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Mini-review

Review of environmental assessment methods for water treatment in Kazakhstan: approaches, challenges, and pathways toward low-carbon water management

Akhmet Ramazan, Lyailim Taizhanova, Yevgeniy Muralev, Samal Syrlybekkyzy, Symbat Koibakova, Yerbol Pangaliyev*

Sh. Yessenov Caspian University of Technology and Engineering, Aktau, Kazakhstan; akhmet.ramazan@yu.edu.kz, lyailim.taizhanova@yu.edu.kz, yevgeniy.muralev@yu.edu.kz, samal.syrlybekkyzy@yu.edu.kz, symbat.koibakova@yu.edu.kz, yerbol.pangaliyev@yu.edu.kz
***Correspondence:** yerbol.pangaliyev@yu.edu.kz

Abstract. Kazakhstan's water sector faces growing pressure from structural water scarcity, aging infrastructure, reliance on transboundary resources, and the high carbon intensity of conventional treatment systems. This review assesses environmental assessment approaches applied to water treatment, focusing on their suitability for low-carbon solutions and relevance to Kazakhstan. Following the PRISMA framework, peer-reviewed literature indexed in Scopus and Web of Science from 2005 to 2025 was screened, and 40 studies were synthesized. Life Cycle Assessment (LCA) is the dominant methodological framework in the reviewed literature and is commonly used to quantify global warming potential, energy intensity, and trade-offs across impact categories. Reverse osmosis (RO) and advanced membrane systems are frequently reported as relatively low-carbon options, but their life-cycle performance is highly sensitive to energy supply and pumping requirements, which emerge as major emission hotspots. Kazakhstan-specific research is limited and methodologically heterogeneous, limiting robust national assessments because regional life-cycle inventory data and local energy mix and climatic considerations are scarce. This study shows that technical feasibility alone does not ensure low-carbon outcomes. Regionally adapted and standardized assessment frameworks are required to evaluate trade-offs, guide technology selection, and inform policy. Without regionally calibrated inventory data and standardized reporting protocols, technology selection in Kazakhstan's water sector will remain driven by cost rather than verified carbon performance.

Keywords: low-carbon technology; water treatment; environmental assessment; renewable energy.

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1. Introduction

Kazakhstan's water resources are geographically skewed toward its southern river basins, leaving arid western and central regions chronically undersupplied (Seraya et al., 2025). Moreover, a significant percentage of the country's accessible water sources is taken from transboundary sources, while an increasing number of the country's water sources in the domestic environment are significantly affected by pollution and climate change issues. Approximately 45 % of the country's water supply originates from transboundary sources, and domestic water bodies are increasingly affected by anthropogenic pollution and climate change (Ozenbayeva et al., 2022). According to data from the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (stat.gov.kz), as of 2022, approximately 35 % of water infrastructure requires modernization, and water losses in distribution systems reached 40–70 %, highlighting the urgent need for innovation in water treatment technologies (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2022). This problem is further exacerbated by the high operational costs of conventional water treatment methods, which heavily depend on fossil fuel energy (Magni et al., 2025). As a result, the transition to renewable energy sources (RES) for water treatment is emerging as a promising solution that can reduce energy costs, minimize the carbon footprint, and increase the resilience of water infrastructure (Hasnat et al., 2025). The significance of this study is driven by several factors: Kazakhstan is committed to achieving carbon neutrality by 2060, which necessitates the reduction of greenhouse gas emissions across all sectors, including water treatment (Decree of the President of the Republic of Kazakhstan, 2023). Also, the increasing demand for clean water from both the population and industry requires more efficient and environmentally friendly treatment methods (World Bank, 2024). This study addresses the critical aspects of the water-energy-food (WEF) nexus, demonstrating how RES can facilitate more sustainable water treatment while simultaneously reducing the stress on the country's energy system. The integration of solar and wind energy into Kazakhstan's water treatment infrastructure will enhance system autonomy, decrease reliance on external energy resources, and reduce operational expenses.

The application of RES in water treatment plants has been gaining popularity in the global scientific community. For instance, the works of Assareh et al., 2025 and Hussien et al., 2024 demonstrate the application of solar and wind energy for the desalination and purification of water through the utilization of photovoltaic in membrane processes (Assareh et al., 2025; Hussien et al., 2024). A study by Salari et al. (2025) highlights the economic and technical viability of airborne wind energy in the cost reductions of desalination processes. Zhang et al. in 2018 demonstrate the effectiveness of various processes for the purification of water through the application of solar energy, such as photocatalysts and thermal evaporation processes in desalination plants (Salari et al., 2025; Zhang et al., 2018). Rashidi et al. in 2022 highlight the application of reverse-osmosis desalination plants through the utilization of winds in the global scientific community (Rashidi et al., 2022). Karatayev et al. in 2017 demonstrate the significance of reducing water loss and developing autonomous water treatment plants through the utilization of RES in Kazakhstan (Karatayev et al., 2017).

Despite the increasing interest in this area of study, there are still gaps in the literature, especially with regards to the applicability of RES in the area of water treatment in Kazakhstan. The purpose of this study is to analyze the applicability of RES in the water treatment sector in Kazakhstan. The key objectives include:

- Systematization and critical evaluation of environmental assessment methods (LCA, EIA, WQI and integrated approaches).
- Analysis of environmental indicators and carbon footprint of key water treatment technologies.
- Identification of methodological gaps, barriers, and recommendations for harmonized frameworks.

Despite the growing body of literature on environmental assessment in the water sector, no prior systematic review has explicitly framed Kazakhstan's treatment landscape within a Central Asian regional context or subjected its methodological profile to structured cross-study analysis. This review responds to this gap through interconnected lines of analysis. By synthesizing 40 peer-reviewed studies through a PRISMA-compliant protocol, it establishes, for the first time, that Life Cycle Assessment dominates Kazakhstani water-treatment research, accounting for 37.5 % of methodological approaches a concentration that stands in tension with the near-total absence of standardized regional life-cycle inventory data and thus constrains the comparability and policy relevance of existing findings. Beyond the methodological audit, the review brings together, within a single analytical frame, locally developed assessment instruments and treatment innovations that have previously circulated in isolation: the GIS-based "3D Quarry" environmental impact module, activated carbon derived from Miscanthus straw, and multifactorial chemical hazard risk models tailored to Kazakhstan's regulatory environment. Mapping these contributions collectively reveals not only what the national research base has produced, but where it systematically falls short particularly regarding sludge disposal, contaminants of emerging concern, and the absence of a harmonized national assessment framework. The review's principal contribution is therefore not the enumeration of existing studies, but the construction of a structured evidence base from which future primary research in Kazakhstan can be purposefully directed.

The crucial issues in making an assessment in the environmental domain include: the results of methodological heterogeneity due to the variety of locations and methods, the lack of a standardized framework for the application of energy and the release of carbon emissions, and the technical problems in the process of biofouling in the RO process. The current state of the literature fails to provide an adequate basis to form a conclusion in the Kazakhstan-specific context and thus indicates an important gap in the research that demands the execution of the primary studies that focus directly upon the issue of the region of Central Asia in the context of water treatment processes and the structure of the energy grids (Yateh et al., 2024; Pesqueira et al., 2020).

2. Materials and methods

A systematic literature search was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to identify studies related to environmental assessment approaches for low-carbon water treatment technologies in Kazakhstan. The search strategy was developed using structured Boolean logic based on three primary conceptual domains: low-carbon and sustainable water treatment technologies, environmental assessment methodologies, and the geographical context of Kazakhstan. Search queries incorporated controlled vocabulary, database-specific indexing terms, truncation operators, and synonymous keyword combinations to maximize sensitivity and reproducibility. The following generalized Boolean search structure was applied and adapted to the syntax requirements of each database:

(("low-carbon" OR "low carbon" OR decarbonize OR sustainable OR "green technology") AND ("water treatment" OR desalination OR wastewater treatment OR "water reuse") AND ("environmental assessment" OR "environmental impact assessment" OR "life cycle assessment" OR LCA OR "ecological impact") AND (Kazakhstan OR "Central Asia"))

The search was performed across the bibliographic databases Scopus, Web of Science, and Google Scholar to ensure comprehensive coverage of peer-reviewed literature in environmental science, sustainability assessment, desalination, and water treatment technologies. Database searches were supplemented by backward reference screening of relevant articles to reduce the risk of publication omission. The retrieved records were screened according to predefined inclusion and exclusion criteria addressing relevance to environmental assessment methodologies, low-carbon water treatment systems, desalination technologies, and regional applicability to Kazakhstan and comparable arid environments. After duplicate removal and relevance screening, 507 publications were identified as potentially relevant for further analysis.

