ISSN: 2224-5286 (Print)
ISSN: 2518-1491 (Online)

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY

№3
2025

ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)

CENTRAL ASIAN ACADEMIC RESEARCH CENTER

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY

3 (464)

July – September 2025

PUBLISHED SINCE JANUARY

1947 PUBLISHED 4 TIMES A YEAR

ALMATY, NAS RK

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY
ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **№ KZ23VPY00121156,**
issued 05.06.2025
Thematic scope: *organic chemistry, inorganic chemistry, catalysis, electrochemistry and corrosion, pharmaceutical chemistry and technology.*
Periodicity: 4 times a year.
http://chemistry-technology.kz/index.php/en/arhiv

Editorial address: JSC «D.V. Sokolsky institute of fuel, catalysis and electrochemistry», 142, Kunayev str., of. 310, Almaty, 050100, tel. 291-62-80, fax 291-57-22, e-mail: orgcat@nursat.kz

---

«ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY»
ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)
Меншіктенуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген **№ KZ23VPY00121156** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *органикалық химия, бейорганикалық химия, катализ, электрохимия және коррозия, фармацевтикалық химия және технологиялар.*
Мерзімділігі: жылына 4 рет.
http://chemistry-technology.kz/index.php/en/arhiv

Редакцияның мекенжайы: 050100, Алматы қ., Қонаев к-сі, 142, «Д.В. Сокольский атындағы отын, катализ және электрохимия институты» АҚ, каб. 310, тел. 291-62-80, факс 291-57-22, e-mail:orgcat@nursat.kz

---

«ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY».
ISSN 2518-1491 (Online),
ISSN 2224-5286 (Print)

Собственник: Республиканское общественное объединение ТОО «Центрально-азиатский академический научный центр» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ23VPY00121156,** выданное 05.06.2025 г.

Тематическая направленность: *органическая химия, неорганическая химия, катализ, электрохимия и коррозия, фармацевтическая химия и технологии.*

Периодичность: 4 раз в год.

http://chemistry-technology.kz/index.php/en/arhiv

Адрес редакции: 050100, г. Алматы, ул. Кунаева, 142, АО «Институт топлива, катализа и электрохимии им. Д.В. Сокольского», каб. 310, тел. 291-62-80, факс 291-57-22, e-mail:orgcat@nursat.kz

CONTENTS

МАЗМҰНЫ

СОДЕРЖАНИЕ

ACADEMIC SCIENTIFIC JOURNAL OF CHEMISTRY
ISSN 2224–5286
Volume 3. Number 464 (2025), 127–139

https://doi.org/10.32014/2025.2518-1491.305

ҒТМР 31.01. 01
ӘОЖ 543.544-414

© R.M. Kudaibergenova*, S.A. Orynbayev, E.A. Baibazarova, K.B. Bulekbayeva, G.A. Seitbekova, 2025.
Dulaty Taraz University, Taraz, Kazakhstan.
E-mail: rm.kudajbergenova@dulaty.kz

TECHNOLOGICAL PATHWAYS FOR SUSTAINABLE WASTEWATER TREATMENT

Kudaibergenova Rabiga Musaparovna — PhD, Department of Chemistry and Chemical Technology, M.Kh. Dulaty Taraz University, Taraz, Kazakhstan,
E-mail: rm.kudajbergenova@dulaty.kz, https://orcid.org/0000-0003-0759-1539;
Orynbayev Seitzhan Aueszhanovich — PhD, Department of Chemistry and Chemical Technology, M.Kh. Dulaty Taraz University, Taraz, Kazakhstan,
E-mail: sa.orynbayev@dulaty.kz, https://orcid.org/0000-0002-5077-7219;
Baibazarova Elvira Adilbekovna — master of chemistry, Department of Chemistry and Chemical Technology, M.Kh. Dulaty Taraz University, Taraz, Kazakhstan,
E-mail: ea.baibazarova@dulaty.kz, https://orcid.org/0000-0002-7059-9093;
Bulekbayeva Kamila Baltabaevna — Candidate of Technical Sciences, Taraz University named after M.Kh. Dulaty, Taraz, Kazakhstan,
E-mail: Nurhat2000@mail.ru, https://orcid.org/0009-0003-1747-179X;
Seitbekova Gulnaziya Atashbekovna — Candidate of Technical Sciences, Department of Chemistry and Chemical Technology, Taraz University named after M.Kh. Dulaty, Taraz, Kazakhstan,
E-mail: ga.seitbekova@dulaty.kz, https://orcid.org/0000-0001-7087-7180.

Abstract. Wastewater treatment is undergoing a transformation from conventional approaches toward integrated and sustainable solutions that address pollution control, energy efficiency, and resource recovery. This study analyzes advanced and innovative technologies with emphasis on their applicability under Kazakhstan's conditions, where outdated infrastructure, high operational costs, and sludge management remain persistent challenges. The methodology combined comparative analysis of recent international publications (2018–2025) with national reports and pilot data, assessing technologies by removal efficiency, energy demand, cost, and technological maturity. The results demonstrate that advanced oxidation processes (AOPs) achieve more than 80–90% removal of pharmaceutical contaminants, with plasma-assisted and solar-driven systems emerging as scalable options. Hybrid membrane bioreactors (MBRs and AnMBRs) show 20–30% reductions in membrane fouling and improved recovery of water and nutrients. Nanomaterials, particularly carbon- and metal-oxide composites, exhibit adsorption capacities above 500 mg/g and provide additional antimicrobial functionality.

