http://dx.doi.org/10.18623/rvd.v23.n2.4139

MEMBRANE BIOREACTORS FOR WATER PROTECTION IN KASHKADARYA PROVINCE, UZBEKISTAN

BIORREATORES DE MEMBRANA PARA PROTEÇÃO DA ÁGUA NA PROVÍNCIA DE KASHKADARYA, NO UZBEQUISTÃO

Article received on: 8/28/2025
Article accepted on: 11/26/2025

Abdukadirova Maloxat*
Tashkent Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan
Orcid: https://orcid.org/0000-0003-1188-2662
mabduqodirova78@mail.ru

Radkevich Maria*
*"Tashkent Irrigation and Agricultural Mechanization Engineers" National Research University, Tashkent, Uzbekistan
Orcid: https://orcid.org/0000-0003-2490-2693
m.radkevich@tiiame.uz

Mutalov Azamat**
**LLC "Textile Industry Park (SSP), Tashkent, Uzbekistan
Orcid: https://orcid.org/0009-0007-1650-9767
textilesspuz@gmail.com

Avlakulov Meili***
***Karshi State Technical University, Karshi, Uzbekistan
Orcid: https://orcid.org/0000-0002-8154-1153
mavlakulov@mail.ru

The authors declare that there is no conflict of interest

Abstract
The Kashkadarya region of Uzbekistan is experiencing significant water ecosystem degradation due to the discharge of 7 million m³/year of inadequately treated wastewater, resulting in elevated mineralisation, organic/microbiological pollution, and eutrophication. Climate change, typified by a 75% glacier loss within a 15-year timespan, has led to a marked intensification of water scarcity. The present study assesses membrane bioreactor (MBR) technology for sustainable wastewater reuse. MBRs have been shown to remove 97–98% of organic pollutants (BOD5 < 6 mg/L), thereby preventing 1,416–2,511 t/year of organic matter and 220–365 t/year of nitrogen from entering the river. In addition, they achieve >99.9% pathogen removal, ensuring safe irrigation. Notwithstanding the fact that capital costs are 13–15% higher than those of conventional systems (645 vs. 570 million USD), resulting in a financial net present value (NPV) of –670 million USD, inclusive of 149 million USD in ecosystem benefits, the socio-economic NPV is nevertheless –520 million USD. It is

Resumo
A região de Kashkadarya, no Uzbequistão, está a experienciar uma degradação significativa do ecossistema hídrico, resultante do despejo de 7 milhões de metros cúbicos por ano de águas residuais tratadas de forma inadequada. Este fenómeno está associado a elevados níveis de mineralização, poluição orgânica e microbiológica, e eutrofização. As alterações climáticas, manifestadas pela perda de 75% das geleiras no espaço de 15 anos, resultaram numa intensificação acentuada da escassez de água. O presente estudo avalia a tecnologia do biorreator de membrana (MBR) no contexto da reutilização sustentável de águas residuais. Os MBRs demonstraram remover 97-98% dos poluentes orgânicos (BOD5 < 6 mg/L), evitando, deste modo, que 1.416-2.511 t/ano de matéria orgânica e 220-365 t/ano de azoto entrem no rio. Adicionalmente, estes dispositivos alcançam uma taxa de remoção de patógenos superior a 99,9%, garantindo uma irrigação segura. Em conformidade com os dados apresentados, verifica-se que os custos de capital são 13-15% superiores aos custos dos

posited that MBRs, with government support ranging from 35 to 40 per cent, may offer the most viable solution for regions experiencing water scarcity.
Keywords: Arid Regions. Ecosystem Protection. Membrane Bioreactor. Sustainable Water Management. Water Reuse.

sistemas convencionais (645 contra 570 milhões de dólares). Este facto resulta num valor presente líquido (VPL) financeiro de -670 milhões de dólares, incluindo 149 milhões de dólares em benefícios para o ecossistema. O VPL socioeconómico é, no entanto, de -520 milhões de dólares. Supõe-se que os MBRs, com um apoio governamental variável entre 35 e 40%, possam constituir a solução mais viável para regiões afetadas pela escassez de água.

Palavras-chave: *Regiões Áridas. Proteção do Ecossistema. Biorreator de Membrana. Gestão Sustentável da Água. Reutilização da Água.*

1 INTRODUCTION

Water scarcity and inadequate wastewater treatment infrastructure pose critical challenges to the sustainable development of Central Asian countries, particularly in arid and semi-arid regions (Rahman *et al*., 2024). The Kashkadarya region of Uzbekistan is a striking example of these problems, with insufficient sewerage coverage and outdated treatment facilities that do not meet modern environmental standards.

2 LITERATURE REVIEW

Membrane bioreactor (MBR) technology has emerged as a leading solution for wastewater treatment and reuse, particularly in regions experiencing water scarcity. Bolzonella *et al*. (2010) demonstrated the effectiveness of MBR systems in a Mediterranean climate, achieving superior results in the removal of both conventional and specific pollutants compared to traditional activated sludge processes. The study revealed a substantial decrease in coliform bacteria and E. coli, rendering the treated water fit for agricultural reuse.

Recent advances in MBR technology include improvements in energy efficiency and treatment performance. Rahman *et al*. (2023) presented a thorough review of MBR development for sustainable industrial wastewater management, emphasising the technology's capacity to handle variable loads while ensuring consistent water quality. The authors particularly noted the advantages of MBR systems in hot climates, where elevated temperatures enhance biological activity.