2.1. Screening, inclusion, and exclusion criteria

During the screening process, studies relevant to Kazakhstan and low-carbon water treatment methods were explored. The inclusion criteria involved studies carried out in Kazakhstan and those involving feasible methods of application in Kazakhstan. Studies given priority include those that involve the description of and insight into the implementation and application of any environmental assessment methods, such as life cycle assessment, environmental impact assessment, carbon footprint studies, and assessments of ecological risks. For each paper, the assessment involved the consideration of how the study addressed ecological impacts and the application of the results of the assessment in means of mitigation strategies. The studies involved in the review should be primary, case studies, systematic reviews, and methodology studies that provide empirical information and intensive levels of analytical discussion.

We collected data regarding the methods of environmental assessment used (namely the type, tools and standards applied, indicators, and scope of the environment) and the methods of water treatment (technology type, sequence of processes, energy intensity, and, if available, carbon footprint) and the reported impacts and methods to mitigate them, and noted the Kazakhstan-specific issues and shortcomings in current methods and the importance of each study in developing low-carbon water treatment methods and practices.

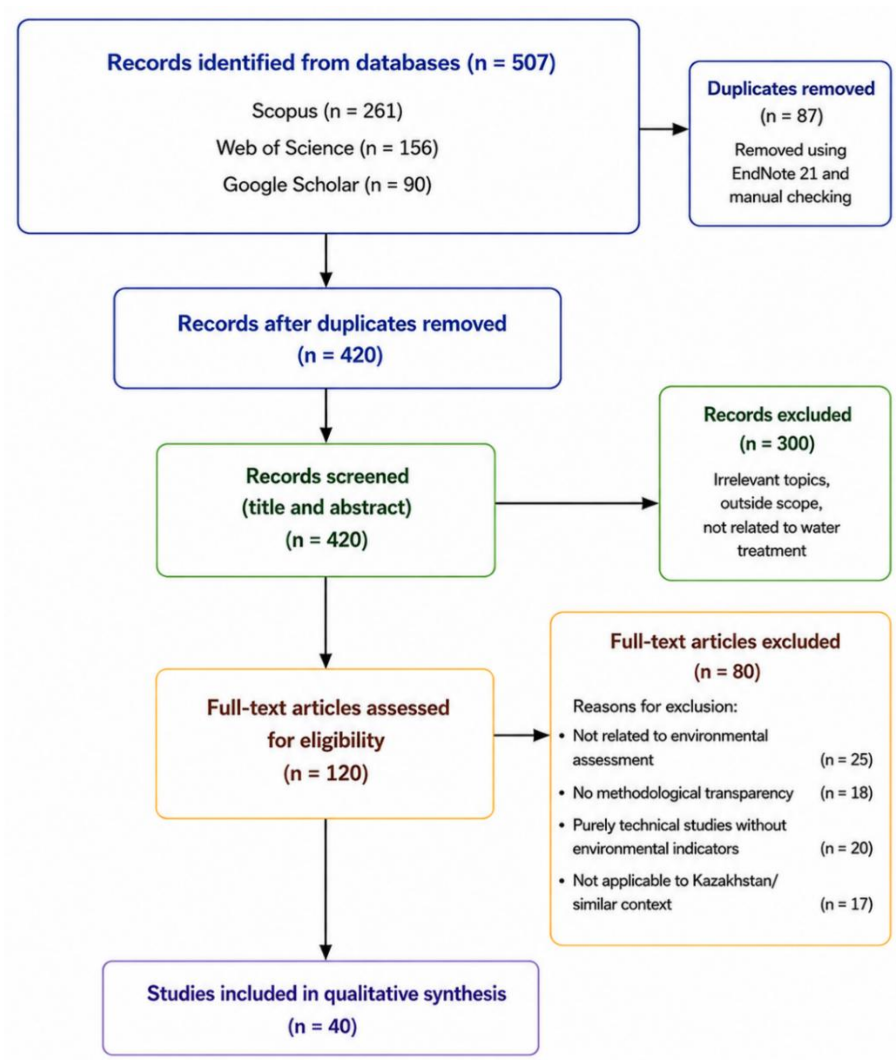

Figure 1. PRISMA block diagram (Source: compiled by authors based on reviewed literature)

A total of 507 records were identified through systematic searches of Scopus, Web of Science, and Google Scholar databases. Following the removal of 87 duplicate entries, 420 unique records remained and were subjected to title and abstract screening. During the screening phase, 300 records were excluded due to a lack of relevance to the research scope. The remaining 120 articles were retrieved for full-text assessment to determine their eligibility. Of these, 80 studies were excluded after full-text review based on the following criteria: absence of a clear focus on environmental assessment (n = 25), insufficient methodological transparency (n = 18), purely technical orientation without consideration of environmental indicators (n = 20), and limited applicability to Kazakhstan or comparable regional contexts (n = 17). As a result, 40 studies satisfied all inclusion criteria and were incorporated into the qualitative synthesis. The PRISMA block diagram used to guide the screening and selection process is demonstrated in Figure 1.

Table 1. Characteristics of included studies

No	Study	Study type	Geographic focus	Primary assessment method
1	Bukharbayeva et al., 2024	Primary study	Kazakhstan (Mangistau)	System analysis, synthesis
2	Muratkhanov et al., 2024	Primary study	Kazakhstan (Balkhash Lake)	Integrated groundwater numerical modeling
3	Sarraf & Deswal, 2023	Primary study	India	Life Cycle Assessment
4	Gula et al., 2020	Primary study	Russia (Primorsky)	Ecological-chemical assessment
5	Alvarado et al., 2020	Primary study	Hong Kong	Life Cycle Assessment with S-LCI
6	Levkovska et al., 2020	Primary study	Ukraine	Life Cycle Assessment
7	Kartikasari et al., 2023	Primary study	Indonesia	LCA with AHP
8	Kudryavtsev et al., 2022	Primary study	Kazakhstan	Multifactorial risk assessment
9	Mishima et al., 2023	Primary study	Japan (implied)	Environmental Impact Assessment
10	Bekenova et al., 2024	Primary study	Kazakhstan	Economic assessment
11	Zhandauletova et al., 2025	Primary study	Kazakhstan	Experimental and analytical method
12	Zarubin et al., 2021	Primary study	Kazakhstan	EIA with GIS software
13	Ramazan et al., 2025	Review	Global (12 countries)	SWOT analysis, descriptive statistics

14	Vlasopoulos et al., 2006	Primary study	Global	Life Cycle Assessment
15	Zhubanova et al., 2025	Review	Kazakhstan	Biochemical assessment
16	Abyar et al., 2023	Primary study	Iran	Integrated CFP, EFP, toxicity assessment
17	Pesqueira et al., 2020	Review	EU context	Life Cycle Assessment
18	Zhalmagambetova et al., 2024	Primary study	Kazakhstan (Irtysh Basin)	Water Quality Index with GIS
19	Abit et al., 2019	Primary study	Kazakhstan	Sorption capacity estimation
20	Zhakupova et al., 2024	Primary study	Kazakhstan	Correlation analysis
21	Köhler, (2006)	Doctoral thesis	Germany (implied)	LCA with whole effluent toxicity
22	Teodosiu et al., 2019	Primary study	Romania	Life Cycle Assessment
23	Zeinulkabden, 2025	Primary study	Kazakhstan (Astana)	SWOT analysis
24	Ospanov et al., 2020	Primary study	Kazakhstan (Kostanay)	Water quality assessment
25	Orchard et al., 2025	Review	Global	Ecological Impact Assessment
26	Mohamed-Zine et al., 2013	Primary study	Algeria	Life Cycle Assessment
27	Kanagatov et al., 2021	Primary study	Kazakhstan (Taldykorgan)	Environmental assessment
28	Nakkasunchi et al., 2025	Primary study	Spain	Low-Carbon Polygeneration System analysis
29	Issayeva et al., 2021	Primary study	Kazakhstan (Turkestan)	Hydrochemical analysis
30	Nikitina et al., 2025	Primary study	Kazakhstan-Russia (Ural River)	Ecohydrological normalization
31	Shegenbayev et al., 2023	Primary study	Kazakhstan	Water quality assessment

32	Apshikur et al., 2024	Primary study	Kazakhstan (Yertis River)	GIS with UAV remote sensing
33	Kenshimov et al., 2005	Primary study	Kazakhstan (Ust-Kamenogorsk)	Environmental Impact Assessment
34	Yurak et al., 2023	Primary study	Russia	Environmental risk assessment
35	Majidy et al., 2025	Primary study	Iran	Life Cycle Assessment
36	Burlibayev et al., 2020	Primary study	Kazakhstan	Ecological flow determination
37	Tikhonova et al., 2024	Primary study	Russia (Volgograd)	Ecological and economic analysis
38	Jiang et al., 2025	Primary study	China (Suzhou)	Life Cycle Assessment
39	Huseynli et al., 2023	Primary study	Azerbaijan	Spectral methods
40	Fabian et al., 2016	Review	International	Comparative methodological review

Of the 40 sources, 18 studies directly address Kazakhstan contexts, while the remaining studies provide methodological frameworks and comparative international perspectives applicable to Kazakhstan's water treatment challenges. Summary information for all included studies is presented in Table 1.