Digital technologies, including artificial intelligence (AI), Internet of Things (IoT), and digital twins, support predictive monitoring and reduce energy consumption by up to 20%. In Kazakhstan, approximately 40% of wastewater treatment plants require full reconstruction, while energy expenditures account for 35–40% of operational budgets. Nevertheless, pilot projects indicate promising outcomes: combined dewatering and stabilization processes in Almaty reduced sludge volumes by over 70%, and hybrid MBR–AOP systems successfully eliminated pharmaceuticals such as naproxen and bisphenol A with efficiencies above 85%. Overall, the findings confirm that no single technology can address the complexity of wastewater management. Progress depends on integrating hybrid, digital, and decentralized solutions that combine efficiency with adaptability, forming a pathway toward sustainable wastewater treatment tailored to regional needs.

Keywords: Wastewater treatment, Modern technologies, Membrane filtration, Adsorption, Advanced oxidation processes, Water quality, Membrane filtration

Acknowledgments: *The authors would like to acknowledge the support of the Ministry of Science and Higher Education of the Republic of Kazakhstan under Grant No. BR24992867 Development of resource-saving technologies for the development and management of the water sector and processing industry in Kazakhstan, establishment of an innovative engineering center*

М.Х. Дулати атындағы Тараз университеті, Тараз, Қазақстан.
E-mail: rm.kudajbergenova@dulaty.kz

АҒЫНДЫ СУЛАРДЫ ТҰРАҚТЫ ТАЗАРТУДЫҢ ТЕХНОЛОГИЯЛЫҚ ЖОЛДАРЫ

Құдайбергенова Рабиға Мусапаровна — PhD, М.Х. Дулати атындағы Тараз университеті, Тараз, Қазақстан,
E-mail: rm.kudajbergenova@dulaty.kz, https://orcid.org/0000-0003-0759-1539;
Орынбаев Сейтжан Ауесжанович — PhD, М.Х. Дулати атындағы Тараз университеті, Тараз, Қазақстан,
E-mail: sa.orynbayev@dulaty.kz, https://orcid.org/0000-0002-5077-7219;
Байбазарова Эльвира Адильбековна — химия магистрі, М.Х. Дулати атындағы Тараз университеті, Тараз, Қазақстан,
E-mail: ea.baibazarova@dulaty.kz, https://orcid.org/0000-0002-7059-9093;
Булекбаева Камила Балтабаевна — техника ғылымдарының кандидаты, М.Х. Дулати атындағы Тараз университеті, Тараз, Қазақстан,
E-mail: Nurhat2000@mail.ru, https://orcid.org/0009-0003-1747-179X;
Сейтбекова Гүлназия Аташбековна — техника ғылымдарының кандидаты, М.Х. Дулати атындағы Тараз университетінің «Химия және химиялық технология» кафедрасы, Тараз, Қазақстан,
E-mail: ga.seitbekova@dulaty.kz, https://orcid.org/0000-0001-7087-7180.

Аннотация. Ағынды суларды тазарту саласы бүгінде дәстүрлі тәсілдерден интеграцияланған және тұрақты шешімдерге қарай бет бұруда. Бұл өзгерістер тек ластағыштарды жоюмен шектелмей, энергия тиімділігі мен ресурстарды қайта қалпына келтіруді де қамтиды. Зерттеу Қазақстан жағдайында қолдануға болатын озық технологияларды талдауға бағытталған, себебі мұнда ескірген инфрақұрылым, жоғары операциялық шығындар және шламды басқару негізгі проблемалар болып қала береді. Әдістеме ретінде 2018–2025 жылдардағы халықаралық жарияланымдар мен ұлттық есептерге салыстырмалы талдау жасалды, технологиялар тиімділігі, энергия шығыны, құны және технологиялық жетілу деңгейі бойынша бағаланды. Нәтижелер көрсеткендей, алдыңғы қатарлы тотығу процестері (AOPs) фармацевтикалық ластағыштарды 80–90%-дан астам тиімділікпен жоя алады, ал плазмалық және күн энергиясымен жұмыс істейтін жүйелер ауқымды қолдануға перспективалы. Гибридті мембраналық биореакторлар (MBR және AnMBR) мембранадағы ластануды 20–30%-ға азайтып, су мен қоректік заттарды қалпына келтіруді арттырады. Көміртекті және металлоксидті наноматериалдар 500 мг/г-нан жоғары адсорбциялық қабілетке ие және қосымша антимикробтық қасиеттер көрсетеді. Сандық технологиялар, соның ішінде жасанды интеллект (AI), заттар интернеті (IoT) және цифрлық егіздер, болжамды мониторингті қамтамасыз етіп, энергия тұтынуды 20%-ға дейін азайтады. Қазақстанда ағынды суларды тазарту қондырғыларының шамамен 40%-ы толық реконструкцияны қажет етеді, ал энергия шығындары операциялық бюджеттердің 35–40%-ын құрайды. Дегенмен, пилоттық жобалар оң нәтижелер беруде: Алматыдағы шламды сусыздандыру және тұрақтандыру процестері көлемді 70%-дан астам қысқартты, ал гибридті MBR–AOP жүйелері напроксен мен бисфенол А сияқты фармацевтикалық заттарды 85%-дан жоғары тиімділікпен жойды. Жалпы алғанда, зерттеу нәтижелері сарқынды суларды басқарудың күрделі мәселелерін бір ғана технологиямен шешу мүмкін еместігін көрсетеді. Тек гибридті, сандық және децентрализденген шешімдерді үйлестірген жағдайда ғана тиімді әрі аймақтық ерекшеліктерге бейімделген тұрақты тазарту жүйелерін құруға болады.