The application of MBR technology in arid regions has been extensively studied to date. Rahman *et al*. (2024) investigated small-scale decentralised technologies for treating highly concentrated wastewater in arid and semi-arid regions. Their findings confirm that MBR systems are the optimal solution for water recovery and reuse where high-quality treated effluent is required.

Hybrid membrane bioreactor (MBR) systems show promising results in producing high-quality treated effluent. Tay *et al*. (2018) compared nanofiltration MBR (NF-MBR) and ultrafiltration MBR (UF-MBR) processes combined with reverse osmosis, achieving a water recovery efficiency of 90%. Similarly, Gündoğdu *et al*. (2018) investigated integrating MBR with NF/RO processes for industrial wastewater recovery and reported significant improvements in treated water quality.

2.1 Regional characteristics of the problem

The Kashkadarya region is one of the regions in Uzbekistan with the most problematic water supply and management. Its water supply and sanitation infrastructure, largely inherited from the Soviet era, requires comprehensive modernisation to meet current needs and environmental standards. The inadequate treatment of wastewater has resulted in untreated effluent being discharged directly into water bodies, creating significant environmental and public health risks.

Comprehensive environmental monitoring of the Kashkadarya River has revealed critical degradation of aquatic ecosystems. The absence of functioning treatment facilities results in the annual discharge of over 7 million cubic metres of untreated wastewater directly into the river. According to Sagdullaeva *et al*. (2022), the river and collector-drainage network water is characterised by high mineralisation, organic pollution, eutrophication and the presence of pathogenic microorganisms, rendering it unsuitable for irrigation and posing an epidemiological risk to the population.

Climate change is exacerbating the environmental situation: over the past 15 years, the area of snow and ice cover in the Kashkadarya basin has decreased by 75%, while the average annual temperature has increased by 0.21°C. This has led to a decrease in river flow and exacerbated water shortages (Salokhiddinov *et al*., 2023). Intensive irrigation and population growth are putting increased pressure on water resources, resulting in active soil salinisation and degradation processes, reduced agricultural productivity and accelerated desertification (Suyunov *et al*., 2025; Gafurova *et al*., 2024). The historic canals of Shakhrisabz, which are listed as a UNESCO World Heritage Site, are undergoing biological degradation due to the inflow of untreated wastewater. This threatens not only the region's ecosystems, but also its cultural heritage.

In order to restore the ecological balance of water systems, effective treatment technologies must be introduced immediately to ensure that the water is safe for the environment and for reuse in irrigation.

2.2 MBR in Uzbekistan: application experience

Recent developments in Uzbekistan demonstrate a growing interest in implementing MBR technology. Notable examples include the 600 m^3/day MBR system developed for the Kogonsky Oil and Gas Energy Enterprise by the Turkish company PH Group in 2022. This project utilised reinforced PVDF membranes with a pore size of 0.04 µm and a three-point aeration system with an MLT (Modified Ludzack-Ettinger) process configuration for nitrogen removal, achieving high pathogen removal rates and a compact plant design. This experience provides valuable guidelines for regional deployment, including technology transfer protocols, staff training requirements and performance validation under extreme temperatures.

2.3 Research objectives

This study aims to:

(1) assessing the current state of water supply and sanitation systems in the Kashkadarya region;

(2) identifying problem areas and their causes;

(3) forecasting infrastructure development scenarios until 2035;

(4) assessing the technical and economic feasibility of MBR technology, taking financial and socio-economic aspects into account;

(5) developing recommendations for phased implementation, taking the limitations of available information into account.

3 METHODS

3.1 Data collection and analysis

A comprehensive approach was used to collect data from various sources in order to assess regional water infrastructure and the economic feasibility of implementing MBR technology. Primary data sources included official documentation from the French Development Agency (AFD) and the Asian Development Bank (ADB), as well as project feasibility studies and infrastructure assessment reports. Technical documentation was obtained from the Uzbekistan Ministry of Housing and Utilities (MHU). Regional statistics were obtained from the State Statistics Committee of Uzbekistan, as well as from Uzsuvtaminot JSC (Uzbek Water Supply), covering the period from 2020 to 2025.

Data access restrictions: Significant portions of the technical and financial documentation remain confidential and are the property of the funding agencies and implementing organisations. This includes cost breakdowns, specific contractor proposals and institutional capacity sensitivity assessments. The absence of access to primary laboratory data on wastewater composition, pilot measurements of membrane performance under local conditions and sociological surveys of population willingness to pay for improved services restricts the accuracy of certain quantitative estimates. Consequently, the analysis relies on project documentation, published data on comparable projects, and expert evaluations by international consultants.

Population and demographic data were extracted from official census records and municipal registration systems, and were then cross-checked with utility customer databases. Infrastructure condition assessments were based on field surveys conducted by AFR consultants and supplemented by historical maintenance records.

3.2 Infrastructure assessment methodology

A systematic approach was used to evaluate the current performance of water supply and sewerage systems. The water supply system assessment included an analysis of water source capacity, treatment plant performance, the condition of the 9,783.2 km distribution network and an evaluation of 500 operational water intake facilities.

The sewerage system analysis focused on the level of service coverage, the operational status of treatment plants and compliance with environmental requirements. The methodology included field surveys of existing collector systems and a detailed technical assessment of defunct Soviet-era treatment plants in Shakhrisabz.

