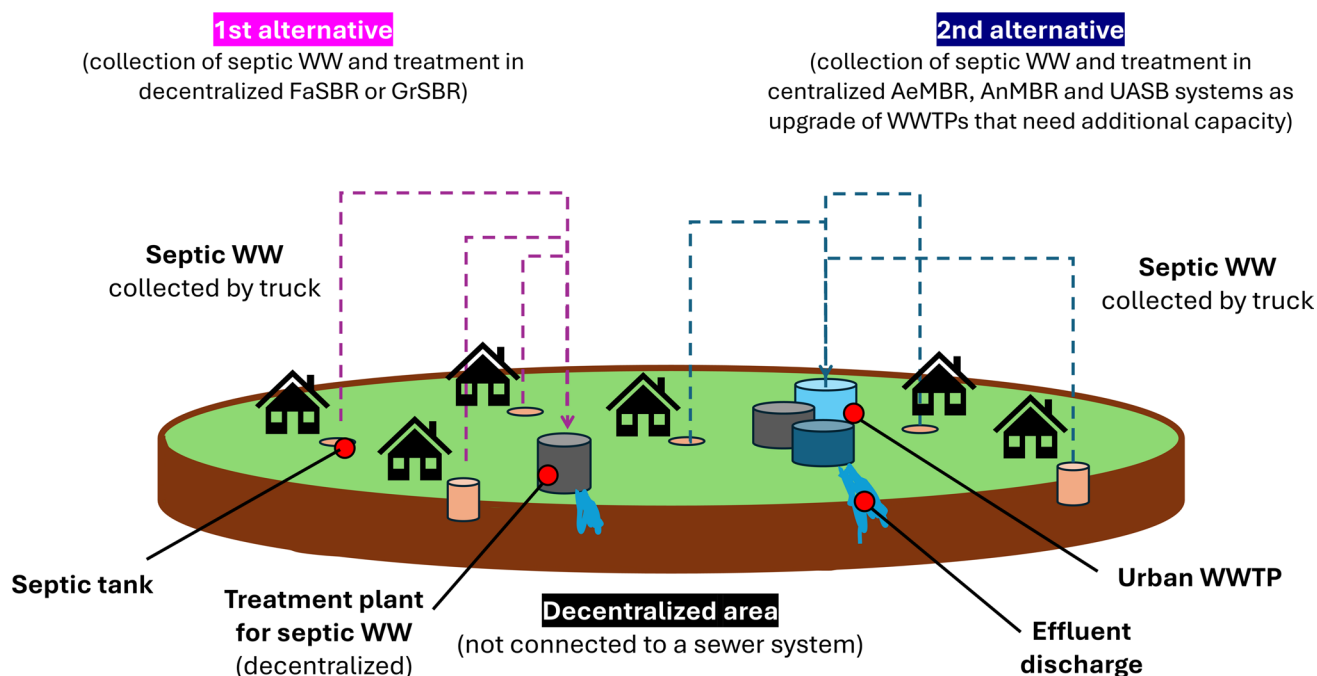


Fig. 4 Alternatives of application of the technologies studied for septic WW treatment in decentralised areas



with available land and moderate effluent standards (Abdel-Shafy et al. 2009; Sha et al. 2024). Fernández del Castillo et al. (2020) studied the coupling of a UASB and a constructed wetland for the treatment of the effluent from a septic tank highlighting that the constructed wetland achieved a removal of almost 60–70% of the COD load from the UASB effluent, 75–80% of TSS, and 30–40% of nitrogen. The same approach has been also applied by de Freitas Bueno et al. (2020) which found that combined UASB-constructed wetland system allows the removal of 96.5%, 98.4% and 98.2% of COD, TSS and faecal coliforms, respectively. By overcoming a major limitation of standalone UASB systems in SWW treatment, this combined approach represents a viable alternative for decentralized applications. Although UASB systems exhibit lower resilience to organic and hydraulic load fluctuations compared to SBRs, consolidating SWW treatment within a sufficiently large-scale decentralized facility would mitigate this limitation.