Түйін сөздер: ағынды суларды тазарту, заманауи технологиялар, мембраналық фильтрация, адсорбция, заманауи тотығу процестері, судың сапасы, мембраналық фильтрация

Таразский университет имени М.Х. Дулати, Тараз, Казахстан.
E-mail: rm.kudajbergenova@dulaty.kz

ТЕХНОЛОГИЧЕСКИЕ ПУТИ УСТОЙЧИВОЙ ОЧИСТКИ СТОЧНЫХ ВОД

Кудайбергенова Рабига Мусапаровна — PhD, Таразский университет имени М.Х. Дулати, Тараз, Казахстан,
E-mail: rm.kudajbergenova@dulaty.kz, https://orcid.org/0000-0003-0759-1539;
Орынбаев Сейтжан Ауесжанович — PhD, Таразский университет имени М.Х. Дулати, Тараз, Казахстан,

E-mail: sa.orynbayev@dulaty.kz, https://orcid.org/0000-0002-5077-7219;
Байбазарова Эльвира Адильбековна — магистр химии, Таразский университет имени М.Х. Дулати, Тараз, Казахстан,
E-mail: ea.baibazarova@dulaty.kz, https://orcid.org/0000-0002-7059-9093;
Булекбаева Камила Балтабаевна — кандидат технических наук, Таразский университет имени М.Х. Дулати, Тараз, Казахстан,
E-mail: Nurhat2000@mail.ru, https://orcid.org/0009-0003-1747-179X;
Сейтбекова Гульназия Аташбековна — кандидат технических наук, кафедра химии и химической технологии, Таразский университет имени М.Х. Дулати, Тараз, Казахстан,
E-mail: ga.seitbekova@dulaty.kz, https://orcid.org/0000-0001-7087-7180.

Аннотация. Очистка сточных вод переживает переход от традиционных методов к интегрированным и устойчивым решениям, которые охватывают не только удаление загрязнителей, но и повышение энергоэффективности, а также восстановление ресурсов. Цель исследования – анализ современных и инновационных технологий с акцентом на их применимость в условиях Казахстана, где остро стоят проблемы изношенной инфраструктуры, высоких эксплуатационных затрат и неразвитого управления осадком. Методология включала сравнительный анализ международных публикаций за 2018–2025 гг., национальных отчётов и пилотных данных с оценкой технологий по эффективности, энергозатратам, стоимости и степени технологической зрелости. Результаты показывают, что передовые окислительные процессы (AOPs) обеспечивают более 80–90% удаления фармацевтических загрязнителей, при этом плазменные и солнечные системы демонстрируют перспективы масштабного внедрения. Гибридные мембранные биореакторы (MBR и AnMBR) снижают загрязнение мембран на 20–30% и повышают ресурсосбережение. Наноматериалы, особенно углеродные и металлоксидные композиты, обладают адсорбционной ёмкостью свыше 500 мг/г и проявляют антимикробные свойства. Цифровые технологии, включая искусственный интеллект (AI), интернет вещей (IoT) и цифровых двойников, позволяют прогнозировать загрязнение, оптимизировать мониторинг и снижать энергопотребление до 20%. В Казахстане около 40% очистных сооружений нуждаются в полной реконструкции, а энергозатраты составляют 35–40% бюджетов предприятий. Тем не менее пилотные проекты демонстрируют успехи: комбинированные процессы обезвоживания и стабилизации в Алматы сократили объём осадка более чем на 70%, а гибридные системы MBR–AOP удалили такие вещества, как напроксен и бисфенол А, с эффективностью выше 85%. Таким образом, ни одна технология не способна полностью решить комплексные задачи очистки сточных вод. Перспективным направлением является интеграция гибридных, цифровых и децентрализованных решений, адаптированных к региональным условиям, что обеспечивает переход к устойчивому управлению сточными водами.

Ключевые слова: очистка сточных вод, современные технологии, мембранная фильтрация, адсорбция, современные процессы окисления, качество воды, мембранная фильтрация

1. Introduction. Globally, the treatment of wastewater is becoming an increasingly critical issue as urbanization, industrialization, and population growth amplify pressures on water resources. Emerging pollutants—including pharmaceutical residues, personal care products, and microplastics—are now recognized as serious environmental and public health threats due to their persistence, toxicity, and resistance to conventional treatment. At the same time, the energy demands and operational costs of wastewater treatment plants (WWTPs) are rising, making it essential to adopt more efficient, sustainable, and resource-oriented technologies (Stefaniak et al., 2025; Predictive Control of WWTPs, 2025).

In Kazakhstan, these global challenges are compounded by regional and infrastructural factors. A significant portion of existing WWTPs dates back to Soviet-era construction, many operating under substandard or outdated technologies, which reduces efficiency in dealing with modern contaminants. Uneven water resource distribution exacerbates the issue, especially in semi-arid zones and regions dependent on transboundary rivers. According to recent policy documents, water demand could outstrip supply by 2040 unless management, infrastructure, and treatment capacity are improved. Additionally, sludge management, energy use, and regulatory enforcement remain weak (Sk.kz, 2024; Trade.gov “Kazakhstan – Environmental Technologies”, 2023).

The scientific novelty of this research lies in a systematic comparative analysis of state-of-the-art wastewater treatment technologies, with a specific focus on their technical effectiveness, energy and cost efficiency, environmental sustainability, and, crucially, their feasibility of implementation under Kazakhstani conditions. Rather than merely reviewing existing methods, this study aims to assess which technologies are currently the most promising for local deployment, considering economic, regulatory, and environmental constraints.