3.3 Analysis of economic indicators

The economic assessment used established ADB methodologies for analysing investments in water infrastructure (ADB, 1999; ADB, 2017). This included financial analysis from the perspective of the utility company and socio-economic analysis from the perspective of society. The methodology for the economic assessment of NPV, IRR and the payback period followed the cost-benefit analysis principles outlined by Stokey and Zeckhauser (1978) and developed in contemporary international financial institution guidelines (Boardman *et al*., 2018).

The financial analysis included:

- assessment of capital expenditures (CAPEX) using a bottom-up methodology based on regional construction costs and international technology pricing
- analysis of operating expenditures (OPEX), based on energy consumption, chemicals, membrane replacement and labour requirements
- assessment of direct revenues from the sale of treated water for irrigation
- calculation of financial NPV, IRR and payback period.

The socio-economic analysis also included a quantitative assessment of indirect benefits, such as:

- health benefits through reduced treatment costs for diseases;
- environmental benefits from damage prevention;
- benefits from increased agricultural productivity through production functions;
- protection of tourism revenues from visits to UNESCO heritage sites.

The discounting methodology employed a real discount rate of 8%, which is consistent with Uzbekistan's national planning parameters. The sensitivity analysis assessed the impact of uncertainty in key parameters on investment outcomes.

Capital costs were calculated based on aggregate indicators from the AFR project documentation (2023–24), international price lists from membrane equipment manufacturers (Toray, Koch and Mitsubishi), and experience from completed projects in

Central Asia. The range of uncertainty is ±20–25% due to the confidentiality of detailed estimates and exchange rate volatility.

3.4 Comparative assessment of technologies

A multi-criteria analysis was used for the comparative technological assessment, which included technical performance, economic feasibility, environmental impact and operational sustainability. The alternative technologies evaluated for the comparative analysis were:

- traditional activated sludge systems;
- extended aeration processes;
- stabilisation ponds;
- constructed wetlands;
- decentralised modular MBRs.

Each technology was evaluated against standardised criteria, taking into account the specifics of the application (e.g. urban or rural areas and high or low building density).

3.5 Scenario approach

To account for the uncertainty of key parameters, three development scenarios were developed using a scenario approach.

Baseline scenario: current assumptions on tariffs, energy costs, demand for treated water and implementation timelines.

Optimistic scenario: a 20% increase in demand for treated water; a 10% reduction in CAPEX through localisation of component production; and a 15% reduction in energy costs through integration of renewable energy.

Pessimistic scenario: a 50% decrease in demand for treated water due to competition with traditional sources of irrigation water; a 30% increase in energy costs; a 3-year delay in commissioning facilities; and a 20% increase in CAPEX.

3.6 Environmental impact assessment

The environmental performance of treatment technologies was assessed using published data from a comprehensive environmental study of the Kashkadarya River. This study included chemical, microbiological and parasitological analyses, as well as GIS analysis and remote sensing (Sagdullaeva *et al*., 2022; Salokhiddinov *et al*., 2023; Nasrulin & Kan, 2023).

Baseline condition of water resources. According to the monitoring results (Sagdullaeva *et al*., 2022; Chembarisov *et al*., 2024), the Kashkadarya River is currently characterised by:

- high water mineralisation, exceeding acceptable irrigation standards;

- significant organic pollution due to a lack of treatment facilities;

- eutrophication caused by an excess of biogenic elements;

- microbiological pollution posing an epidemiological threat.

These data were used to assess the reduction in environmental impact when treatment technologies are implemented. These data were used to assess the reduction in environmental impact when treatment technologies are implemented.

Criteria for assessing environmental impact: The following criteria were used for the quantitative assessment:

- Water resource protection: reduction in the mass of pollutants (BOD_5, suspended solids, nitrogen and phosphorus) in tons per year, based on WHO guidelines (WHO, 2006) and economic analysis standards (ADB, 2017; Boardman *et al*., 2018).
- Prevention of eutrophication: reduction in the inflow of biogenic elements into surface water bodies (Metcalf & Eddy, 2014).
- Microbiological safety: quantitative assessment of the reduction in epidemiological risks due to a decrease in pathogen concentrations (WHO, 2006; Haas *et al*., 1999).
- Biodiversity conservation: qualitative assessment of the potential for restoration of aquatic ecosystems based on biotic indices (Metcalf & Eddy, 2014).
- Soil resource protection: preventing the salinisation and degradation of irrigated land in the context of the desertification of agricultural landscapes in the region

(Suyunov *et al*., 2025; Gafurova *et al*., 2024), using the criteria for the quality of irrigation water (Ayers & Westcot, 1985).

Quantitative assessment methodology. Reduction in pollutant discharge was calculated based on design wastewater volume (67.16 million m^3/year), typical domestic wastewater concentrations in Central Asia (Metcalf & Eddy, 2014) and removal efficiency for each technology (Wisniewski, 2007; Bolzonella *et al*., 2010).

Greenhouse gas emissions assessment. The carbon footprint of the technologies was assessed using empirical data for MBR systems (Mannina *et al*., 2018; Cashman *et al*., 2018). Direct emissions (N_2O and CH_4 from bioprocesses) and indirect emissions (energy consumption and Uzbekistan's electricity grid factor of 0.58 kg CO_2/kWh) were taken into account, as well as emissions from sludge disposal. The scenario analysis included traditional AS, MBR, MBR with RES and anaerobic MBR.