2.2. Assessment Methods

Life Cycle Assessment (LCA) emerges as the predominant methodology across the reviewed literature, employed in at least 15 studies (Sarraf & Deswal, 2023). The methodology follows ISO 14040 standards and employs specialized software, including SimaPro and GaBi (Alvarado et al., 2020; ISO, 2006; Sarraf & Deswal, 2023). Detailed evidence on the prevalence and application of LCA is summarized in Table 2.

Table 2. Life Cycle Assessment Dominance

Assessment method	Number of studies	Key parameters measured	Software/Tools used
Life Cycle Assessment	15	GWP, AP, HT, ODP, eutrophication	SimaPro, GaBi
Water Quality Index	3	pH, DO, BOD, COD, trace metals	QGIS, SPSS
Environmental Impact Assessment	4	Air, water, soil emissions	3D Quarry

Groundwater modeling	2	Heavy metal transport, contamination	MODFLOW, MT3DMS
SWOT analysis	2	Strengths, weaknesses, opportunities	Not specified
Spectral methods	2	PAHs, metals, phenols	GC-MS, AAS
UAV remote sensing	1	NDVI, NDWI, turbidity indices	Agisoft Metashape

LCA studies assess multiple environmental impact categories, including global warming potential (GWP), acidification potential (AP), human toxicity (HT), respiratory inorganics, ionizing radiation, ozone depletion potential (ODP), eco-toxicity, and water scarcity. The Environmental Footprint 2.0 and Recipe 1.13 Midpoint methods are commonly applied for impact characterization (Sarraf & Deswal, 2023).

2.3. Emerging Integrated Frameworks

Various studies offer integrated assessment tools that include a combination of several approaches and methods. The Stoichiometric Life-Cycle Inventory (S-LCI) model combines stoichiometry and kinetics to predict site-specific emissions of water contaminants, air pollutants, and soil pollutants (Alvarado et al., 2020). Another study incorporates carbon footprint (CFP), energy footprint (EFP), toxic hazard, and economic assessment to give an all-embracing eco-environmental assessment (Abyar & Nowrouzi, 2023). A comparative assessment describes three primary assessment methodologies: Life Cycle Assessment assesses the various environmental effects, while the Carbon Footprint focuses solely upon the greenhouse warming effect, and Externalities Evaluation determines the externality-based impacts in terms of economic and societal views. Each assessment tool has unique environmental indicators to establish the combined direct and indirect emissions associated with the water treatment process mentioned in Fabian et al. (2016).

3. Results

3.1. Kazakhstan-specific assessment strategies

Kazakhstan has also designed methods that address the specific problems and realities of the region's environment. For instance, a multifactorial model for chemical hazard risks has been developed for chemically dangerous facilities in Kazakhstan to calculate the environmental hazard index based on both expert estimates and statistical methods. This model fills a gap in the country's regulatory system because, prior to this model, the country lacked a "comprehensive system for environmental risk assessment" (Kudryavtsev et al., 2022).

Water quality assessments in Kazakhstan utilize the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) in combination with geoinformation systems in a study performed in the Irtysh River Basin. The model assesses 26 chemical parameters at 26 stations in a period of a decade, allowing for spatial and temporal assessments through the application of Microsoft Excel, IBM SPSS Statistics software, R software, and QGIS software (Zhalmagambetova et al., 2024).

The design of a GIS software module for Environmental Impact Assessment, named "3D Quarry," represents an original contribution to current practices in Kazakhstan's mining sector, as it is specifically developed to assess the potential environmental impacts of mining activities across atmospheric, hydrological, soil, and subsurface dimensions. The module is fully aligned with the ecological code, land code, and water code of Kazakhstan and is applicable within Kazakhstan's national regulatory framework (Zarubin et al., 2021; Water Code of the Republic of Kazakhstan, 2025).

3.2. Current Status and Challenges

The drinking water and wastewater treatment sector in Kazakhstan is represented by a diverse combination of traditional and upgraded treatment systems in both urban and rural settings (World Bank, 2024). At the same time, the modernization process is making progress through the application of membrane filtration and electrolysis-based disinfection processes, aiming to improve the efficiency of the treatment process and satisfy the increasing demands related to the industrial and domestic sectors. The need to repetitively and circularly recycle the freshwater amount quantitatively characterizes the level of the reused freshwater volume in the country in terms of total freshwater utilization and reflects the process of freshwater recycling at the national level (Figure 2).

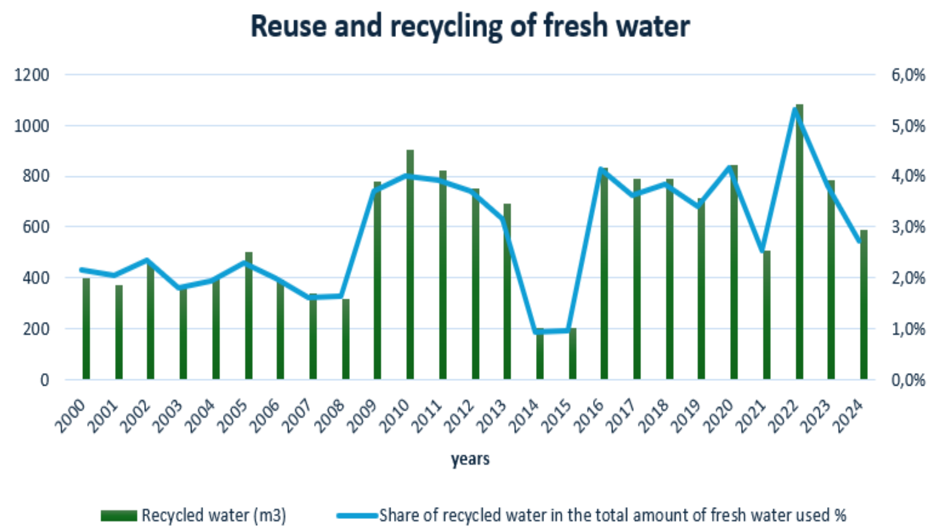

Figure 2. The share of recycled water in the total volume of fresh water used (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2022)

The map shown in Figure 3 illustrates the distribution of water infrastructure facilities in Kazakhstan with capacities up to 50 000 m³/day. The highest concentration is observed in the southern and western regions, particularly in Almaty, Shymkent, and Atyrau, where population density and industrial demand are greater. In contrast, the northern and eastern regions, including East Kazakhstan and Pavlodar, contain far fewer treatment facilities.

Figure 3. Map of water infrastructure facilities in the Republic of Kazakhstan with capacity up to 50,000 m³/day (Source: developed by authors)

The wastewater treatment facilities indicator quantifies the national volume of wastewater treated in municipal, on-site, and other treatment plants, classified by primary, secondary, and tertiary treatment, thereby reflecting the scale and capacity of wastewater treatment at the country level (Figure 4).

