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MEMBRANE-BASED VALORIZATION OF SLUDGE DIGESTATES: LINKING PRETREATMENT EFFECTS TO SEPARATION PERFORMANCE

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Abstract

Anaerobic digestion residues are increasingly treated as secondary resources for water, nutrient and energy recovery rather than as wastes for disposal, a shift reinforced in the European Union by the recast Urban Wastewater Treatment Directive. Membrane processes are leading candidates for fractionating the liquid fraction of digestate, but their stability depends on feed properties that upstream pretreatment strongly modifies. This contribution summarizes a recently published review [1] that treats pretreatment and membrane separation as one conditioning-to-separation pathway. Evidence on thermal hydrolysis, microwave, alkaline, ozone and enzymatic conditioning is linked to the behavior of pressure-driven membranes (MF, UF, NF, RO), electrodialysis and bipolar membrane electrodialysis (ED, BMED) and membrane distillation (MD). Pretreatments that raise solubilization and improve bulk rheology can also increase the load of soluble biopolymers and fine colloids: microwave treatment of activated sludge at 80 °C, for example, lowered the median particle size from 228 to 45 µm while the sludge filter resistance increased about twentyfold. The reported indicators show that ammonium is the most consistently recoverable or removable target, that a staged UF–selective ED–RO train raised clean-water recovery from about 38% to 88% at pilot scale, and that digestate-specific energy data exist mainly for electro-driven processes. Condition-explicit reporting and long-term operation on real digestate are identified as the main prerequisites for scale-up.

Introduction

Municipal wastewater treatment plants are being reframed as water resource recovery facilities, in which sludge and digestate are regarded as sources of energy, nutrients, organic carbon and water rather than as residues to be stabilized and disposed of. In the European Union, the recast Urban Wastewater Treatment Directive (Directive (EU) 2024/3019), in effect since 1 January 2025, strengthens nutrient-removal and resource-recovery requirements, introduces quaternary treatment for micropollutants and pushes the sector toward energy and climate neutrality [2]. Within such schemes, membranes can split the liquid fraction of digestate (LFD) into a clarified permeate and a concentrate, reduce transport volumes, and prepare process-ready streams for struvite crystallization, ammonia stripping and absorption, or electrochemical recovery [3].

Digestate is, however, a challenging membrane feed. It behaves as a non-Newtonian suspension, and its soluble extracellular polymeric substances (EPS) and soluble microbial products (SMP) – proteins, polysaccharides, humic-like substances and other cell- or hydrolysis-derived compounds – can adsorb on membrane surfaces, constrict or block pores and promote gel-layer formation [4–6]. Because hydrolysis usually limits the rate of anaerobic digestion, sludge is often pretreated before digestion [7], and this pretreatment changes the rheology, particle-size distribution and soluble-organic content of the digestate that later reaches the membranes. Existing reviews usually treat digestate management, pretreatment, membrane nutrient recovery and fouling separately, and few follow how upstream choices carry through to flux, fouling, scaling and energy demand.

This contribution presents the main findings of our recent review [1], which addresses that gap by (i) relating pretreatment-induced changes in digestate properties to membrane behavior, (ii) compiling reported performance indicators for membrane options applied to real digestate-type streams, and (iii) identifying the fouling, scaling, energy and reporting constraints that currently limit scale-up.

Review methodology

The work was prepared as a structured narrative review. Web of Science, Scopus and ScienceDirect were searched, with Google Scholar and the reference lists of key papers used as supplementary sources, covering 2000 to June 2026 with emphasis on studies published from 2010 onward. Search strings combined feedstock terms (e.g., sludge digestate, liquid fraction of digestate, digested sludge centrate) with membrane terms (MF, UF, NF, RO, ED, BMED, MD) and outcome terms (nutrient, ammonium, phosphorus and potassium recovery, volatile fatty acids, fouling, scaling) using Boolean operators. Studies reporting quantitative indicators – permeate flux, recovery, fouling resistance, solubilization, particle-size change or specific energy consumption – were prioritized, and pilot- and full-scale data were preferred where available. Non-peer-reviewed sources were used only for regulatory and market context. Because feeds, operating conditions and performance metrics differ widely between studies, results were not pooled statistically; reported trends, mechanisms and performance ranges were compared instead, and quantitative values were tabulated with their metric type and scale.