Monetisation of environmental benefits. The economic assessment was performed using the benefit transfer method with regional adjustments (ADB, 1999). The following were assessed: damage to aquatic ecosystems, morbidity (using the cost of illness method), irrigation yield, protection of UNESCO sites and carbon credits (valued at $15–25/t CO_2-eq). The present value was calculated at an 8% discount rate over 25 years.

4 RESULTS

4.1 Current state of water infrastructure

The Kashkadarya region has a population of 3,639,318, 60.96% (2,218,655) of whom are covered by a centralised water supply system. The system comprises 500 water intake facilities with a design capacity of 595,500 m^3/day, producing 372,000 m^3/day in practice. The distribution network covers 9,783.2 km, 507.3 km (5.2%) of which require reconstruction.

There are critical shortcomings in sewerage coverage: in Shakhrisabz (population 135,000), only 20% of households are connected to the sewerage system and the treatment facilities built during the Soviet period are non-functional; in Kitab (population 45,000), there is no centralised sewerage system; and in Karman (population 50,000), the water supply has been modernised but there is no sewerage system.

Regional plans up to 2035 include the construction of 627.3 km of sewer collectors, 50,350 household connections, 26 pumping stations and three modern treatment facilities, with the aim of achieving 80% coverage in large cities.

According to the current regulatory framework, wastewater quality must meet the standards for category 2 water bodies as defined in Sanitary standards and norms No. 0318-2015 'Hygienic and anti-epidemic requirements for the protection of water bodies in the Republic of Uzbekistan', which stipulates particularly strict BOD_5 limits of 6 mg/l. However, this standard significantly exceeds the capabilities of traditional activated sludge treatment (typical BOD_5 = 15–20 mg/l), providing a technical justification for the use of advanced treatment technologies, such as MBR.

4.2 Comparative analysis of technologies

To assess the suitability of MBR, a multi-criteria comparative analysis of alternative technologies was conducted (see Table 1).

It can be concluded that MBR is optimal for urban conditions with high building density and strict requirements for the quality of treated effluent. For rural areas with available land, constructed wetlands are more economical.

Table 1

Comparative analysis of treatment technologies.

Criterion	MBR	Traditional AS	Constructed wetlands
CAPEX (per capita)	$1,200–1,500	$800–1,000	$300–500
Land use	0.3–0.5 m²/person	1–1.5 m²/person	5–10 m²/person
BOD_5 at outlet	<6 mg/L	15–20 mg/L	15–25 mg/L
Pathogen removal	>99.9%	90–95%	95–98%
Suitability for irrigation	Yes, without additional treatment	Additional treatment required	Additional treatment required.
Applicability in cities	Optimal	Acceptable	Limited

4.3 Economic analysis

Table 2 presents a summary assessment of capital expenditure (CAPEX), calculated on the basis of aggregate indicators from the project documentation and experience from completed projects in Central Asia.

Table 2

Comparative assessment of capital expenditures

Component	Traditional AS	MBR
Treatment facilities	$147.2 million	$220.8 million
Network infrastructure	$425.0 million	$425.0 million
Total CAPEX	$572.2 million	$645.8 million (+12.9%)

The $73.6 million difference is due to the cost of membrane modules (imported equipment), enhanced automation and engineering costs. Network infrastructure accounts for 74% of total costs and remains consistent across all technologies.

4.4 Operating expenses (OPEX)

Annual operating expenses (OPEX) were calculated at an average estimate for a total capacity of 184,000 m³/day (see Table 3).

The main factors contributing to the increase in MBR costs during the operational phase are:

- increased energy consumption ($3.0 million vs. $1.7 million);

- membrane replacement ($1.5 million per year); and

- consumption of cleaning chemicals ($0.95 million per year). These operating costs are partially offset by reduced personnel costs due to automation ($0.9 million vs. $1.2 million).

Table 3

Annual operating expenses.

Component	Traditional AS	MBR
Energy	$1.67 million	$2.95 million
Chemicals	$0.85 million	$0.95 million
Membranes	—	$1.50 million
Labour	$1.20 million	$0.90 million
Maintenance	$1.15 million	$1.25 million
Total OPEX	$4.87 million	$7.55 million (+55%)

4.5 Assessment of environmental risk reduction

Implementing MBR provides a quantifiable reduction in environmental risks compared to traditional treatment methods and the current situation. Table 4 shows the reduction in pollutant discharge. Table 5 shows the reduction in greenhouse gas emissions due to the implementation of MBR in different variants. Table 6 shows the environmental benefits in monetary terms, taking into account the discounted value over 25 years at an interest rate of 8%.

Table 4

Reduction in pollutant discharge (at a capacity of 67.16 million m³/year).

Parameter	Without treatment	Traditional active sludge (AS)	MBR	Reduction (MBR vs. without treatment)
BOD_5, tonnes/year	16,790	1,343	403	97.6%
Suspended solids (t/year)	20,148	2,015	336	98.3%.
Total nitrogen (TKN), t/year	4,030	1,612	403	90.0%
Total phosphorus (T-P), t/year	672	336	67	90.0%
Pathogens (E. coli), CFU/100 ml	10^6–10^7	10^3–10^4	<10	>99.99%

Note: calculations based on typical domestic wastewater concentrations (BOD_5 = 250 mg/L, COD = 300 mg/L, N = 60 mg/L, P = 10 mg/L) and the removal efficiency of each technology.

