APPLICATION AND EFFICIENCY OF MEMBRANE BIOREACTOR TECHNOLOGY IN ADVANCED WASTEWATER TREATMENT

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Annotation. Aholi sonining tez sur'atlar bilan o'sishi va sanoat korxonalari sonining ko'payishi bilan suvga bo'lgan talab keskin o'sib bormoqda, bu esa qayta foydalanish uchun yuqori sifatli tozalangan oqava suvlarni talab qiladi. Biologik tozalashni membranani filtrlash bilan birlashtirgan membrana bioreaktori (MBR) bir vaqtning o'zida ushbu muammolarni hal qilish uchun eng samarali texnologiyalardan biri ekanligini isbotladi. MBR tizimlari organik va noorganik ifloslantiruvchi moddalarni yuqori darajada samarali ravishda olib tashlaydi. An'anaviy faollashtirilgan loy (CAS) usuli bilan solishtirganda - faollashtirilgan loy (mikroorganizmlarni o'z ichiga olgan biomassa) bilan aeratsiya tankida biologik parchalanish va keyin ikkilamchi tindirgichda ajratish - MBR ko'plab afzalliklarga ega va shahar va sanoat oqava suvlarini tozalashda keng qo'llaniladi. Ikkilamchi tozalashda ham, MBRda ham asosiy maqsad faollashtirilgan loyni tozalangan oqava suvdan samarali ajratishdir.

Kalit so'zlar: membrana bioreaktori, oqava suvlarni tozalash, suvni tozalash, biologik tozalash, membranani ajratish, membranani ifloslantirish

Аннотация. В связи с быстрым ростом населения и увеличением числа промышленных предприятий резко возрастает спрос на воду, что обуславливает необходимость получения высококачественных очищенных сточных вод, пригодных для повторного использования. Мембранный биореактор (МБР), сочетающий биологическую очистку с мембранной фильтрацией, доказал свою эффективность как одна из наиболее действенных технологий для одновременного решения этих задач. Системы МБР эффективно удаляют как органические, так и неорганические загрязнители в высокой степени. По сравнению с традиционным методом активного ила (CAS), включающим биологическую деградацию активного ила (биомассы, содержащей микроорганизмы) в аэрационном резервуаре с последующим отделением во вторичном отстойнике, мембранный биореактор (МБР) обладает многочисленными преимуществами и широко применяется в очистке муниципальных и промышленных сточных вод. Основная цель как вторичного отстойника, так и МБР — эффективное отделение активного ила от очищенных сточных вод.

Ключевые слова: мембранный биореактор, очистка сточных вод, очистка воды, биологическая очистка, мембранное разделение, загрязнение мембран.

Abstract. With the rapid growth of population and the increasing number of industrial enterprises, water demand is rising sharply, necessitating high-quality treated wastewater suitable for reuse. The **membrane bioreactor (MBR)**, which integrates biological treatment with membrane filtration, has proven to be one of the most effective technologies for simultaneously addressing these challenges. MBR systems efficiently remove both organic and inorganic contaminants to a high degree. Compared to the conventional activated sludge (CAS) method—involving biological degradation by activated sludge (biomass containing microorganisms) in an aeration tank followed by separation in a secondary clarifier—MBR offers numerous advantages and is widely applied in municipal and industrial wastewater treatment. The primary objective in both secondary clarification and MBR is the effective separation of activated sludge from the treated effluent.

Keywords: membrane bioreactor, wastewater treatment, water purification, biological treatment, membrane separation, membrane fouling

Introduction.

The escalating global population and proliferation of industrial facilities are generating severe ecological issues while dramatically increasing the demand for water resources. Considering the current state of water supplies, introducing innovative solutions for managing water cycles in public and industrial sectors is essential. Sustainable technologies that account for the true value of water are increasingly vital. In this context, advanced treatment and reuse of wastewater for industrial processes and irrigation represent a highly valuable approach [1-3].

One prominent alternative for wastewater treatment is the **membrane bioreactor (MBR)**, which enhances biological treatment efficiency by combining it with membrane filtration. Biomass degradation occurs within the bioreactor, while microorganisms are separated from the purified water via membrane modules. Over the past two decades, MBR technology has gained substantial attention for producing high-quality effluents and is now recognized as a mature solution in wastewater treatment [4-7].

The first MBR was introduced in 1969 by Smith and colleagues under the Dorr-Oliver research program [8,9]. The goal was to treat wastewater from the Sandy Hook plant in Connecticut, USA, at high quality for a half-year period [10]. This pioneering work combined activated sludge treatment with ultrafiltration membrane technology, replacing conventional sedimentation tanks with membrane modules for solid-liquid separation [11]. However, due to high energy costs and membrane fouling challenges at that time, the widespread adoption of MBR technology was initially limited [12].