Results and discussion

Pretreatment effects on digestate properties

Pretreatment disrupts flocs and EPS networks, often lowering the yield stress and consistency index of the Herschel–Bulkley model and thereby improving pumping and mixing. Improved bulk rheology does not, however, guarantee improved separability, because membrane performance is often limited by colloidal and soluble-biopolymer loading rather than by viscosity [1,6]. Thermal hydrolysis (commonly around 150–170 °C under pressure, followed by rapid decompression) is frequently associated with some of the largest viscosity reductions and generally improves dewaterability [8], but it also moves organic matter into the liquid phase: in thermally pretreated secondary sludge, about 30% of the particulate organic matter and 34% of the volatile solids fed were shifted to the liquid fraction [9]. At high severity, colored and more refractory melanoidin-like compounds can form [10], adding to the organic load on NF/RO polishing.

Microwave conditioning shows the clearest particle-size trade-off. In waste activated sludge treated at 80 °C for 5 min, soluble COD increased from 88.5 to 2380 mg/L, d_{50} decreased from 228 to 44.6 μm , d_{90} from 368 to 72.8 μm , and sludge filter resistance rose from 1.02×10^{13} to 2.15×10^{14} m/kg [11]. Although measured before digestion, these data show how severe disintegration can move the dominant resistance from largely reversible cake filtration toward more persistent pore-scale deposition by fines; MW pretreatment should therefore be paired with an upstream MF/UF barrier or equivalent solids management before tighter membranes. Alkaline treatment ($\text{pH} \approx 10\text{--}12$) raises ionic strength and the precipitation potential of carbonate and phosphate minerals, whereas controlled under-stoichiometric ozonation increased UF flux of digestate by about 50–80% [12]; overdosing, however, can fragment organics and damage polymeric membranes. Combined pretreatments can intensify these effects: ultrasonic–alkaline treatment increased the fraction of organics above 300 kDa from 7.8% to 42.3% [13], a macromolecular fraction closely related to gel-layer formation, adsorption and pore blocking. Most of these pretreatment data, however, come from raw or thickened sludge rather than digestate liquors.

Membrane processes and reported performance

The behavior of pressure-driven membranes on digestate can be interpreted with the resistance-in-series model and the concentration-polarization (CP) relation [6,14]:

$$J = \Delta P / [\mu (R_m + R_c + R_f + R_{cp})], \quad C_w = C_b \exp(J/k) \quad (1)$$

where R_m , R_c , R_f and R_{cp} are the membrane, cake, pore-blocking/adsorption and polarization resistances, and k is the mass-transfer coefficient. Lower viscosity helps hydraulics, but more soluble biopolymers and fines increase R_f and CP-driven gel formation, which is why conservative flux targets relative to a system-specific critical flux are typically decisive for stable operation [14]. In practical applications (Figure 1), MF/UF serve as front-end clarification, NF acts as an intermediate concentrator, and RO provides final refining for reusable water. Selective ED and BMED are placed after clarification to recover ionic nutrients or generate acid and base, and MD can use low-grade heat (50–90 °C) available from combined heat and power units for ammonia recovery [1,3].

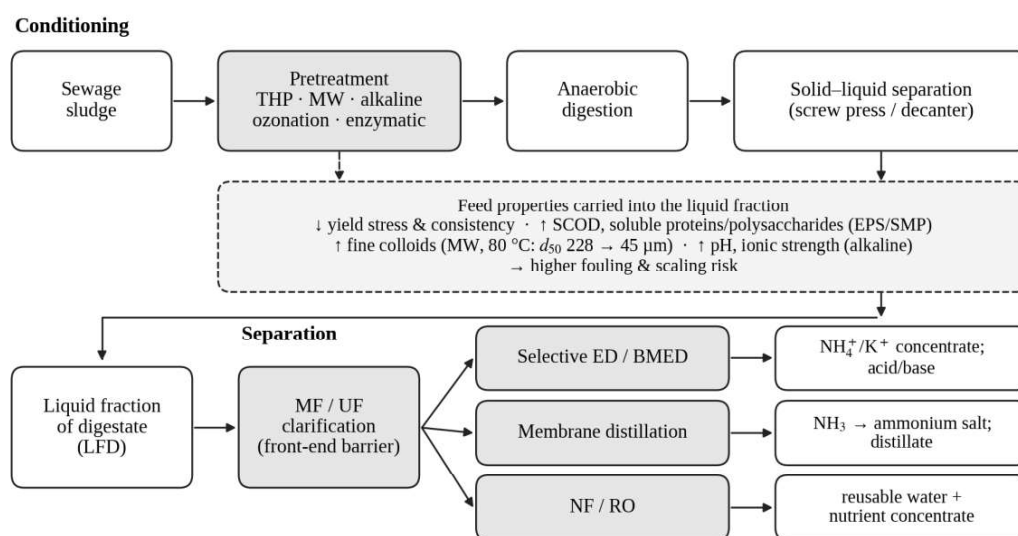


Figure 1. Conditioning-to-separation pathway for membrane-based digestate valorization; downstream stages may be used alone or in series, e.g., UF–selective ED–RO (schematic summary based on [1])