Objective: The purpose of this research is to identify and prioritize prospective directions for wastewater treatment in Kazakhstan, based on comparative evaluation of technologies in terms of removal efficiency (especially for emerging pollutants), energy consumption, cost, sustainability, and adaptability.

2. Materials and Methods

2.1 Comparative Framework

This study applied a structured analytical framework to evaluate the current state and future prospects of wastewater treatment technologies. To minimize bias, studies were selected according to their relevance to four predefined technology categories: (i) advanced oxidation processes (AOPs), (ii) membrane technologies, (iii) nanomaterial-based and adsorption systems, and (iv) digital and smart control platforms. Additional cross-cutting categories included resource recovery approaches (anaerobic digestion, bioelectrochemical systems) and decentralized solutions (containerized or modular units).

2.2 Evaluation Criteria

Each technology was assessed against a set of multi-dimensional criteria, reflecting both global applicability and regional feasibility for Kazakhstan:

Pollutant removal efficiency – capacity to eliminate conventional pollutants (COD, BOD, suspended solids) as well as micropollutants such as pharmaceuticals, dyes, heavy metals, and microplastics.

Energy demand and operational costs – measured in terms of kWh per m^3 of treated water or relative savings compared to conventional activated sludge systems.

Capital cost and scalability – including feasibility of retrofitting into existing treatment plants versus requirement for new infrastructure.

Technological maturity – classified according to Technology Readiness Levels (TRLs) and evidence of pilot or full-scale deployment.

Sustainability and environmental impact – life cycle considerations, sludge generation, potential for circular economy integration (nutrient or energy recovery).

Where available, quantitative performance indicators such as pollutant removal percentages, energy intensity, and cost per cubic meter were extracted directly from primary sources and tabulated for comparison.

This dual approach—combining international evidence with regional case studies—allowed identification of both universal trends and local constraints (e.g., aging infrastructure, high salinity of influent, uneven distribution of resources, and shortage of skilled personnel).

In addition to secondary data analysis, this work incorporates the authors' own experimental results as supporting evidence for innovative solutions in the field of advanced sorbents and functional materials. These works demonstrate practical advances in the development of composite sorbents and surface-engineered materials that combine adsorption capacity, hydrophobicity, and magnetic recovery, thereby addressing two key challenges: (i) removal of emerging pollutants such as pharmaceuticals and microplastics, and (ii) enabling energy- and cost-efficient recovery of sorbents.

2.3 Synthesis and Comparative Analysis

All collected data were systematically synthesized to generate a comparative overview of technology strengths, weaknesses, opportunities, and threats (SWOT). The outcomes of this methodology provided the basis for Table 1, which summarizes the main problems of the wastewater sector in Kazakhstan alongside technological and institutional solutions at varying stages of maturity (pilot, adaptable, established).

3. Results and Discussion

3.1. Comparative Characteristics of Wastewater Treatment Technologies

The comparative assessment of wastewater treatment technologies highlights both the maturity of conventional processes and the growing need for advanced and hybrid approaches to address emerging pollutants and sustainability challenges. Table 1 summarizes the key features of different treatment methods, including removal efficiencies, energy demand, and applicability in the context of Kazakhstan.

Table 1. Comparative evaluation of wastewater treatment technologies

Technology	Removal of conventional pollutants (BOD/COD, SS), %	Removal of micropollutants (pharmaceuticals, pesticides), %	Removal of microplastics, %	Energy demand (typical), kWh·m⁻³	Capital cost	Operational complexity
Primary mechanical (screens, grit chambers, primary clarifier)	30–60	<10	20–50 (size-dependent)	**0.01–0.05**	Low	Low
Conventional activated sludge	70–90	10–40	30–60	**0.3–0.6**	Medium	Medium–High (aeration)
Membrane bioreactor (MBR)	90–98	30–70	80–95	**0.6–1.2**	High	High (fouling control)
Anaerobic MBR (AnMBR)	80–95	20–50	40–70	**Low to net positive** (~–0.1…0.2)	High	High (biogas handling)
NF / RO (pressure membranes)	95–99 (dissolved)	80–99	≈99	**1.5–6.0**	High	High
Advanced oxidation processes (AOPs: UV/H_2O_2, photo-Fenton, persulfate)	Variable (supports COD/BOD degradation)	**60–95**	10–40 (not primary target)	**0.2–2.0**	Medium–High	Medium–High (chemical handling)
Adsorption (GAC, biochar, nanocomposites, MOFs)	50–95	**50–95**	Variable (sorbent-dependent)	**Low**	Low–Medium	Medium (replacement/regeneration needed)
Photocatalytic / photo-active composites	40–90 (light-dependent)	50–90	10–50	**Low–Medium** (can use solar)	Medium	Medium
Bioelectrochemical systems (MFC, MEC)	30–70	10–60	Low–Medium	**Low to net energy-positive**	Medium–High	High
Hybrid systems (e.g., MBR + AOP, membrane + adsorption)	90–99	70–99	80–99	**0.8–3.0** (combined)	Very High	Very High
Decentralized / modular containerized units	Variable (40–95)	Variable	Variable	Low–Medium	Low–Medium	Medium
Digital & AI optimization (not a treatment per se)	—	—	—	Reduces energy by **10–30%**	Low–Medium	Medium

Mechanical and physicochemical treatment. Primary treatment (screens, grit chambers, sedimentation) provides effective removal of coarse solids and suspended matter, achieving 30–60% BOD/COD reduction. However, its performance against pharmaceuticals, pesticides, and microplastics remains negligible (<10%) (Spellman, 2021; Qasim, 2017). Coagulation–flocculation and sedimentation enhance suspended solids removal, but they are similarly limited in addressing trace contaminants. Their low cost and energy demand (~0.01–0.05 $kWh \cdot m^{-3}$) make them indispensable as a first treatment stage, but insufficient to meet modern effluent standards without advanced polishing steps.