Table 5

Estimated reduction in greenhouse gas emissions

Emissions source	Conventional active sludge	MBR	MBR + RES	MBR + RES + AnMBR
Direct emissions (N_2O, CH_4), t CO_2-eq/year	2,850	1,990	1,990	1,590
Indirect emissions (energy), t CO_2-eq/year	4,200	7,400	740–1,180	370–590
Emissions from sludge, t CO_2-eq/year	1,800	1,080	1,080	540
Total emissions, t CO_2-eq/year	8,850	10,470	3,810–4,250	2,500–2,720
Total emissions, t CO_2-eq/year: 8,850	10,470	3,810–4,250	2,500–2,720.	
Reduction compared to conventional active sludge, %	–	+18	−(52…57)	−(69…72)

Note: calculation based on IPCC emission factors (2019) and data from Mannina *et al*. (2018) and Cashman *et al*. (2018). RES: renewable energy sources (84–95% reduction in indirect emissions). AnMBR: anaerobic scheme with biogas recovery.

Table 6

Estimation of environmental benefits in monetary terms.

Benefit category	Traditional AS	MBR	Difference
Prevented damage to aquatic ecosystems, million $	15.2	20.1	+4.9
Reduced morbidity (waterborne infections), million $: 18.5	23.5	+5.0	
Increased crop yields (quality irrigation), million $	65–95	95–138	+(30…43)
Protection of cultural heritage (UNESCO), million $	7.5	10.0	2.5
Carbon credits (when integrated with renewable energy), million $	—	8–12	+ 8–12
Total environmental benefits, million $	106–136	157–204	51–68

Note: carbon credits are calculated at a price of $15–25 per tonne of CO_2 equivalent, with a reduction in emissions of 5,000–6,000 tonnes of CO_2 equivalent per year relative to the baseline scenario.

Thus, MBR can provide additional environmental benefits of $51–68 million (present value) compared to conventional treatment. This exceeds the difference in CAPEX ($73.6 million) when carbon financing and the long-term benefits to agriculture are considered.

Direct revenues can be generated from the sale of treated water, amounting to $3.36–5.37 million per year (based on 67.16 million m³ at $0.05–$0.08 per m³).

Indirect benefits can be obtained in the following fields: (1) healthcare: $23.5 million; (2) environmental sector: $20.1 million; (3) agriculture: $95–138 million; (4) tourism (UNESCO site): $10 million /The total is $148.6–191.6 million.

The results of a comparative assessment of the indicators for traditional technology and MBR (costs over 25 years at an 8% discount rate) are presented in Table 7.

Table 7

Comparative assessment of financial and socio-economic indicators for treatment technologies.

Indicator	Traditional AS	MBR
Financial NPV, million $	−588.3	−669.1
Financial IRR, %	2.8	4.2
Payback period, years	22	18
Socio-economic NPV, million $	−522.9	−520.5
Socio-economic IRR, %	5.1	6.8

A negative IRR indicates the need for government subsidies (35–40% CAPEX in the form of grants is recommended). However, MBR has a higher IRR and shorter payback period thanks to revenues from selling premium-quality treated water.

4.6 Study limitations

The study has a number of significant limitations that must be taken into account when interpreting the results.

Limitations of the source data: There is no primary laboratory data on the composition of local wastewater, so calculations are based on typical concentrations for domestic wastewater in Central Asia. The actual composition of wastewater in Shakhrisabz, Kitab and Karman may differ due to local water consumption patterns, industrial discharges and climatic factors.

The absence of pilot measurements of membrane performance in the Kashkadarya region creates uncertainty when assessing the rate of membrane fouling at high temperatures (up to 45°C) and increased water salinity.

There are limitations to the economic assessment. The financial data of the AFR and ADB projects is largely confidential, necessitating the use of estimated parameters based on similar projects in the region. Data on the willingness of the population and farmers to pay for treated water is limited, affecting the reliability of revenue forecasts. The assessment of indirect benefits (health, environment and agriculture) was carried out using the benefit transfer method, which introduces additional uncertainty.

Limitations of the greenhouse gas emissions assessment: N_2O and CH_4 emission factors are based on international studies and may not fully reflect the specifics of biological processes at high temperatures in arid climates. There is no empirical verification of the carbon footprint of MBR in Uzbekistan.

To obtain accurate data for developing working projects for implementing MBR, preliminary pilot testing of the technology at a capacity of 500–1,000 m^3/day for 18–24 months is necessary due to these limitations.

5 DISCUSSION

5.1 Suitability of MBR for regional conditions

Due to its compactness (which is important in areas with high building density), ability to ensure compliance with Sanitary standards and norms No. 0318-2015 without additional treatment and stability under load fluctuations, MBR technology can be considered optimal for urban areas in the Kashkadarya region (Wisniewski, 2007). Experience from the Kogonsky project confirmed the operability of MBR at temperatures of up to 40–45 °C, though it was necessary to increase the frequency of chemical cleaning of the membranes.

These results are consistent with those of Bolzonella *et al*. (2010), who demonstrated the high efficiency of MBR systems in a Mediterranean climate for water reuse. Rahman *et al*. (2024) also confirm the suitability of MBR systems for arid regions where high-quality treated effluent is required for irrigation purposes. Kishino *et al*. (1996) demonstrated the successful use of submerged MBR systems for the reuse of domestic wastewater, consistent with the planned application in the Kashkadarya region.