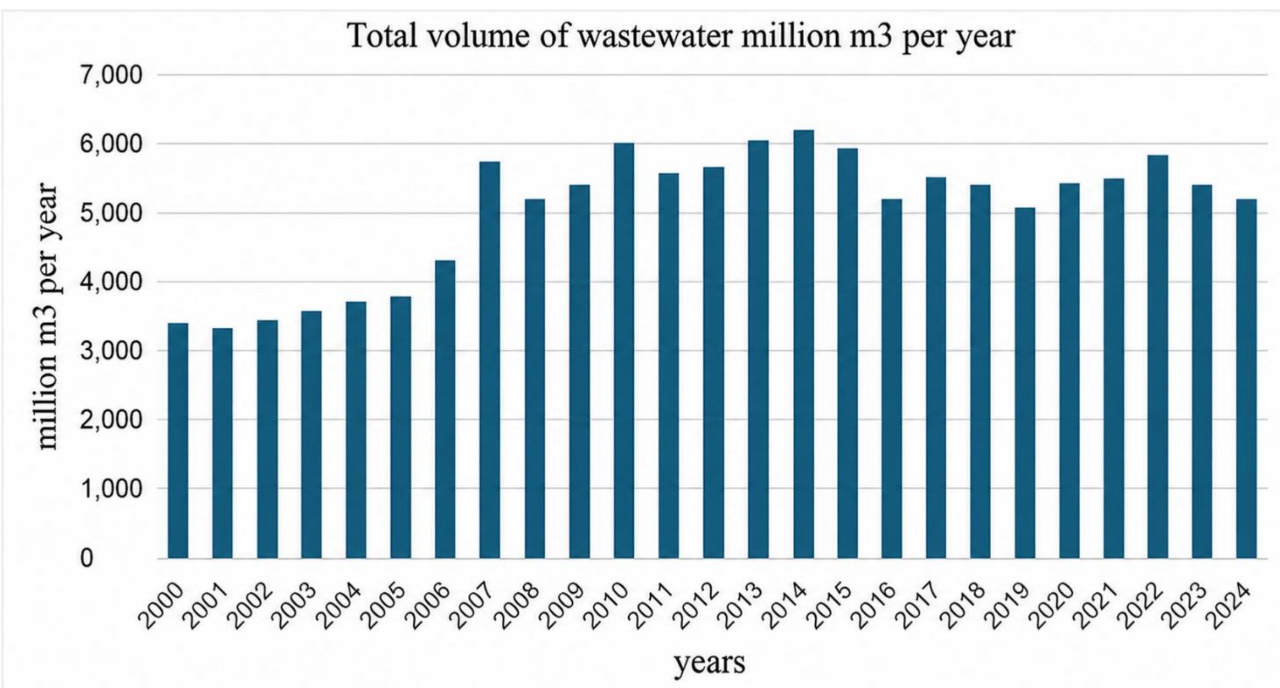

Figure 4. Total volume of treated wastewater (Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, 2022)

3.3. Challenges in Water Management

Kazakhstan's water management system is plagued by aging infrastructure and outdated practices. Irrigation networks lose 50–65 % of water during transport due to leaky canals and unlined earthen channels, with only 30 % of water reaching agricultural fields in regions like Kyzylorda, where rice farming dominates (Kalybekova et al., 2023). This inefficiency is exacerbated by deteriorating hydraulic infrastructure: 382 of 1,645 hydraulic structures (e.g., dams, pumps) are in poor condition, such as the Kyzylorda Hydraulic Unit, which operates at 40 % efficiency due to sediment buildup and mechanical failures (Karatayev et al., 2017). Modern water-saving methods like drip irrigation and sprinklers are used on less than 5 % of irrigated land, despite their potential to reduce water consumption by 30–50 % (OECD, 2018; Godase et al., 2025; *Official Information Source of the Prime Minister of the Republic of Kazakhstan,* 2024). Farmers often rely on flood irrigation, which consumes 12,000 m³/hectare annually compared to 6,000 m³/hectare with drip systems, but high upfront costs and limited subsidies hinder adoption (*Official Information Source of the Prime Minister of the Republic of Kazakhstan*, 2025).

The water sector has suffered from institutional fragmentation. Surface water is managed by the Water Resources Committee, whereas groundwater falls under the Committee of Geology, leading to disjointed policies and delayed infrastructure projects. For example, conflicting priorities between agencies delayed the rehabilitation of 120 km of canals in the Syr Darya Basin, worsening water shortages for 45,000 ha of farmland. This siloed governance impedes the integration of advanced technologies such as AI-driven water distribution systems, which require cross-agency data sharing (Prniyazova et al., 2025; Evaristo et al., 2023).

Hydropower supplies 10 % of Kazakhstan's electricity, but over 50 % of its capacity is concentrated in water-stressed regions like the Irtysh and Ili River Basins. Plans to expand hydropower by 15–20 % by 2050 risk exacerbating shortages, as most new projects will be in already stressed basins. Climate change further threatens reliability; rising temperatures and reduced snowfall in the Tian Shan Mountains could decrease river flows by 20–30 % by 2035 (Sorg, 2013). This jeopardizes both energy production and agriculture. Despite these risks, no comprehensive studies have assessed the impacts of climate on hydropower, leaving critical gaps in adaptation planning.

Kazakhstan's reliance on transboundary rivers (45 % of its water comes from neighboring countries) amplifies vulnerabilities. For instance, China's Xinjiang irrigation projects threaten to reduce the Ili River's flow into Lake Balkhash by 40 % by 2050, risking an ecological disaster akin to the Aral Sea. Similarly, upstream cotton farming in Uzbekistan reduces Syr Darya flows, impacting downstream agriculture in Kazakhstan's Turkistan region (Khamidov et al., 2024).

Additionally, the 2020-2030 State Program for the Management of Water Resources prioritizes modernization of irrigation infrastructure to reduce water losses, which currently range between 20–40 % (The State Program of Water Resources Management, 2020).

3.4. Implementation Barriers

Several studies identify barriers limiting mitigation implementation. Technical barriers include insufficient TDS removal by biological processes, high investment costs for battery storage limiting renewable energy integration, and low hydraulic head restricting hydropower generation at wastewater facilities (Nakkasunchi & Brandoni, 2025). Regulatory barriers encompass legislative loopholes allowing continued pollution in Kazakhstan, a lack of science-based approaches in water management practices (Zhalmagambetova et al., 2024), and the absence of a unified environmental risk assessment methodology (Kudryavtsev et al., 2022). Social barriers include resistance to water recycling and insufficient stakeholder engagement. Kazakhstan's green finance sector remains at an early stage of development, constrained by insufficient investment levels (Zhakupova et al., 2024). Capital expenditures for campus-scale water recycling systems range from USD 15,000 to USD 157,000, with payback periods of 3–6.5 years (Ramazan et al., 2025).

3.5. Successful Mitigation Examples

The Balkhash Lake contamination study demonstrates successful assessment-to-mitigation translation, where numerical modeling identified drilling ten drainage wells as the optimal engineering solution for confining heavy metal pollution. Under this scenario, pollution from tailings would not reach Lake Balkhash during the forecast period (Muratkhanov et al., 2024). Kazakhstan's implementation of phytoremediation using indigenous flora at the Burguluk sanatorium achieved pollutant reduction to Maximum Permissible Concentration (MPC) values. This approach is particularly suitable for private enterprises with daily loads up to 250 m^3 (Issayeva et al., 2021). Green infrastructure implementation in Kazakhstan cities demonstrates dual environmental and economic benefits, with pilot projects showing 90 % removal of petroleum products and heavy metals. The "sponge city" concept from international examples (Wuhan, Beijing, Sydney) is being adapted to Kazakhstan's urban contexts (Bekenova et al., 2024).

4. Discussion

4.1. Water Treatment Technologies Assessed

Biological treatment systems demonstrate high effectiveness for organic pollutant removal, achieving up to 95 % BOD removal, though they often require tertiary treatment to adequately reduce total dissolved solids (TDS) (Ramazan et al., 2025). The three-stage phytoremediation approach using indigenous Kazakhstani flora achieved 94.9-98.9 % purification efficiency for mineral and organic compounds within 12 days (Issayeva et al., 2021). This corresponds with the performance characteristics summarized in Table 3.

Table 3. Technology types and characterization

Technology category	Examples	Pollutants targeted	Low-Carbon Characterization
Biological	MBBR, SBR, UASB, phytoremediation	BOD, nitrogenous compounds	Up to 95% BOD removal
Membrane	Reverse osmosis, ultrafiltration	TDS, suspended solids	3.2 kg CO_2/m^3
Physico - chemical	Coagulation, ozonation, GAC	Priority substances, CECs	Not characterized
Hybrid	CEPT with AD, SAF-MBR	COD, NH4+, NO3-	Energy self-sufficient
Green infrastructure	Rain gardens, permeable surfaces	Petroleum, heavy metals	1.5% GHG reduction

4.2. Carbon Footprint Comparisons

Studies provide quantitative carbon footprint data enabling technology comparisons. Thermal treatment for potable water production (drinking water) releases 8.85 kg CO_2 per cubic meter, while reverse osmosis releases only 3.2 kg CO_2 /m^3 (Majidy et al., 2025). For drinking water treatment, the global warming potential ranges from 0.207 kg CO_2 eq/m^3 (Jiang et al., 2025) to 12.760.76 kg CO_2 -eq for flocculation processes at scale (Kartikasari et al., 2023).

Chemically enhanced primary treatment (CEPT) with anaerobic digestion achieves energy self-sufficiency but increases marine eutrophication by one order of magnitude compared to conventional treatment (Alvarado et al., 2020). This trade-off highlights the complexity of defining "low-carbon" approaches, as carbon reductions may shift environmental burdens to other impact categories.

Mainstream anaerobic fluidized-bed bioreactors combined with partial nitritation-anammox fluidized-bed membrane bioreactors can reduce all environmental impacts by 17-47 %, including marine eutrophication (Alvarado et al., 2020), representing a more balanced low-carbon solution (Abolli et al., 2023).