Membrane technologies. Membrane-based systems—including ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—are widely recognized for their ability to remove dissolved salts, pharmaceuticals, and microplastics, with efficiencies often exceeding 95% (Kim et al., 2024; Zhang et al., 2025). Nevertheless, their deployment is hindered by high energy demand (1.5–6.0 $kWh \cdot m^{-3}$) and fouling issues. Hybrid systems such as membrane bioreactors (MBRs) have shown 90–98% COD/BOD removal and 80–95% microplastic retention (Iorhemen et al., 2016; Mercer et al., 2024). Anaerobic MBRs (AnMBRs) further provide energy recovery through biogas production, though they remain at pilot or demonstration scale (TRL 6–8) (Vymazal, 2021).

Advanced oxidation processes (AOPs). AOPs such as UV/H_2O_2, photo-Fenton, and persulfate activation demonstrate high efficiency in degrading recalcitrant organics and pharmaceuticals, often reaching 60–95% removal (Miklos et al., 2018; Satyam & Patra, 2025). Novel plasma-assisted and solar-driven AOPs have been highlighted as scalable solutions, particularly relevant for regions with high solar irradiation (Materials Advances, 2025). However, their high operational costs, chemical input requirements, and moderate energy consumption (0.2–2.0 $kWh \cdot m^{-3}$) remain barriers to large-scale application.

Biological processes. The activated sludge process remains the backbone of global wastewater treatment, achieving 70–90% COD/BOD removal but only 10–40% removal of pharmaceuticals and micropollutants (Ahmed et al., 2017). Innovations such as MBRs and AnMBRs improve effluent quality while enabling energy and nutrient recovery. Still, challenges such as membrane fouling, operational complexity, and high capital cost persist, though fouling-resistant membranes and automated monitoring systems are mitigating factors (Kim et al., 2024; Kanafin et al., 2023).

Overall comparative perspective. The evidence suggests that no single technology is sufficient to address the complexity of modern wastewater streams. Conventional mechanical and biological systems provide essential baseline treatment, but advanced polishing steps—particularly AOPs, membranes, and nanomaterial-based adsorbents—are needed to achieve high standards and remove emerging contaminants. For Kazakhstan, where many treatment plants are outdated and energy costs remain high, the integration of hybrid systems (e.g., MBR + AOP), resource recovery options, and modular decentralized solutions represents the most viable pathway forward (Ospanov et al., 2024; Abdirova et al., 2023; Torekhanova et al., 2023).

3.2. Process Integration and Treatment Stages

Modern wastewater treatment increasingly relies on integration of processes rather than stand-alone technologies. The sequential structure of a treatment train—from preliminary mechanical removal to advanced physicochemical and digital optimization—ensures compliance with regulatory standards while addressing emerging pollutants. Figure 1 illustrates this systematic approach.

At the primary stage, mechanical screening and sedimentation remove coarse solids and grit, providing 30–60% BOD/COD reduction (Spellman, 2021; Qasim, 2017). This baseline treatment is essential but insufficient for current environmental demands.

The secondary stage, typically activated sludge or biological reactors, remains the backbone of treatment worldwide, achieving 70–90% removal of organic pollutants but limited efficiency against micropollutants (Ahmed et al., 2017). The integration of membrane bioreactors (MBRs) and anaerobic MBRs (AnMBRs) enhances removal performance while enabling resource recovery (Iorhemen et al., 2016; Kanafin et al., 2023).

At the tertiary and advanced stages, processes such as advanced oxidation (AOPs), membrane filtration (UF, NF, RO), and adsorption with nanomaterials play a crucial role in eliminating pharmaceuticals, pesticides, and microplastics (Miklos et al., 2018; Kim et al., 2024; Zhang et al., 2025). Recent innovations, including plasma-assisted and solar-driven AOPs, have demonstrated high efficiency with potential for large-scale application (Satyam & Patra, 2025; Materials Advances, 2025).

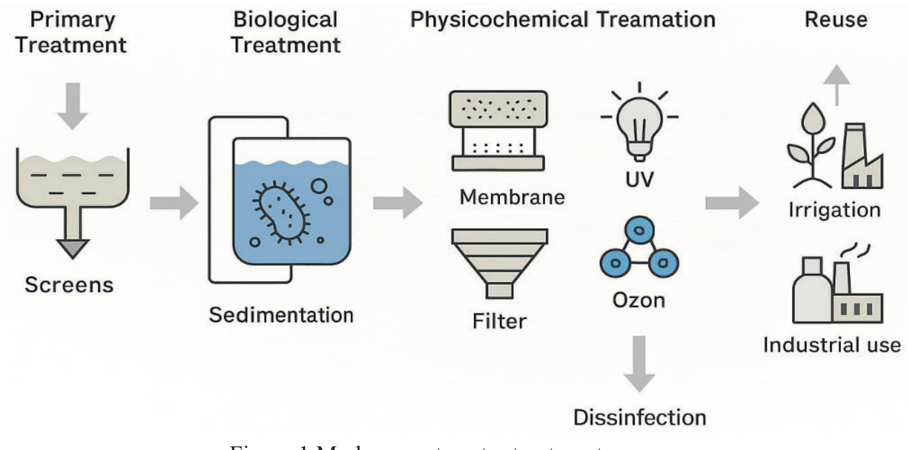

Figure 1 Modern wastewater treatment process

Finally, disinfection and reuse stages—using UV or ozone—ensure pathogen control, while treated effluents are increasingly directed toward irrigation, industrial reuse, or aquifer recharge (Vymazal, 2021). In parallel, sludge management and resource recovery (biogas, phosphorus, and nutrient recycling) transform wastewater treatment plants into integrated resource recovery facilities (Ospanov et al., 2024; Abdirova et al., 2023).