Similarly, pairing a FaSBR with a downstream polishing filter could expand the application of SBR technology to stringent scenarios requiring very low suspended solids or stringent pathogen limits (Khudair and Jasim 2018). MBR-based systems may also be combined with nutrient polishing or disinfection to target water reuse. These combined approaches can optimize treatment efficiency, operational complexity, and capital investment, especially when single-treatment approach fails to meet all effluent requirements. Sludge management also requires attention as part of regulatory compliance. Accumulated excess sludge, membrane cleaning residues, or anaerobic sludge must be safely stabilized, transported, and disposed of, or further treated, as required by to local regulations.

The selection of most proper technology in decentralised areas should also reflect socio-economic and operational limitations. Capital costs are affected by factors such as reactor complexity, land requirements, membranes, and automation. Operation and maintenance (O&M) requirements differ substantially among the reviewed technologies. SBR systems require reliable control of cycle phases and aeration (EPA 1999b) while MBRs necessitate continuous membrane monitoring and regular cleaning (EPA 2007). UASB and AnMBR systems demand careful start-up procedures, control of anaerobic conditions, and management of biogas or dissolved methane (Tilley et al. 2014; Dvořák et al. 2016). In rural and peri-urban areas, community acceptance may also influence implementation, especially when concerns arise regarding odour, visual impact, transport of septage, affordability, or the need for skilled operators.

Assessment of long-term sustainability should consider not only effluent quality but also energy demand, sludge production, and the potential for resource recovery. Aerobic systems, including FaSBR, GrSBR, and AeMBR, generally require energy for aeration (Drewnowski et al. 2019).

However, GrSBR may reduce overall energy consumption by improving settling and reducing recirculation (Xu et al. 2020). In contrast, anaerobic systems such as UASB and AnMBR have lower aeration demands and enable biogas recovery (Tomczak et al. 2023). Nevertheless, their sustainability may be limited by methane emissions, insufficient nutrient removal, or the requirement for post-treatment processes. Anaerobic systems generally produce less sludge, while aerobic systems often generate greater quantities of excess biomass that require additional management (Zieliński et al. 2022). Nutrient recovery is limited in most single-treatment configurations, but integration of phosphorus recovery, nitrogen polishing, or nature-based treatment units into combined systems could enhance resource recovery.

Continued research and technological innovation are essential to overcome existing limitations and expand the applicability of these systems in decentralised and resource-constrained settings. By leveraging the strengths of each technology, efficient, sustainable, and scalable solutions for global wastewater treatment challenges can be achieved. Future works should focus on the comparison of different scale plants under diverse climatic conditions and highly variable loads, typical of septage treatment. Research should also address specifically the efficiency of pathogen removal, determine of the requirement and role of post-treatment, optimise of nutrient polishing steps, and integrate of energy and greenhouse gas balances into system performance assessment.

Conclusion

The sanitation of SWW is a priority, especially in rural and peri-urban areas. After a review of literature, various technologies have been investigated for the potential treatment of this type of wastewater using a single-treatment approach, namely: FaSBR, GrSBR, AeMBR, AnMBRs, and UASB reactors. Each technology presents different advantages and disadvantages, making it difficult to propose a single solution for all situations. Indeed, the selection of the most appropriate technology for the treatment of SWW depends on several site-specific conditions, such as the characteristics of the wastewater, the morphological characteristics of the site, and the legislation that must adhered to. In general, given their high flexibility, effectiveness, and versatility, FaSBR and GrSBR can potentially be applied directly in decentralised areas without the need to transport septic WW to a more structured WWTP. By contrast, AeMBR, AnMBRs, and UASB have demonstrated potential effectiveness in the management of SWW but, given their complexity and, in some cases (e.g., UASB), the need for subsequent polishing treatments, their application in existing structured



WWTP is suggested. Their potential application can be seen as an upgrade to WWTPs that have reached the full capacity, in order to allow the treatment of additional septic WW brought from decentralised areas. The comparison further demonstrates that regulatory compliance, sludge management, capital and O&M costs, energy demand, community acceptance, and resource recovery potential must be evaluated alongside removal efficiency. Combined treatment systems, such as a UASB systems followed by constructed wetlands, can mitigate the inherent limitations of standalone technologies, thereby positioning them as a viable alternative for decentralized applications.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval and consent to participate This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication Not applicable.

Generative AI and AI-assisted technologies in the writing process During the preparation of this work the author(s) used OpenAI's ChatGPT to improve the language and readability of the manuscript. Elicit and SciSpace software were used to select some of the relevant articles used in the review. After using this tool/service, the author(s) screened the publications and decided whether to use them or not.

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