MBR technology integrates membrane filtration processes, such as microfiltration or ultrafiltration, with biological wastewater treatment through the

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activated sludge process [13]. This combination offers several significant advantages compared to conventional activated sludge systems, including higher effluent quality, reduced footprint, enhanced removal of suspended solids and pathogens, and elimination of secondary clarifiers [14,15]. The membrane acts as a physical barrier that retains biomass within the bioreactor while allowing treated water to pass through, resulting in complete retention of bacteria and suspended solids [16].

Results and Discussion. An ultrafiltration membrane was installed externally as a substitute for the secondary clarifier, separating treated water from activated sludge. Although this side stream configuration yielded excellent effluent quality, high energy consumption and membrane fouling limited its widespread commercialization at the time.

To overcome these limitations, Yamamoto and colleagues developed a new configuration in 1989: hollow-fiber membranes were submerged directly into the activated sludge aeration tank. Instead of an external pressurized pump, suction pressure was applied to the submerged membrane.

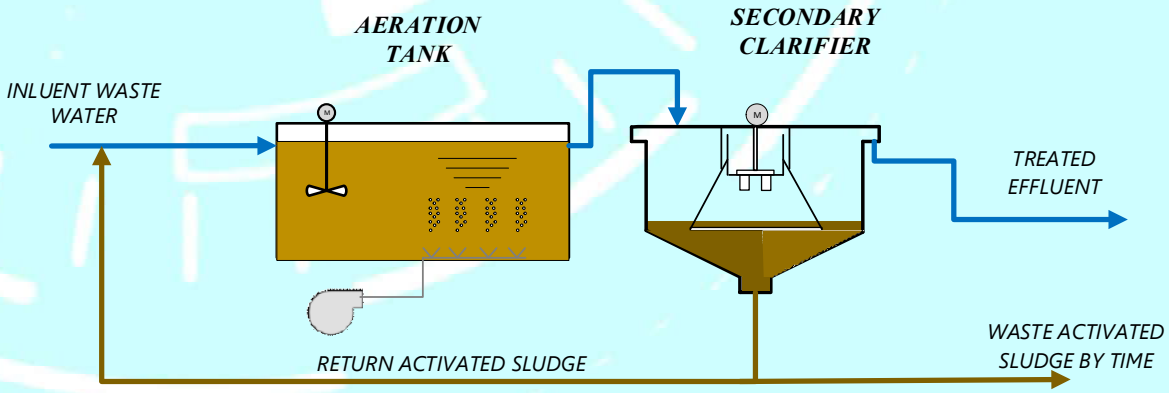


Figure 1. Schematic diagram of a conventional activated sludge (CAS) bioreactor showing the aeration tank and secondary clarifier.

Following the introduction of the submerged configuration, extensive research in the 1990s focused on reducing capital costs and producing large volumes of high-quality effluent. Key parameters investigated included membrane module geometry, pore size distribution, operating conditions to minimize fouling, and novel cleaning methods for fouled membranes.

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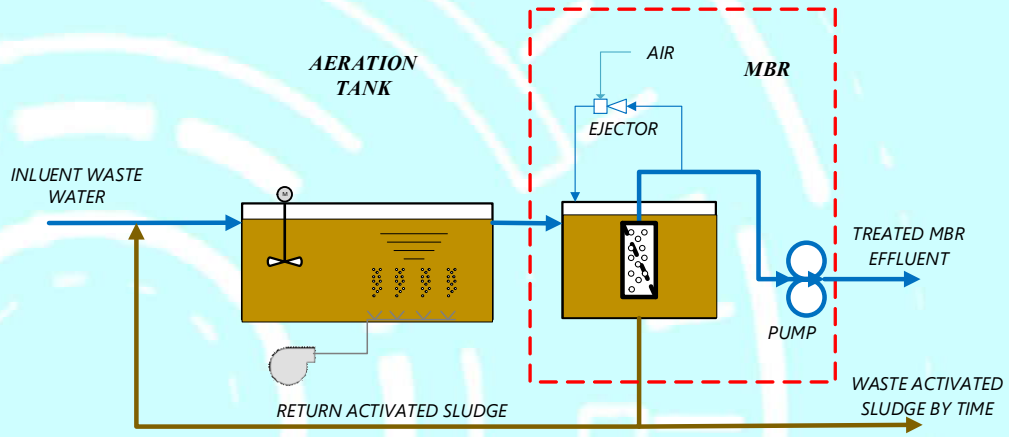


Figure 2. Schematic diagram of the submerged (immersed) membrane bioreactor (MBR) system.