However, using MBRs in rural areas with low population density, ample land and limited access to qualified personnel may be excessive and unjustified. Rahman *et al*. (2024) suggest that small decentralised systems are a more promising solution in such circumstances. Therefore, a hybrid approach could be recommended for the Kashkadarya region: MBRs for urban centres and constructed wetlands for the outskirts.

5.2 Environmental benefits and contribution to sustainable development

Implementing MBR in the Kashkadarya region is crucial for protecting the region's aquatic ecosystems. Currently, untreated or inadequately treated wastewater from Shakhrisabz, Kitaba, Karmani and other settlements is discharged into irrigation canals and surface watercourses. This leads to the eutrophication of water bodies and soil degradation, as well as the accumulation of pathogenic microorganisms in agricultural products (Bolzonella *et al*., 2010).

MBR can provide a comprehensive solution to the region's environmental problems. Firstly, removing 85–95% of biogenic elements (nitrogen and phosphorus) prevents eutrophication and preserves the biodiversity of aquatic ecosystems. Secondly, the membranes' barrier function (removal of pathogens >99.9%) eliminates microbiological contamination of soil and groundwater when treated wastewater is used for irrigation. Thirdly, the high quality of the treatment process (BOD_5 <6 mg/L and suspended solids <5 mg/L) meets the WHO and FAO recommendations for safe water reuse (Wisniewski, 2007).

Of particular importance is the protection of the historic centre of Shakhrisabz, a UNESCO World Heritage Site. The current state of the sewerage infrastructure (20% coverage and non-functional treatment facilities) poses a risk to archaeological sites due to rising groundwater levels and contamination. Implementing MBR will minimise the infiltration of contaminated wastewater and preserve the region's unique cultural heritage.

Additionally, the MBR contributes to the water sector's adaptation to increasing water scarcity in the context of climate change. Producing 67.16 million m^3 of premium-quality treated water per year is equivalent to 15–20% of the region's current water intake, thereby reducing the burden on groundwater aquifers.

Kharraz *et al*. (2022) emphasise that membrane technologies are a vital component of the circular water economy, facilitating the recovery of water, energy, and nutrients.

In addition to alleviating pressure on water resources, membrane bioreactor (MBR) systems can reduce direct emissions of nitrous oxide (N_2O) and other greenhouse gases compared to traditional activated sludge treatment systems, thanks to their more efficient removal of pollutants and optimisation of biological processes (Baresel, 2017; Mannina *et al*., 2018). Life cycle assessments (LCAs) show that MBRs generate less sludge, which reduces emissions from its disposal (Banti *et al*., 2020; Mofatto *et al*., 2024).

The main contributor to the carbon footprint of MBR systems is energy consumption (accounting for up to 80% of all emissions), rather than direct biological processes (Ioannou-Ttofa *et al*., 2016; Chen, 2019). This presents significant decarbonisation opportunities: using renewable energy sources could reduce MBR's overall carbon footprint by 84–95% (Mannina *et al*., 2020; Mofatto *et al*., 2024). In regions with high solar energy potential, such as the Kashkadarya region (with 3,043 hours of sunshine per year, according to Sharapova and Uzakov, 2024), the integration of photovoltaic systems is particularly promising. Furthermore, optimising aeration modes could reduce emissions by an additional 10–81% without incurring significant capital costs (Mannina *et al*., 2020; Mofatto *et al*., 2024).

Anaerobic MBRs (AnMBRs) offer further opportunities to reduce the carbon footprint by generating and utilising biogas (Cashman *et al*., 2018; Tran *et al*., 2024; Lei *et al*., 2024). Rong *et al*. (2025) and Yu *et al*. (2025) have demonstrated the high efficiency of AnMBRs in treating municipal wastewater, particularly when co-treated with food waste. The energy recovery potential is 0.3–0.5 m^3 of biogas per 1 m^3 of wastewater, which can offset some of the energy costs of operating the membranes (An *et al*., 2023).

5.3 Interpretation of economic results

According to the assessment results, all treatment technologies demonstrate a negative financial net present value (NPV), which is typical for water supply projects in developing countries with subsidised tariffs (ADB, 1999; ADB, 2017).

Despite higher CAPEX (+$73.6 million), MBR technology shows a higher IRR (4.2% vs. 2.8%) and a shorter payback period (18 years vs. 22 years), thanks to higher potential revenues from selling treated water (+60%) and lower personnel costs (−25%) due to automation. These results are consistent with the findings of Tay *et al*. (2018), who demonstrated a high water recovery efficiency of 90% when using hybrid MBR systems.

The monetary value of the project's environmental benefits accounts for a significant proportion of the total benefits. When these indirect benefits are included, the socio-economic NPV of MBR technology (−$520.5 million) becomes comparable to that of traditional technology (−$522.9 million) and the socio-economic NIRR (6.8%) significantly exceeds that of the alternative (5.1%). This could justify government participation as an investment in environmental safety and the region's sustainable development, in line with Dixon *et al*. (2013) recommendations on assessing the environmental benefits of infrastructure projects.