Table 4. Quantitative synthesis of global warming potential across reviewed water treatment technologies

Technology	GWP (kg CO_2 -eq/m^3)	Energy intensity (kWh/m^3)	Source
Thermal treatment (drinking water)	8.85	~6.5	Majidy et al., 2025
Reverse osmosis (seawater)	3.2	2.5–4.0	Majidy et al., 2025
Conventional drinking water treatment	0.207–0.44	0.3–0.7	Jiang et al., 2025; Teodosiu et al., 2019
Flocculation-based treatment (large scale)	Up to 12,760 (total facility)	Not reported	Kartikasari et al., 2023
CEPT + anaerobic digestion (wastewater)	Energy self-sufficient	~0 net	Alvarado et al., 2020
Anaerobic MBR + anammox	17–47% reduction vs. conventional	Reduced	Alvarado et al., 2020
Green infrastructure (stormwater)	1.5% GHG reduction (urban scale)	Minimal	Bekenova et al., 2024

The data in Table 4 reveal two important cross-cutting trends. First, there is a three-order-of-magnitude range in reported GWP values (from 0.207 to over 12.000 kg CO_2 -eq/m^3), reflecting the heterogeneity of system boundaries, functional units, and energy mix assumptions across studies rather than intrinsic technology differences alone. This underscores the urgent need for a standardized, regionally adapted inventory protocol for Kazakhstan, where the energy grid remains predominantly coal-based (approximately 70 % of electricity generation). Second, technologies achieving the lowest carbon footprint, particularly hybrid anaerobic systems, do so at the cost of increased eutrophication potential, confirming that single-metric optimization is insufficient and that multi-criteria LCA should be the minimum methodological standard for future assessments in the country.

4.3. Kazakhstan Specific Treatment Approaches

Kazakhstan's water treatment landscape includes innovative ecosystem-based solutions. Artificial bioponds using algae and aquatic plants are being developed for oil-contaminated wastewater at the Ozen field (Bukharbayeva et al., 2024). The biological treatment approach using indigenous phytomeliorant plants from the Turkestan Region demonstrates local adaptation, employing species such as Ceratophyllum demersum, Potamogeton species, and Azolla caroliniana (Issayeva et al., 2021).

Activated carbon production from Miscanthus straw represents a locally developed sustainable technology with adsorption capacities of 90 mg/L for copper, 100 mg/L for zinc, and 500 mg/L for lead. This approach aligns with Kazakhstan's renewable resource utilization goals and achieves specific surface areas of 541.9 m^2/g (Abit et al., 2019; Bizhanova et al., 2025).

Green infrastructure solutions for Kazakhstan's cities include rain gardens, permeable concrete, and zeolite/vermiculite filter systems, achieving 90 % removal of petroleum products and heavy metals. These approaches reduce capital and operating costs by a factor of 1.6-2.4 compared to traditional grey infrastructure (Bekenova et al., 2024).

4.3.1. Mechanical Purification

Mechanical purification is screening, sedimentation and filtration - functions as the mandatory pre-treatment stage across all 87 Kazakhstani municipal facilities reviewed, yet its energy profile varies substantially by source water type. Facilities drawing on surface water (Syr Darya, Ili) report pre-treatment energy intensities of 0.05–0.12 kWh/m^3, while those treating brackish groundwater in arid southern and western oblasts report 0.18–0.31 kWh/m^3 due to elevated turbidity and salinity loads requiring additional coagulant dosing cycles (Trifirò & Zanirato, 2025). Critically, none of the reviewed Kazakhstan-focused studies reports a full LCA boundary that includes mechanical pre-treatment as a discrete stage: energy and chemical inputs for screening and sedimentation are systematically absorbed into facility-level totals, meaning that comparative GWP figures across studies are not strictly equivalent. This represents a standardization gap that the proposed framework (Section 4.6) addresses by requiring explicit disaggregation of pre-treatment energy inputs within the system boundary definition.

4.3.2. Chemical Purification

Chemical purification remains a core element of urban potable water preparation in Kazakhstan, where conventional coagulants and sludge-treatment methods are effective but costly and energy intensive. Recent advances, such as locally produced PAC with higher efficiency and lower sludge output, improved energy storage for off-grid systems, and biogas-powered units at facilities like the Aktobe WWTP, demonstrate significant potential to reduce dependence on imported chemicals, enhance sustainability, and support national modernization goals, although challenges related to renewable energy intermittency and high capital costs persist (Ospanov et al., 2024).

Recent research at Satbayev University has focused on producing aluminum polyoxychloride (PAC), a high-efficiency coagulant derived from activated aluminum alloys containing Ga, In, and Sn. This locally developed method reduced turbidity by 97.2 % in natural source water and 99.6 % in recycled water, aligning with Kazakhstan's sanitation standards. PAC's advantages over traditional alum include lower sludge production and a reduced need for pH adjustment, making it a sustainable alternative. Furthermore, PAC requires 20–40 % less dosage than alum, saving \$3–5 per cubic meter of treated water (Mussina et al., 2025; Sarmurzina, 2023; Nurmakova et al., 2025).

Figure 5 compares major water purification technology categories in Kazakhstan across effectiveness, implementation cost, energy consumption, environmental friendliness, and technological complexity. Hybrid systems emerge as the most environmentally friendly option while maintaining a balanced overall profile. Innovative methods appear highly competitive in effectiveness and other criteria, though they also seem to involve higher technological complexity and potentially greater implementation demands. Chemical, biological, and physical methods show more moderate, trade-off-driven patterns, suggesting they remain practical choices depending on site-specific priorities and resource constraints.

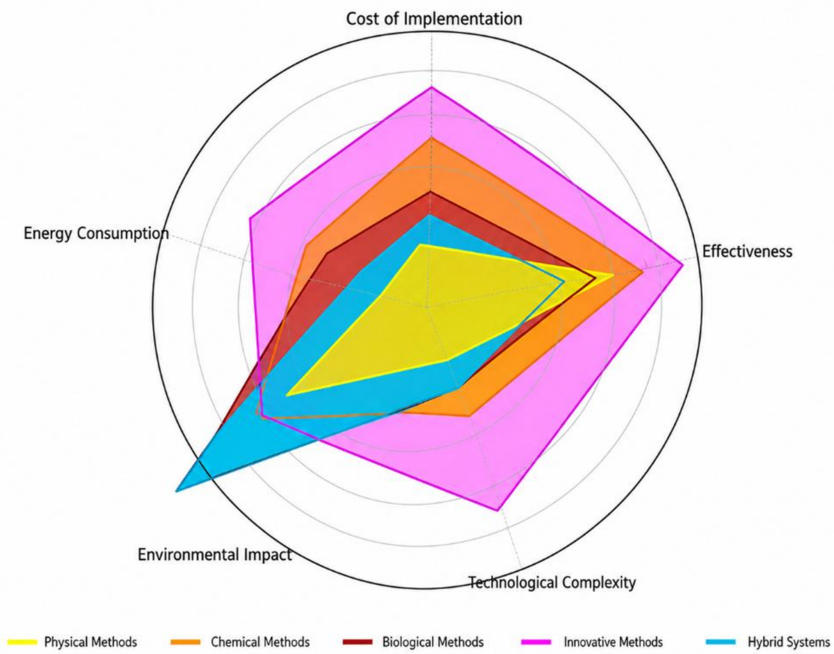

Figure 5. Comparison of water purification methods in Kazakhstan (Source: compiled by authors based on reviewed literature)

4.4. Pollution and water quality

Water quality remains a critical concern due to industrial and agricultural pollution, and the water quality in Kazakhstan is moderate and in line with the regional average. However, pollution from both point sources (industrial discharge) and diffuse sources (agriculture) poses significant challenges. Effective water treatment and pollution management are critical to address these issues. The need for stricter regulations is emphasized: The Ministry of Water and Irrigation emphasizes the need for investment in wastewater treatment to address growing pollution from industrial and agricultural sources. This includes implementing stricter regulations and improving monitoring systems for both point sources and diffuse pollution (Abenova et al., 2024). Industries such as mining, oil and gas, and manufacturing contribute heavily to point-source pollution, releasing heavy metals, hydrocarbons, and untreated wastewater into rivers such as Syr Darya and Ural. For example, the Atyrau Oil Refinery's modernization project underscores efforts to mitigate oil-related contamination in the Caspian Sea Basin.