Representative indicators are compiled in Table 1. Among the pressure-driven examples, UF showed the highest real-feed flux, while NF and RO/ULPRO (ultra low-pressure RO) gave lower initial fluxes, in line with higher selectivity and greater susceptibility to CP, organic fouling and scaling. MD flux is thermally driven and ED performance is expressed through removal, recovery and energy, so these values are not ranked against hydraulic flux. Ammonium is the most consistently recoverable or removable target, particularly through selective ED, BMED and MD-based ammonia recovery. Phosphate behavior is route-dependent: selective ED mobilizes only part of the phosphate into a liquid product [15], whereas full-scale pressure-driven cascades remove most phosphorus upstream of RO into solid or concentrate fractions [16,17], so phosphate removal should not be equated with recovery.

Fouling, scaling and energy constraints

Fouling remains the main technical limitation. EPS proteins and polysaccharides form cohesive deposits and gel-like layers, dissolved and colloidal SMP intensify pore constriction, higher fractions of fine flocs are associated with denser cake layers, and elevated pH and CP at the membrane surface favor precipitation of struvite and calcium carbonate, particularly in NF and RO [1,6]. Mitigation is best framed as a combination of staged clarification, feed conditioning

(oxidation or pH control where appropriate), conservative flux relative to the critical flux and hydrodynamic enhancement, e.g., vibratory shear-enhanced processing. Digestate-specific energy data are concentrated in electro-driven processes: about 0.44 kWh/m³ at ~93% total ion removal and 0.24–15.2 kWh/kg N depending on the removal target in laboratory ED [18], and 4.9 ± 1.5 kWh/kg N in pilot ED on digester centrate [19]. Specific thermal energy for MD on real post-digestion digestate and comparable kWh/m³ values for pressure-driven digestate treatment are not consistently reported, so these are reporting gaps rather than evidence of favorable or unfavorable energetics. Because electrical, thermal and pressure-driven energy metrics are physically distinct, they should be reported by driving force rather than ranked together.

Table 1. Representative indicators reported for membrane treatment of real digestate-type streams (metric types differ and are not directly comparable across rows; *scale given where reported in [1])

Process	Feed; scale*	Reported indicator	Ref.
UF (PES, 5–50 kDa)	Swine-manure digestate	Flux ≈ 60 L m ⁻² h ⁻¹ (3 bar, 25 °C)	[20]
NF (NF90) / ULPRO (XLE)	Liquid digestate	Initial flux ≈ 27 / ≈ 20 L m ⁻² h ⁻¹ (5 bar)	[21]
MD	Anaerobic digestate; lab	Vapor flux ≈ 5.5 L m ⁻² h ⁻¹ (70 °C); 40% water recovery	[22]
UF–selective ED–RO	Digested sludge liquid fraction; pilot	Clean-water recovery 38% → 88%; permeate TDS 869.0 → 10.3 mg/L	[23]
Selective ED	Digested sludge liquor; pilot	>95% NH ₄ ⁺ and K ⁺ recovery; $\approx 55\%$ PO ₄ ³⁻	[15]
ED	Swine digestate; lab	$\approx 93\%$ total ion removal at 0.44 kWh/m ³	[18]
Vacuum MD	Liquid digestate; lab	Ammonia removal fraction >0.85	[24]
UF–RO cascade	Co-digestion digestate; full scale	>99% of P removed before RO; RO permeate 48% of feed	[17]

Conclusion

Membrane-based valorization of sludge digestate is technically promising, but its outcome depends strongly on upstream conditioning: pretreatment that improves digestion and rheology can simultaneously raise the soluble-biopolymer, fine-colloid and scaling-ion load that governs membrane fouling. Hybrid trains in which MF/UF protect selective ED/BMED, MD or NF/RO stages, operated at conservative flux relative to the critical flux, are currently the most defensible configuration. Progress toward full-scale application will depend on standardized, condition-explicit reporting of flux, recovery, rejection and energy; on long-term pilot operation with real digestate; and on measuring pretreatment severity and membrane fouling on the same feed rather than inferring the link across separate studies.

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