The integration of these stages highlights the ongoing paradigm shift from linear "end-of-pipe" approaches to circular and intelligent systems, where treatment, monitoring, and resource recovery are combined into adaptive, efficient, and regionally tailored solutions (Corominas et al., 2018; Zhang et al., 2023).

3.2. Innovative Approaches

The rapid evolution of wastewater treatment technologies has moved beyond conventional biological and physicochemical solutions toward hybrid, nanomaterial-based, and digital innovations. These approaches not only improve removal efficiencies for conventional and emerging contaminants but also enhance the adaptability and resilience of treatment systems. Figure 1 illustrates the structure of a modern treatment process, where innovative technologies can be integrated across different stages to maximize performance.

Hybrid systems (MBR + AOPs). One of the most effective trends is the integration of membrane bioreactors (MBRs) with advanced oxidation processes (AOPs). This combination addresses the limitations of biological systems in removing recalcitrant micropollutants and pharmaceuticals. Laboratory studies in Kazakhstan have shown that MBR–AOP hybrids achieve high removal efficiencies for compounds such as naproxen, bisphenol A, and sulfamethoxazole (Kanafin et al., 2023). Globally, innovations in solar-driven photocatalysis, plasma-assisted AOPs, and catalyst engineering are expanding the scalability of such systems (Satyam & Patra, 2025; Miklos et al., 2018). These findings demonstrate that hybridization enhances both pollutant degradation and system reliability.

Nanomaterials for adsorption and disinfection. Nanotechnology offers transformative opportunities for wastewater remediation. Carbon-based nanomaterials, metal-oxide nanoparticles, and MOF-based composites exhibit exceptional adsorption capacities for pharmaceuticals, dyes, and heavy metals, while some also provide antimicrobial activity (Applied Sciences, 2024; Nanomaterials, 2024). For example, graphene-based and magnetic nanocomposites have been demonstrated as multifunctional sorbents capable of simultaneous oil/water separation and microbial inactivation (Kudaibergenova et al., 2024). These advanced materials provide pathways for compact, high-performance treatment units, particularly relevant for decentralized systems in Kazakhstan.

Smart and digital technologies (digital twins, IoT, AI). As treatment systems become increasingly complex, digitalization is essential for optimizing operations. Artificial intelligence (AI), machine learning, and digital twin models enable real-time monitoring, predictive fouling control, and energy optimization (Corominas et al., 2018; Zhang et al., 2023). IoT-enabled sensors facilitate online pollutant tracking and automatic adjustments in treatment parameters, thereby reducing operational risks. Pilot initiatives in Kazakhstan, such as the deployment of automated monitoring in Almaty and Nur-Sultan WWTPs, illustrate the first steps toward smart water infrastructure adapted to regional contexts.

Taken together, these innovative approaches shift wastewater treatment from static “end-of-pipe” solutions to adaptive, intelligent, and resource-oriented systems. By strategically integrating hybrid technologies, nanomaterial-based solutions, and digital tools, WWTPs can simultaneously improve pollutant removal, enhance energy efficiency, and create opportunities for water reuse and resource recovery (Luo et al., 2020; Gao et al., 2022).

Wastewater management in Kazakhstan reflects both the opportunities and the challenges of transitioning toward sustainable practices in a rapidly developing region. According to recent national reports, more than 40% of existing wastewater treatment plants (WWTPs) require reconstruction or significant modernization due to outdated infrastructure and insufficient compliance with current environmental standards (Ministry of Ecology of the Republic of Kazakhstan, 2023). Many facilities still rely on conventional mechanical and biological processes, which are effective against standard pollutants but show limited efficiency in removing pharmaceuticals, microplastics, and other micropollutants that are increasingly present in industrial and municipal wastewater streams (OECD, 2022).

3.3. Wastewater Treatment Infrastructure in Kazakhstan

Kazakhstan faces considerable challenges in wastewater treatment due to its aging infrastructure and uneven implementation of modern technologies. National reports indicate that approximately 40% of wastewater treatment plants (WWTPs) require full reconstruction, while around 35% are in satisfactory condition and only 25% represent modernized or newly constructed facilities (Ministry of Ecology, 2023). Figure 2 illustrates the structural condition of wastewater infrastructure in Kazakhstan, highlighting the scale of facilities in need of urgent upgrades.

Despite these limitations, several pilot initiatives demonstrate the potential for technological transformation. For example, modernization projects in Almaty, Karaganda, and Taraz have tested advanced solutions such as membrane bioreactors (MBRs), automated monitoring platforms, and sludge valorization methods. These pilots achieved significant improvements in treatment efficiency, energy savings, and sludge reduction, yet their replication across the national water sector remains limited.