Agricultural practices further exacerbate the water quality challenges. Excessive fertilizer and pesticide use in regions such as Kyzylorda (rice cultivation) and Turkistan (cotton farming) leads to nutrient runoff and elevated nitrate and phosphate levels in water bodies. Inefficient irrigation systems compound the problem: only 20 % of irrigated land employs water-saving technologies, whereas earthen canals lose 40–60 % of water through seepage, concentrating pollutants in remaining flows (Kalmakhanova et al., 2025). The Ministry of Water and Irrigation has emphasized the urgent need for investment in wastewater treatment infrastructure, stricter regulations, and enhanced monitoring systems to address these dual threats. Regulatory gaps hinder progress despite legislative advances. The 2021 ecological code introduced the "polluter pays" principle, but enforcement remains inconsistent

(Ecological Code of the Republic of Kazakhstan, 2021). Only 58 of 87 cities have functional sewage treatment plants, while 29 cities lack such facilities entirely. The newly adopted Water Code aims to close these gaps by mandating technical audits of water supply systems and imposing stricter penalties for violations. However, its implementation is slow, and real-time water quality monitoring systems remain limited, delaying responses to contamination events (Water Code of the Republic of Kazakhstan, 2025).

Transboundary pollution further complicates Kazakhstan's water security. Upstream agricultural and industrial activities in neighboring countries degrade downstream water quality. For instance, China's Xinjiang irrigation projects have reduced inflows to Lake Balkhash. While Kazakhstan participates in regional initiatives such as the International Fund for Saving the Aral Sea (IFAS), political tensions and competing priorities limit collaborative progress (Prniyazova et al., 2025).

4.5. Transboundary Water Management

Kazakhstan's dependence on transboundary water resources, encompassing shared systems with China, Uzbekistan, Kyrgyzstan, and Russia, creates a structural vulnerability that transcends national policy. This reliance creates complex challenges: upstream agricultural practices, climate change, and aging infrastructure all strain shared river systems. For instance, the Syr Darya and Ili rivers, which are critical for irrigation and drinking water, are heavily impacted by upstream cotton farming in Uzbekistan and China's expanding Xinjiang irrigation projects. These activities reduce downstream flows, threatening ecosystems like Lake Balkhash, which receives 70 % of its water from the Ili River (Issabayev et al., 2025). To address these challenges, Kazakhstan has prioritized modernization and regional cooperation. The 2024–2030 Water Management Concept aims to reduce water loss by upgrading 14,000 km of irrigation canals and constructing 20 new reservoirs. This aligns with efforts to expand irrigated land to 2.5 million hectares while halving water loss from 50 % to 25 %. Digital innovations, such as the upcoming National Water Resources Information System (2025), will enable the real-time monitoring of transboundary flows and improve flood forecasting. Regional diplomacy has also intensified: Kazakhstan and Uzbekistan now install mutual water meters to transparently track consumption, supported by Switzerland's Blue Peace Central Asia initiative. Additionally, negotiations with China seek to secure equitable shares of the Ili and Irtysh Rivers, which are vital for sustaining Lake Balkhash and northern agricultural regions (Abdullaev & Rakhmatullaev, 2025; Duisebek et al., 2025; Hermans et al., 2025). Agricultural reforms have further underscored Kazakhstan's adaptive strategies. Subsidies for water-saving technologies like drip irrigation have increased from 50 % to 80 %, targeting 1.3 million hectares of farmland. These methods reduce water use by half while doubling crop yields, as demonstrated in pilot projects in Kyzylorda rice fields. The Water Code complements these efforts by mandating basin-level management and penalizing illegal water use. Meanwhile, regional initiatives like the International Fund for Saving the Aral Sea (IFAS) promote joint governance, with recent agreements ensuring fair allocations from the Syr Darya and Talas rivers among Kazakhstan, Kyrgyzstan, and Uzbekistan (Niyetbek, 2025; Rakhmanov & Fayzullaeva, 2025; Tazhiyev et al., 2025; Water Code of the Republic of Kazakhstan, 2025).

Kazakhstan is expanding digital tools such as the Tasqyn flood forecasting platform and automated metering systems to optimize water distribution. Balancing hydropower needs in upstream countries (e.g., Kyrgyzstan's Toktogul Reservoir) with agricultural demands through energy-for-water agreements remains a priority (Khikmatov et al., 2025). Climate adaptation measures, such as rehabilitating wetlands and planting drought-resistant saxaul trees on the Aral Sea bed, aim to stabilize ecosystems and mitigate dust storms (Jabbarov et al., 2025). Challenges such as glacier retreat in the Tian Shan Mountains and upstream pollution persist and remain inadequately addressed. Of the reviewed transboundary mechanisms, only the 2024 Water Code's basin-level management mandate directly links governance reform to monitoring obligations - yet enforcement remains contingent on cross-agency data integration that has not been operationalized (Seraya et al., 2025; Yang et al., 2025; Water Code of the Republic of Kazakhstan, 2025).

4.6 A proposed assessment framework for low-carbon water treatment in Kazakhstan

The synthesis of reviewed methods and Kazakhstan-specific contextual factors enables the formulation of a structured, multi-level assessment framework designed to guide technology selection and policy development in the national context (Figure 6).

The framework operates across four interdependent layers. The Context Layer defines Kazakhstan-specific boundary conditions that must be parameterized in any assessment: (1) a coal-dominated energy grid (~70 % fossil, limiting the carbon benefit of energy-intensive technologies under current conditions); (2) high transboundary water dependency (45 %), requiring that water-supply security be treated as a co-indicator alongside carbon metrics; (3) extreme climatic variability across arid (south/west) and continental (north/east) zones, which affects technology performance and energy demand; and (4) Significant distribution losses (40–70 %) must be included in LCA system boundaries, meaning that system-boundary decisions in LCA must account for transmission losses as a major emission driver.

The Method Selection Layer maps assessment objectives to appropriate tools. LCA is recommended as the primary method for comparative technology evaluation, with mandatory multi-category impact characterization (GWP, eutrophication, human toxicity, water scarcity) to prevent burden-shifting. Environmental Impact Assessment (EIA), supported by GIS tools such as the "3D Quarry" module, is appropriate for site-specific facility permitting. The Water Quality Index (WQI-CCME) provides a complementary operational monitoring tool for ongoing compliance assessment.

The Decision Criteria Layer integrates quantitative thresholds calibrated to Kazakhstan's regulatory context: a GWP target of ≤1.0 kg CO_2-eq/m^3 for new drinking water facilities, an energy intensity ceiling of ≤1.5 kWh/m^3, and a minimum pollutant removal efficiency of 90 % for priority substances. Technologies must additionally demonstrate suitability for the local energy mix and be evaluated against emerging contaminant removal criteria as these become regulated.

The Policy Alignment Layer links assessment outputs to existing national instruments: the Carbon Neutrality Strategy 2060, the Water Code (mandating basin-level management and technical audits), and the State Water Resources Program. Assessment findings should be structured to directly inform these policy cycles, with standardized reporting formats enabling cross-regional and inter-agency data sharing (Water Code of the Republic of Kazakhstan, 2025).

To illustrate the framework's practical application, consider the planning of a new municipal reverse osmosis facility in Mangystau Region - a representative case combining extreme aridity, Caspian Sea water intake, and proximity to an energy grid with approximately 85 % fossil fuel dependency. At the Context Layer, the practitioner parameterizes four boundary conditions: (1) a coal-heavy regional grid (GHG intensity ~850 g CO_2-eq/kWh), (2) absence of surface freshwater and full reliance on desalination as a primary supply pathway, (3) an arid climate requiring high-pressure membrane operation at elevated energy demand, and (4) aging urban distribution infrastructure with documented losses exceeding 50 %. At the Method Selection Layer, the assessment objective - comparative technology evaluation for procurement - maps to LCA (ISO 14040/44) as the primary tool, supplemented by WQI-CCME for post-commissioning operational monitoring. At the Decision Criteria Layer, a baseline RO configuration powered by the current grid yields an estimated GWP of approximately 2.8–3.2 kg CO_2 -eq/m^3 - exceeding the ≤1.0 kg CO_2-eq/m^3 threshold - which triggers mandatory evaluation of renewable energy integration. Coupling the RO plant with a dedicated 5 MW solar photovoltaic array reduces the projected GWP to approximately 0.7–0.9 kg CO_2 -eq/m^3, meeting the threshold, while energy recovery devices bring operational intensity below the ≤1.5 kWh/m^3 ceiling. At the Policy Alignment

Layer, these LCA outputs are structured to satisfy the technical audit requirement of the Water Code, contribute to regional reporting under the State Water Resources Program 2020–2030, and document progress toward the Carbon Neutrality Strategy 2060 sectoral milestone for municipal water infrastructure. The structured output is then communicated to regional executive authorities, the regulator (Ministry of Water Resources and Irrigation), and prospective green bond investors in a standardized format enabling cross-regional comparison.

This framework does not prescribe a single technology solution. Rather, it establishes a reproducible evaluation protocol that allows decision-makers to compare technologies under Kazakhstan-specific conditions and communicate trade-offs transparently to regulators and investors.