Comparison of Conventional Activated Sludge (CAS) and MBR

The conventional activated sludge (CAS) process consists of two main stages: biological treatment in an aeration tank using activated microorganisms (sludge), followed by separation of treated water from sludge in a secondary clarifier. Complete separation is challenging in the clarifier, allowing lighter fractions to escape with the effluent. In MBR, membranes with varying pore sizes enable nearly complete retention of activated sludge.

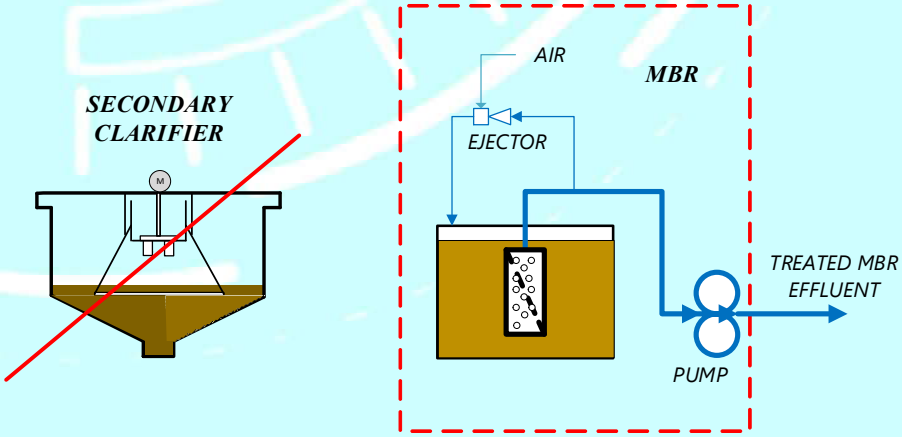


Figure 3. Visual comparison highlighting the key advantages of membrane bioreactors (MBR) over conventional secondary clarifiers in wastewater treatment plants.

The relative strengths and limitations of MBR compared to the conventional activated sludge (CAS) process are outlined in Table 1 (see Table 1 for a detailed cross-referenced analysis). The central objective of this manuscript is to equip readers with a foundational understanding of MBR fundamentals, followed by an exposition of cutting-edge advancements in alleviating membrane fouling—a pivotal determinant of operational efficacy. The narrative initiates with an overview of biological wastewater remediation and membrane-based separation principles. Subsequent segments delve into the fouling dynamics, spanning elementary causative factors to contemporary attenuation tactics implemented in

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the last decade. Thereafter, innovative MBR architectures are scrutinized extensively, grounded in peer-reviewed publications from recent years. The entrenched impediments to the progressive evolution of MBR paradigms, alongside pragmatic remedial frameworks, are delineated to guide future discourse. Microbial stoichiometric equations closely resemble chemical stoichiometric relationships and are essential for predicting biological process yields and oxygen/nutrient requirements. In microbial kinetics, the organic substrate simultaneously serves as both an energy source and a precursor for biomass synthesis. Thus, microorganisms not only catalyze degradation reactions but also proliferate as a direct product of the treatment process. The ratio of newly formed biomass to the amount of organic substrate consumed — commonly referred to as the biomass yield coefficient (Y, g MLVSS/g COD) — is strongly dependent on microbial community composition, electron donor type (e.g., acetic acid at the Uzbekistan GTL biotreatment facility, or glucose in analogous plants), terminal electron acceptor, and environmental conditions.

Balanced microbial stoichiometric equations enable precise quantification of the consumption or production rates of key components: primary electron donor, terminal electron acceptor (typically O_2 under aerobic conditions), macro- and micronutrients, biomass, and oxidized end-products (CO_2, H_2O, NO_3^-, etc.). However, stoichiometry alone cannot predict the rate at which the reaction proceeds.

Determining the actual reaction rate is critical for sizing the bioreactor volume, establishing the required biomass concentration, and estimating treatment efficiency under specific operating regimes.

For this reason, continuous monitoring of mixed liquor suspended solids (MLSS) kinetics is implemented in many modern facilities. At the Uzbekistan GTL Process Effluent Biotreatment Unit, for example, an online MLSS analyzer is installed on the return activated sludge (RAS) channel to provide real-time data for process control and kinetic model validation.

Bioreactor performance — including biomass production rate and residual substrate concentration in the effluent — as well as key design parameters such as reactor volume, are calculated by establishing mass-balance equations grounded in microbial kinetics. Microbial kinetics primarily focuses on the specific growth rate of microorganisms and the rate of organic substrate utilization.

MBR systems are primarily categorized into two configurations: submerged (immersed) and sidestream (external). In submerged MBRs, the most prevalent design for large-scale applications, membrane modules are placed directly within the aeration tank or a dedicated membrane tank.