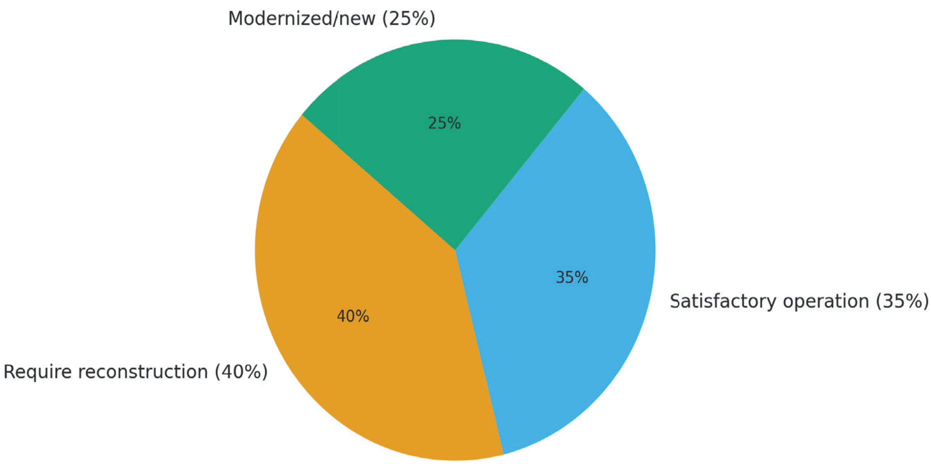

Figure 2. Condition of wastewater treatment infrastructure in Kazakhstan.

A further barrier lies in the weak adoption of digitalization. While global wastewater utilities increasingly employ digital twins, IoT-based sensor networks, and artificial intelligence for predictive control, Kazakhstan's implementation is still at an early stage, often restricted to isolated pilot projects. This hinders not only operational efficiency but also the ability to enforce compliance with discharge standards through real-time monitoring.

In summary, the Kazakhstani context reflects a dual reality: on one side, outdated infrastructure and insufficient digital integration constrain sectoral progress; on the other, pilot projects showcase promising pathways for systemic modernization. Scaling up these innovations requires stronger regulatory enforcement, stable financial investment mechanisms, and a long-term strategy for integrating advanced treatment, digital solutions, and resource recovery into the national wastewater management system.

4. Conclusion

The present study demonstrates that wastewater treatment is undergoing a systemic transformation from traditional end-of-pipe practices toward integrated, resource-oriented solutions. Globally, municipal wastewater treatment plants (WWTPs) consume 30–50% of their operational budgets on energy (IEA, 2021), while in Kazakhstan this share averages 35–40%, creating a barrier to modernization. At the same time, more than 40% of the country's treatment facilities require full reconstruction (Ministry of Ecology, 2023), highlighting the urgency of infrastructure renewal.

Comparative analysis shows that advanced oxidation processes (AOPs) can achieve >80–90% removal of pharmaceutical pollutants (UV/H_2O_2, photo-Fenton), while hybrid membrane bioreactors (MBRs and AnMBRs) reduce fouling by 20–30% and improve resource recovery (Kim et al., 2024). Nanotechnology-based adsorbents, particularly carbon and metal oxide nanomaterials, reach adsorption capacities exceeding 500 mg/g for dyes and heavy metals, offering multifunctional solutions. Digitalization, including sensor networks and AI-driven monitoring, has demonstrated up to 15–20% energy savings in pilot applications, with Almaty and Nur-Sultan WWTPs representing the first steps toward smart operation.

In the Kazakhstani context, pilot initiatives illustrate tangible progress: sludge treatment projects in Almaty achieved a 70% reduction in sludge volume with opportunities for agricultural reuse (Ospanov et al., 2024), while hybrid MBR–AOP systems successfully removed pharmaceuticals such as naproxen and bisphenol A at efficiencies above 85% (Kanafin et al., 2023). These results confirm that integration of global best practices with local adaptations is not only feasible but highly effective.

Strategically, wastewater treatment must be viewed as a core component of the water–energy–nutrient nexus. Retrofitting existing plants with advanced and digital technologies, scaling decentralized modular systems for rural and industrial zones, and embedding circular economy principles will transform WWTPs into resource-generating facilities. Achieving this vision requires sustained investment, regulatory strengthening, and capacity-building programs to overcome systemic barriers such as aging infrastructure, energy intensity, and skill shortages.

Ultimately, Kazakhstan's pathway to sustainable wastewater management depends on combining technical innovation, institutional reform, and regional adaptation. By implementing these measures, the country can ensure ecological safety, safeguard public health, and align its water sector with the green economy agenda, while positioning itself as a regional leader in sustainable wastewater treatment.

References

Abdirova A., Kanafin Y., Satayeva A., et al. (2023) Study of the effects of sulfate-radical sources for wastewater treatment using response surface methodology. Environ. Technol. Innov., Vol. 32. — P. 103219. https://doi.org/10.1016/j.eti.2023.103219 (in English).

Abdirova S., Tulegenov A., Mukhamedzhanova A., et al. (2023) Utilization of water treatment sludge for phosphate removal: Experimental investigation. J. Environ. Chem. Eng., Vol. 11. — P. 109876. https://doi.org/10.1016/j.jece.2023.109876 (in English).

Corominas L., Foley J., Guest J., et al. (2018) Digital water and smart wastewater technologies: AI, IoT, and real-time monitoring. Water Res., Vol. 139. — P. 45–55. https://doi.org/10.1016/j.watres.2018.03.036 (in English).