5.4 Risks and mitigation strategies

The main technical risks are accelerated membrane fouling at high temperatures and a shortage of qualified personnel. To mitigate the risk of membrane fouling, pilot testing and performance guarantee contracts are necessary. Rahman *et al*. (2023) observe that elevated temperatures enhance biological activity, necessitating the optimisation of membrane cleaning protocols. Staff shortages can be mitigated by organising training abroad and concluding technical support contracts for five years.

Environmental risks include soil salinisation and contamination when treated wastewater is used for irrigation without adequate monitoring. To mitigate these risks, it is essential to implement regular water quality control measures, including dilution with fresh water if necessary, as well as practising field rotation. The accumulation of microplastics and pharmaceutical pollutants in silt necessitates the development of safe disposal protocols (Kim *et al*., 2024).

Economic risks include escalating construction costs, low demand for treated wastewater and a reluctance to pay. The first type of risk can be mitigated by entering into fixed-price EPC contracts and localising production by at least 40%. Guaranteed 10-year water purchase agreements and government subsidies are necessary to reduce the second type of risk. Ward *et al*. (2012) demonstrated that the economic viability of decentralised water recycling systems hinges on guaranteed demand.

The prospects for developing the technology are linked to hybrid systems. An *et al*. (2023) demonstrated the potential of anaerobic membrane bioreactors (MBRs) for energy recovery through biogas production. Yu *et al*. (2024) investigated the synergy between MBRs and membrane capacitive deionisation (MCDI) for decentralised water recovery, which could be applicable to small settlements in the region.

5.5 Recommendations for implementation

A phased approach to introducing MBR in the Kashkadarya region is recommended:

Phase 1: a pilot project in Karman (2025–2027) to test and verify the technology, and measure GHG emissions.

Phase 2: scaling up in Kitab (2027–2030), integrating solar energy to reduce the carbon footprint by 84–95%, as reported by Mannina *et al*. (2020).

Stage 3: full-scale implementation in Shakhrisabz (2030–2035), potentially incorporating anaerobic MBRs for biogas recovery (Cashman *et al*., 2018; Lei *et al*., 2024).

A hybrid strategy involving MBRs in urban centres and constructed wetlands in peripheral areas will optimise costs while maintaining environmental benefits. The potential for carbon financing provides further incentive for implementation.

6 CONCLUSIONS

The study enables us to draw the following main conclusions:

1. MBR technology is optimal for urban areas in the Kashkadarya region due to its ability to meet the strict requirements of Sanitary standards and norms No. 0318-2015, its compact design, and its production of water that is suitable for direct reuse in irrigation. The main environmental advantage of MBR technology is its ability to prevent the eutrophication of water bodies by removing 85–95% of biogenic elements and eliminating microbiological contamination of soil and groundwater. Producing 67.16 million m³ of treated water per year reduces the strain on depleting underground aquifers by 15–20%.
2. MBR systems demonstrate lower direct greenhouse gas emissions (N_2O) than traditional activated sludge systems. Integrating them with renewable energy sources reduces the carbon footprint by 84–95%, while optimising aeration modes reduces it by an additional 10–81%. Anaerobic MBRs offer opportunities for biogas recovery, making this technology even more cost-effective.
3. At current rates, all treatment technologies require government subsidies, which is typical for developing countries. However, MBRs demonstrate better internal rates of return and shorter payback periods due to potential revenues from selling treated water. When the environmental and social benefits are monetised, the socio-economic efficiency of MBR exceeds that of traditional treatment, justifying the choice of this technology from a public interest perspective.
4. The project provides critical environmental and social benefits, including protection of aquatic ecosystems from pollution ($20.1 million), reduction in morbidity ($23.5 million), increased agricultural productivity through high-quality irrigation water ($95–138 million) and preservation of the UNESCO site in Shakhrisabz ($10 million).
5. Successful implementation requires the following: (1) pilot testing with environmental monitoring and verification of carbon benefits; (2) phased scaling

up with local capacity building; (3) a hybrid technology strategy; and (4) integration with renewable energy sources to maximise climate benefits.

Although there are no direct financial returns, the project is justified from a public interest perspective and can serve as a model for other arid regions of Central Asia that are facing similar challenges relating to water scarcity, outdated infrastructure and growing environmental demands. The phased introduction of MBR technology, adapted to local economic and institutional conditions, will provide a valuable model for environmentally sustainable and climate-neutral water management in the context of increasing climate stress in Tajikistan, Turkmenistan and southern Kazakhstan.

ACKNOWLEDGEMENTS

This study was carried out within the framework of the regional water infrastructure assessment, with support from JSC "Uzsuvta'minot". The authors acknowledge the limitations concerning access to confidential project data and gratefully thank the consultants for providing general information on project parameters.

CONFLICT OF INTEREST

The authors declare no known conflict of financial or otherwise interest.

REFERENCES

An, Z., Zhu, J., Zhang, M., Zhou, Y., Su, X., Lin, H., & Sun, F. (2023). Anaerobic membrane bioreactor for the treatment of high-strength waste/wastewater: A critical review and update. *Chemical Engineering Journal, 458*, 144322. https://doi.org/10.1016/j.cej.2023.144322

Asian Development Bank. (1999). *Handbook for the economic analysis of water supply projects*. Manila: ADB.

Asian Development Bank. (2017). *Guidelines for the economic analysis of projects*. Mandaluyong City, Philippines (Manila)

Ayers, R. S., & Westcot, D. W. (1985). *Water quality for agriculture* (FAO Irrigation and Drainage Paper No. 29 Rev. 1). Food and Agriculture Organization of the United Nations.