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Table-1

Comparative Overview of MBR and CAS Systems

Aspect	MBR Strengths over CAS	MBR Limitations Relative to CAS	CAS Baseline Features
Effluent Purity	Exceptional: Achieves near-total retention of particulates, minimal TSS, reduced BOD/COD, and enhanced nutrient/pathogen removal; ideal for direct reuse	N/A	Adequate but inconsistent; often necessitates additional polishing steps
Spatial Requirements	Space-efficient: Reduced reactor sizing and elimination of clarifier infrastructure	N/A	Extensive: Demands larger footprints for sedimentation basins and ancillary structures
Biomass Management	Optimized: Extended SRT and elevated MLSS levels minimize surplus sludge generation	N/A	Elevated: Greater waste sludge volumes due to shorter retention cycles
Process Resilience	Robust: Superior tolerance to hydraulic/organic shocks; facilitates complete nitrification	Increased energy footprint for enhanced aeration and flux maintenance	Moderate: Prone to disruptions from poor settling or variable influent loads
Economic Considerations	N/A	Elevated upfront investments in membranes; higher ongoing costs for power and upkeep	Cost-effective at scale: Lower CAPEX/OPEX for conventional large installations

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Maintenance Challenges	N/A	Demands proactive fouling mitigation (e.g., intermittent backwashing, chemical dosing)	Simplified: Avoids membrane-related degradation or cleaning protocols

Filtration occurs under suction pressure, with the retained activated sludge, suspended solids, bacteria, and macromolecules recirculated via return activated sludge (RAS) channels. This recirculated sludge mixes with incoming wastewater at the inlet of the biological treatment system, undergoes biodegradation in the aeration tank (bioreactor), and then flows to the membrane zone for separation. This configuration significantly reduces energy consumption compared to sidestream systems (see Figure 2 for the schematic diagram of the submerged (immersed) membrane bioreactor (MBR) system).

The sidestream MBRs position the membrane modules externally, requiring high-pressure pumps to drive the mixed liquor through the membranes. This setup offers advantages in maintenance and handling challenging feeds but incurs higher energy costs due to pumping requirements.

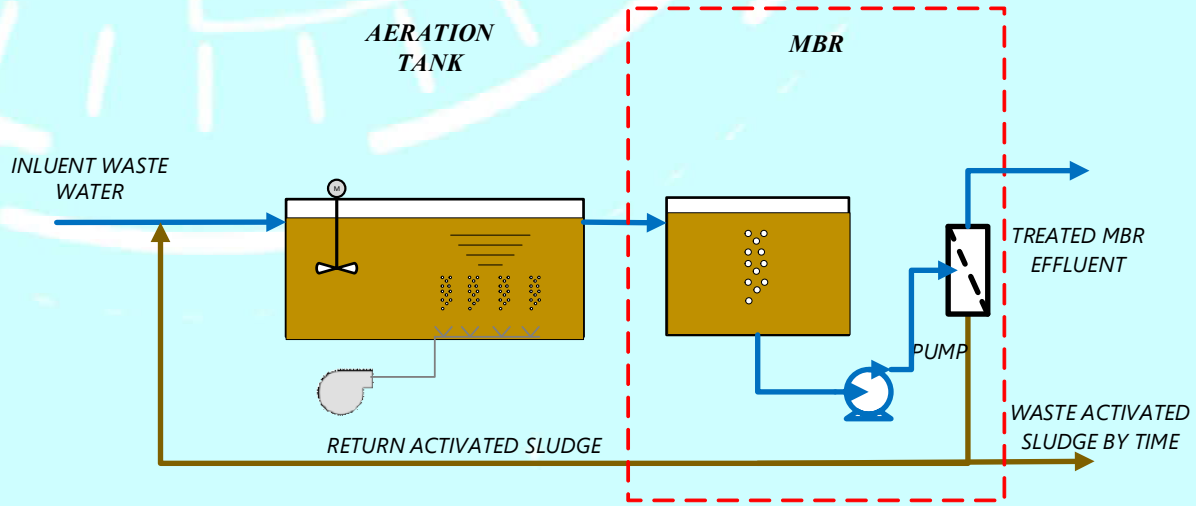


Figure 4. Schematic diagram of the sidestream (external) membrane bioreactor (MBR) system.

Conclusion. While membrane fouling and energy consumption remain the primary hurdles, ongoing innovations in materials science, process control, hybrid configurations, and anaerobic resource recovery are rapidly transforming MBRs into a technically mature, economically viable, and environmentally sustainable platform-one that is uniquely positioned to address 21 century water challenges and support the transition toward a circular water economy.

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