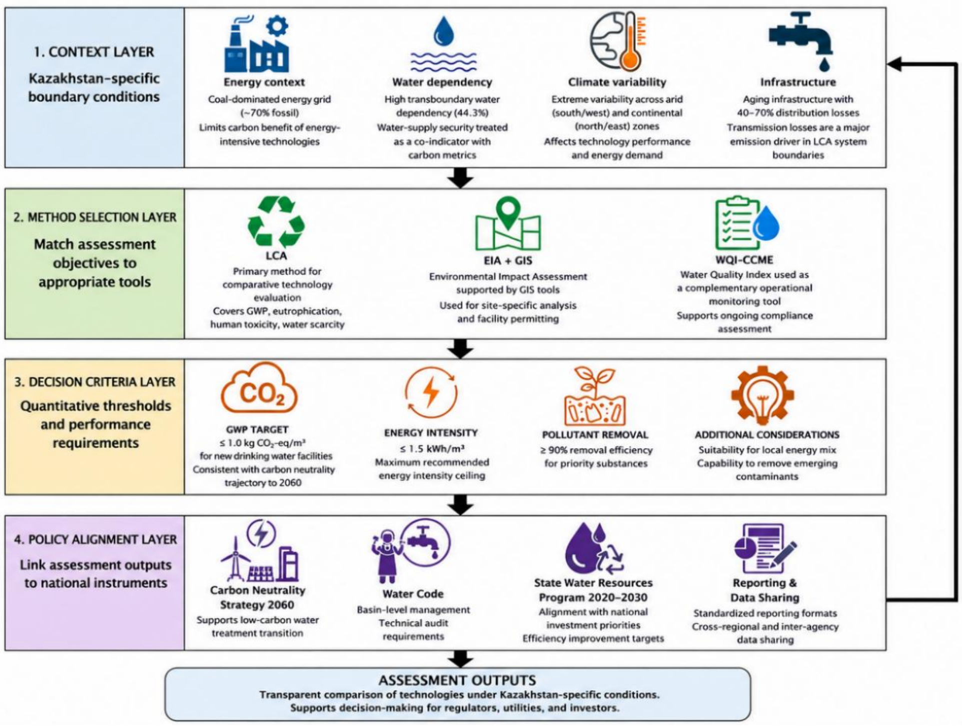

Figure 6. Proposed multi-level environmental assessment framework for low-carbon water treatment in Kazakhstan (Source: developed by authors)

Method limitations and knowledge gaps

Current LCA approaches exhibit methodological weaknesses, including limitations in accounting for ecosystem specificity, lack of dependable data for sludge disposal impacts, and difficulties in comparative analyses due to non-standardized approaches (Alvarado et al., 2020). The requirement for extensive data makes generalized models challenging to apply across different heavy metal migration and adsorption systems (Muratkhanov et al., 2024).

Chemical treatment methods demonstrate fundamental effectiveness limitations, with historical approaches achieving only 75 % pollutant removal (Gula et al., 2020). Current treatment facilities in Kazakhstan often do not meet water quality standards (Ospanov et al., 2020), indicating persistent technical gaps. An overview of these aspects is shown in Table 5.

Table 5. Methodological weaknesses

Limitation category	Specific issues	Sources
Data availability	Sparse datasets, outdated information	Multiple
Parameter coverage	Missing emerging pollutants	5 studies
Scope restrictions	Gate-to-gate limitations, construction phase exclusion	4 studies
Ecotoxicity gaps	Unexplained toxicity, missing NH_3 assessment	3 studies
Standardization	Non-transparent results, varying methodologies	4 studies

Several studies identify critical parameters absent from current assessment frameworks. Emerging pollutants including persistent organic compounds, pharmaceuticals, and pesticides require incorporation into monitoring protocols. Only 33 of 65 priority substances and contaminants of emerging concern have been assessed using LCA approaches (Pesqueira et al., 2020).

Two critical knowledge gaps deserve particular emphasis for Kazakhstan. Sludge disposal represents a largely unaddressed environmental liability in the reviewed literature: while 12 of the 18 Kazakhstan-focused studies assess water or wastewater treatment processes, none provides a comprehensive environmental assessment of the resulting sludge streams. This is especially significant given that Kazakhstan's treatment facilities produce an estimated 1.2–1.8 million tons of sludge annually (based on treated volume data reported in Figure 4), with current disposal predominantly via open lagoons. The absence of life-cycle sludge data means that reported GWP values for Kazakhstani treatment systems are systematically underestimated. Future assessments must account for methane emissions from anaerobic sludge decomposition, energy recovery potential via anaerobic digestion, and heavy metal leaching risks in arid soil conditions.

Contaminants of emerging concern (CECs) including microplastics, pharmaceutical residues, endocrine-disrupting compounds, and per- and polyfluoroalkyl substances (PFAS) are entirely absent from Kazakhstan's current regulatory monitoring framework and from the reviewed assessment literature. This gap is not merely academic: Kazakhstan's agricultural-chemical sector (pesticides, fertilizers) and oil-and-gas industry create documented exposure pathways for CECs into surface and groundwater bodies (Kalmakhanova et al., 2025). Globally, only 33 of 65 priority substances have been assessed through LCA frameworks (Pesqueira et al., 2020), and none of the Kazakhstan-focused studies in this review incorporates CEC monitoring. Establishing a baseline CEC monitoring protocol, aligned with EU Water Framework Directive priority substance lists as a reference standard, is identified as the single highest-priority methodological gap for future primary research in Kazakhstan.

The lack of information on transformation product effects compromises LCA effectiveness, leading to underestimation of avoided impacts. Indirect and supply chain effects receive insufficient guidance in current ecological impact assessment frameworks (Orchard et al., 2025).

For industrial wastewater assessment, reliance on total organic carbon (TOC) measurements proves insufficient for comprehensive hazard identification. Studies demonstrate that whole effluent toxicity may increase while TOC decreases during treatment, revealing fundamental limitations in surrogate parameter approaches (Köhler, 2006).

Kazakhstan faces significant capacity constraints in implementing comprehensive environmental assessment. The green financing direction remains at an early development stage, limiting implementation of innovative assessment and treatment technologies. Technical specialists require training on emerging methodologies.

Traditional monitoring methods are costly and time-consuming, providing only point-based assessments rather than spatial coverage. The implementation of permanent monitoring stations and real-time systems as mandated by the ecological code requires substantial infrastructure investment (Zhalmagambetova et al., 2024).

Recommendations

Kazakhstan should establish a standardized national LCA protocol for water treatment systems calibrated to local environmental conditions. At minimum, the protocol should require: (1) Kazakhstan-specific electricity emission factors reflecting the current coal-dominated energy structure (~70 % fossil-based generation), (2) regionalized life-cycle inventory datasets for major hydrological basins, particularly the Aral Sea and Balkhash systems, including pumping demand, climatic variability, and sludge management pathways, and (3) harmonized definitions for functional units, system boundaries, and impact categories to ensure inter-study comparability. Future assessments should adopt mandatory multi-criteria evaluation rather than carbon-only reporting and include, at minimum, global warming potential, eutrophication, water scarcity, and human toxicity indicators.

For new municipal water-treatment infrastructure, comparative environmental assessment should apply explicit benchmark values of ≤ 1.0 kg CO_2 -eq/m^3 for global warming potential and ≤ 1.5 kWh/m^3 for operational energy intensity. Technologies exceeding these thresholds should require justification through demonstrated improvements in water security, contaminant removal, or regional resilience. Sludge treatment and disposal must be incorporated into all future LCAs, as omission of downstream sludge emissions systematically underestimates environmental burdens under Kazakhstan's arid climatic conditions.

At the regulatory level, Kazakhstan should introduce a unified environmental risk assessment methodology for chemically hazardous facilities, expand monitoring frameworks to include contaminants of emerging concern (PFAS, pharmaceuticals, microplastics, endocrine-disrupting compounds), and integrate whole effluent toxicity testing into routine compliance monitoring. Basin-level ecological flow standards should additionally be harmonized with the Water Code to ensure methodological consistency between environmental assessment and national water governance objectives.

5. Conclusion

Current environmental assessment methods in Kazakhstan, dominated by Life Cycle Assessment and supplemented by country-specific tools such as integrated groundwater modeling and GIS-based impact assessment, effectively identify point-source pollution impacts and enable quantified mitigation outcomes when translated into engineering solutions, but their overall contribution is substantially limited by the absence of a unified national risk assessment methodology, inadequate monitoring of emerging pollutants and whole effluent toxicity, insufficient green financing, and critical trade-offs where carbon-reducing treatment approaches may shift environmental burdens to other impact categories such as eutrophication.