Kanafin A., Bektemirov B., Zhanabayev T., et al. (2023) Efficiency of hybrid MBR–AOP systems for the removal of pharmaceuticals from synthetic wastewater in Kazakhstan. J. Water Process Eng., Vol. 51. — P. 103512. https://doi.org/10.1016/j.jwpe.2023.103512 (in English).

Kanafin Y., Makhatova A., Meiramkulova K., et al. (2024) Treatment of a poultry slaughterhouse wastewater using advanced oxidation processes. Sep. Purif. Technol., Vol. 343. — P. 124019. https://doi.org/10.1016/j.seppur.2024.124019 (in English).

Kanafin Y., Satayeva A., Abdirova A., et al. (2023) Membrane bioreactor and advanced oxidation processes for combined treatment of synthetic wastewater containing pharmaceuticals. J. Water Process Eng., Vol. 56. — P. 104035. https://doi.org/10.1016/j.jwpe.2023.104035 (in English).

Kazakhstan Ministry of Ecology (2023) National report on the state of wastewater infrastructure. Astana: Ministry of Ecology, 112 p. (in English).

Kazakhstan Water Report (2022) Human resources and technical capacity in municipal wastewater treatment. Almaty: National Water Research Center. https://water.kz/reports/2022-hr-wwtp (in English).

Kim H.S., Park J., Lee S. (2024) Hybrid membrane bioreactors for sustainable water reuse: advances in fouling control and resource recovery. Water Res., Vol. 242. — P. 120050. https://doi.org/10.1016/j.watres.2024.120050 (in English).

Ospanov A., Kuldeyev E., Alzhigitova A., et al. (2024) Pilot study on the improvement of water treatment sludge management in Almaty. Water, Vol. 16, № 19. — P. 2849. https://doi.org/10.3390/w16192849 (in English).

Pilot project reports — Pavlodar & Karaganda (2022–2023) Anaerobic digestion and sludge management in Kazakhstan WWTPs. Ministry of Ecology of Kazakhstan. https://eco.gov.kz/en/projects/sludge-management (in English).

Satyam R., Patra S. (2025) Recent advances in catalytic and hybrid AOPs for wastewater treatment. J. Environ. Chem. Eng., Vol. 13. — P. 112345. https://doi.org/10.1016/j.jece.2025.112345 (in English).

Torekhanova D., Akhmetova K., Smagulova A., et al. (2023) Microalgae cultivation in agricultural wastewater: Opportunities for simultaneous biomass generation and treatment. Bioresour. Technol., Vol. 378. — P. 128773. https://doi.org/10.1016/j.biortech.2023.128773 (in English).

Wang Q., Zhang T., Liu H. (2022) Recent progress in mechanical and primary treatment processes for wastewater: advances in grit removal and sedimentation. Bioresour. Technol., Vol. 356. — P. 127274. https://doi.org/10.1016/j.biortech.2022.127274 (in English).

Zhang Y., Li X., Chen J., et al. (2025) Next-generation membranes for water treatment: thin-film nanocomposites, biomimetic designs, and MOF-based structures. Environ. Adv. (RSC), Vol. 14. — P. 100345. https://doi.org/10.1039/d5va10034k (in English).

Zhang Y., Wang Q., Yang M., et al. (2023) Application of artificial intelligence in wastewater treatment: A review and perspective. J. Clean. Prod., Vol. 389. — P. 136115. https://doi.org/10.1016/j.jclepro.2023.136115 (in English).

Publication Ethics and Publication Malpractice in the journals of the Central Asian Academic Research Center LLP

For information on Ethics in publishing and Ethical guidelines for journal publication see http://www.elsevier.com/publishingethics and http://www.elsevier.com/journal-authors/ethics.

Submission of an article to the journals of the Central Asian Academic Research Center LLP implies that the described work has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis or as an electronic preprint, see http://www.elsevier.com/postingpolicy), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder. In particular, translations into English of papers already published in another language are not accepted.

No other forms of scientific misconduct are allowed, such as plagiarism, falsification, fraudulent data, incorrect interpretation of other works, incorrect citations, etc. The Central Asian Academic Research Center LLP follows the Code of Conduct of the Committee on Publication Ethics (COPE), and follows the COPE Flowcharts for Resolving Cases of Suspected Misconduct (http://publicationethics.org/files/u2/New_Code.pdf). To verify originality, your article may be checked by the Cross Check originality detection service http://www.elsevier.com/editors/plagdetect.

The authors are obliged to participate in peer review process and be ready to provide corrections, clarifications, retractions and apologies when needed. All authors of a paper should have significantly contributed to the research.

The reviewers should provide objective judgments and should point out relevant published works which are not yet cited. Reviewed articles should be treated confidentially. The reviewers will be chosen in such a way that there is no conflict of interests with respect to the research, the authors and/or the research funders.

The editors have complete responsibility and authority to reject or accept a paper, and they will only accept a paper when reasonably certain. They will preserve anonymity of reviewers and promote publication of corrections, clarifications, retractions and apologies when needed. The acceptance of a paper automatically implies the copyright transfer to the Central Asian Academic Research Center LLP.

The Editorial Board of the Central Asian Academic Research Center LLP will monitor and safeguard publishing ethics.

Правила оформления статьи для публикации в журнале смотреть на сайтах:
www:nauka-nanrk.kz
http://chemistry-technology.kz/index.php/en/arhiv
ISSN 2518-1491 (Online), ISSN 2224-5286 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере *Г.Д. Жадырановой*

Подписано в печать 29.09.2025.
Формат 60x88 $^{1}/_{8}$. 18,0 п.л.
Заказ 3.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142