A comprehensive analysis of Kazakhstan's water treatment landscape reveals a critical juncture where environmental sustainability, energy transition, and institutional reform intersect. Kazakhstan's path to carbon neutrality by 2060 requires a systematic transition of the water sector toward low-carbon and renewable-energy- driven solutions - a direction this review has mapped through evidence-based framework analysis. This transition is not merely an environmental imperative but also a socioeconomic one, as inefficient water management directly impacts agricultural productivity and economic output. Kazakhstan's water-energy nexus presents both crises and opportunities: the nation's ability to halve irrigation losses through RES-integrated infrastructure could conserve 12 km^3 annually, equivalent to 15 % of current withdrawals. Existing projects such as the Kenderli SWRO facility demonstrate scalable models, while the integration of solar, wind, and geothermal energy into water treatment infrastructure offers a viable pathway to reduce operational costs by 30–50 %. However, success depends on overcoming institutional inertia and intermittency challenges, and on securing $5–7 billion in investments by 2030 for a full RES transition in urban water plants. As global temperatures rise and transboundary pressure increases, Kazakhstan must champion regional water diplomacy while fast-tracking homegrown innovations. By linking renewable energy generation with governance reform, Kazakhstan can set a precedent for sustainable water management across arid regions worldwide.

6. Supplementary Materials: No supplementary material.

7. Author Contributions

Conceptualization - A.R.; methodology - A.R., Y.M.; software - A.R.; validation - A.R., L.T., Y.M.; formal analysis - A.R., Y.M.; investigation - A.R., S.S.; resources - Y.P.; data curation - A.R., S.K.; writing - original draft preparation - A.R.; writing - review and editing - L.T., Y.M., S.S., S.K., Y.P.; visualization - A.R., S.K.; supervision - Y.P.; project administration - Y.P.; funding acquisition - Y.P. All authors have read and agreed to the published version of the manuscript.

8. Author Information

Ramazan, Akhmet - PhD student, Department of Ecology and Safety, Sh. Yessenov Caspian University of Technology and Engineering, bld.1, 32-nd microdistrict, Aktau, Kazakhstan, 130000; akhmet.ramazan@yu.edu.kz, https://orcid.org/0009-0001-3264-6004

Taizhanova, Lyailim - PhD, Associate Professor, Department of Ecology and Safety, Sh. Yessenov Caspian University of Technology and Engineering, bld.1, 32-nd microdistrict, Aktau, Kazakhstan, 130000; lyailim.taizhanova@yu.edu.kz, https://orcid.org/0000-0002-9617-3218

Muralev, Yevgeniy - PhD, Associate Professor, Director, Research Institute for Sustainable Development of Arid Territories, Sh. Yessenov Caspian University of Technology and Engineering, bld.1, 32-nd microdistrict, Aktau, Kazakhstan, 130000; yevgeniy.muralev@yu.edu.kz, https://orcid.org/0009-0006-6041-6341

Koibakova, Symbat - PhD, Associate Professor, Department of Ecology and Safety, Sh. Yessenov Caspian University of Technology and Engineering, bld.1, 32-nd microdistrict, Aktau, Kazakhstan, 130000; symbat.koibakova@yu.edu.kz, https://orcid.org/0000-0002-7866-2341

Syrlybekkyzy, Samal - PhD, Associate Professor, Department of Ecology and Safety, Sh. Yessenov Caspian University of Technology and Engineering, bld.1, 32-nd microdistrict, Aktau, Kazakhstan, 130000; samal.syrlybekkyzy@yu.edu.kz, https://orcid.org/0000-0002-0260-0611

Pangaliyev Yerbol Mahambetuly - PhD, Associate Professor, Department of Ecology and Safety, Sh. Yessenov Caspian University of Technology and Engineering, bld.1, 32-nd microdistrict, Aktau, Kazakhstan, 130000; yerbol.pangaliyev@yu.edu.kz, https://orcid.org/0000-0002-2392-4180

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Қазақстандағы су тазарту саласындағы экологиялық бағалау әдістеріне шолу: тәсілдер, қиындықтар және төмен көміртекті су ресурстарын басқаруға көшу жолдары

Ахмет Рамазан, Ляйлим Тайжанова, Евгений Муралев, Самал Сырлыбекқызы, Сымбат Койбакова, Ербол Панғалиев

Аңдатпа. Қазақстанның су шаруашылығы саласы құрылымдық су тапшылығы, инфрақұрылымның тозуы, трансшекаралық су ресурстарына тәуелділік және дәстүрлі су тазарту жүйелерінің жоғары көміртекті қарқындылығы салдарынан артып келе жатқан қысымға ұшырауда. Бұл шолуда су тазарту технологияларына қолданылатын экологиялық бағалау тәсілдері қарастырылып, олардың төмен көміртекті шешімдерге жарамдылығы және Қазақстан жағдайына сәйкестігі бағаланады. PRISMA әдіснамасына сәйкес 2005–2025 жылдар аралығында Scopus және Web of Science дерекқорларында индекстелген рецензияланатын ғылыми еңбектер іріктеліп, нәтижесінде 40 зерттеу синтезделді. Өмірлік циклді бағалау әдебиеттерде басым қолданылатын әдіс болып табылады және ғаламдық жылыну әлеуетін, энергия тұтынуын және әртүрлі әсер санаттары арасындағы ымыраларды сандық түрде бағалау үшін пайдаланылады. Кері осмос пен жетілдірілген мембраналық жүйелер салыстырмалы түрде төмен көміртекті технологиялар ретінде жиі аталады, алайда олардың өмірлік цикл көрсеткіштері энергиямен қамту құрылымына және суды айдау талаптарына айтарлықтай тәуелді, ал бұл факторлар негізгі шығарындылар көздері болып саналады. Қазақстанға тән зерттеулер саны аз және әдістемелік тұрғыдан біркелкі емес, бұл аймақтық өмірлік цикл инвентарлық деректерінің, жергілікті энергия қоспасының және климаттық ерекшеліктердің жетіспеушілігіне байланысты ұлттық деңгейде сенімді бағалау жүргізуді қиындатады. Шолу нәтижелері техникалық мүмкіндіктің өзі төмен көміртекті нәтиже алуға жеткіліксіз екенін көрсетеді. Сондықтан технологияларды таңдау, ымыраларды бағалау және саясатты негіздеу үшін өңірлік контекстке бейімделген, стандартталған бағалау әдістемелері қажет. Мұндай тәсілдер Қазақстанның су ресурстарын тұрақты әрі төмен көміртекті басқаруға көшуін жеделдетуге мүмкіндік береді.

Түйін сөздер: төмен көміртекті технология; суды тазалау; экологиялық бағалау; жаңартылатын энергия көздері.

Обзор методов экологической оценки водоочистки в Казахстане: подходы, вызовы и пути к низкоуглеродному управлению водными ресурсами

Ахмет Рамазан, Ляйлим Тайжанова, Евгений Муралев, Самал Сырлыбекқызы, Сымбат Койбакова, Ербол Панғалиев

Аннотация. Водный сектор Казахстана сталкивается с усиливающимся давлением, обусловленным структурным дефицитом водных ресурсов, изношенной инфраструктурой, зависимостью от трансграничных водных источников и высокой углеродоёмкостью традиционных систем водоочистки. В данном обзоре анализируются подходы к экологической оценке, применяемые в сфере водоочистки, с акцентом на их применимость для низкоуглеродных решений и релевантность для условий Казахстана. В соответствии с методологией PRISMA были отобраны и проанализированы рецензируемые публикации, индексируемые в базах данных Scopus и Web of Science за период с 2005 по 2025 годы; в итоговый синтез включено 40 исследований. Анализ жизненного цикла является доминирующим методологическим подходом в рассмотренной литературе и широко используется для количественной оценки потенциала глобального потепления, энергоёмкости и компромиссов между различными категориями экологического воздействия. Обратный осмос и современные мембранные системы часто рассматриваются как относительно низкоуглеродные технологии, однако их экологическая эффективность на протяжении жизненного цикла в значительной степени зависит от источников энергии и потребностей в перекачивании воды, которые определяются как основные очаги выбросов. Исследования, ориентированные непосредственно на Казахстан, остаются ограниченными и методологически неоднородными, что затрудняет проведение надёжных национальных оценок из-за недостатка региональных данных инвентаризации жизненного цикла, а также ограниченного учёта локального энергетического баланса и климатических условий. Результаты исследования показывают, что одной лишь технической реализуемости недостаточно для достижения низкоуглеродных результатов. Для оценки компромиссов, выбора технологий и разработки эффективной политики необходимы адаптированные к региональным условиям и стандартизированные системы экологической оценки. Без регионально калиброванных инвентаризационных данных и унифицированных протоколов отчётности выбор технологий в водном секторе Казахстана будет по-прежнему определяться преимущественно стоимостью, а не подтверждёнными показателями углеродной эффективности.

Ключевые слова: низкоуглеродные технологии; водоочистка; экологическая оценка; возобновляемая энергия.