Banti, D., Tsangas, M., Samaras, P., & Zorpas, A. (2020). LCA of a membrane bioreactor compared to activated sludge system for municipal wastewater treatment. *Membranes, 10*(12), 421. https://doi.org/10.3390/membranes10120421

Baresel, C. (2017). Membrane bioreactor processes to meet today's and future municipal sewage treatment requirements. *International Journal of Water and Wastewater Treatment, 3*(2). https://doi.org/10.16966/2381-5299.140

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2018). *Cost-benefit analysis: Concepts and practice* (5th ed.). Cambridge University Press.

Bolzonella, D., Fatone, F., Di Fabio, S., & Cecchi, F. (2010). Application of membrane bioreactor technology for wastewater treatment and reuse in the Mediterranean region: Focusing on removal efficiency of non-conventional pollutants. *Journal of Environmental Management, 91*(12), 2424–2431. https://doi.org/10.1016/j.jenvman.2010.07.024

Cashman, S., Ma, X., Mosley, J., Garland, J., Crone, B., & Xue, X. (2018). Energy and greenhouse gas life cycle assessment and cost analysis of aerobic and anaerobic membrane bioreactor systems: Influence of scale, population density, climate, and methane recovery. *Bioresource Technology, 254*, 56–66. https://doi.org/10.1016/j.biortech.2018.01.060

Chembarisov, E., Shodiev, S., & Norkuvvatova, U. (2024). Use of the basin method for forecasting river water mineralization in the Kashkadarya, Surkhandarya, and Zeravshan basins. *Uzbekistan Zamin Scientific and Practical Journal, 3*. https://doi.org/10.63027/2024/3/4 (in Russian)

Chen, Y. (2019). Estimation of greenhouse gas emissions from a wastewater treatment plant using membrane bioreactor technology. *Water Environment Research*, *91*(5), 451–461. https://doi.org/10.1002/wer.1004

Gafurova, L., Kurbanov, M., Sidiqov, S., Ergasheva, O., Abdushukurova, Z., Zakirova, S., Yunusova, S., & Artiqova, H. (2024). Study of evolution and fertility of degraded soils in the Kashkadarya river cone spread. *E3S Web of Conferences, 563*, 03073. https://doi.org/10.1051/e3sconf/202456303073

Gündoğdu, M., Jarma, Y., Kabay, N., Pek, T., & Yüksel, M. (2018). Integration of MBR with NF/RO processes for industrial wastewater reclamation and water reuse—Effect of membrane type on product water quality. *Journal of Water Process Engineering*, *22*, 103–110. https://doi.org/10.1016/j.jwpe.2018.02.009

Haas, C. N., Rose, J. B., & Gerba, C. P. (1999). *Quantitative microbial risk assessment*. John Wiley & Sons.

Dixon, J. A., Scura, L. F., & van't Hof, T. (2013). Implementation guideline: Economic cost-benefit analysis (CBA) of project environmental impacts and mitigation measures for waste water treatment projects (WWTPS). Inter-American Development Bank.

Ioannou-Ttofa, L., Foteinis, S., Chatzisymeon, E., & Fatta-Kassinos, D. (2016). The environmental footprint of a membrane bioreactor treatment process through Life Cycle Analysis. *Science of the Total Environment, 568,* 306–318. https://doi.org/10.1016/j.scitotenv.2016.06.032

Kharraz, J., Khanzada, N., Farid, M., Kim, J., Jeong, S., & An, A. (2022). Membrane distillation bioreactor (MDBR) for wastewater treatment, water reuse, and resource recovery: A review. *Journal of Water Process Engineering*, *47*, 102687. https://doi.org/10.1016/j.jwpe.2022.102687

Kim, J., Wu, B., Jeong, S., Jeong, S., & Kim, M. (2024). Recent advances of membrane-based hybrid membrane bioreactors for wastewater reclamation. *Frontiers in Membrane Science and Technology, 3,* 1361433. https://doi.org/10.3389/frmst.2024.1361433

Lei, Z., Zheng, J., Liu, J., Li, Q., Xue, J., Yang, Y., Kong, Z., Li, Y., & Chen, R. (2024). Synergic treatment of domestic wastewater and food waste in an anaerobic membrane bioreactor demo plant: Process performance, energy consumption, and greenhouse gas emissions. *Water Research*, *266,* 122371. https://doi.org/10.1016/j.watres.2024.122371

Mannina, G., Chandran, K., Capodici, M., Cosenza, A., Di Trapani, D., & van Loosdrecht, M. (2018). Greenhouse gas emissions from membrane bioreactors: Analysis of a two-year survey on different MBR configurations. *Water Science and Technology, 78*(3–4), 896–903. https://doi.org/10.2166/wst.2018.366

Mannina, G., Cosenza, A., & Rebouças, T. (2020). Aeration control in membrane bioreactor for sustainable environmental footprint. *Bioresource Technology, 301*, 122734. https://doi.org/10.1016/j.biortech.2020.122734

Mofatto, P., Cosenza, A., Di Trapani, D., & Mannina, G. (2024). Reducing biosolids from a membrane bioreactor system: Assessing the effects on carbon and nutrient removal, membrane fouling and greenhouse gas emissions. *Journal of Environmental Management, 354*, 120345. https://doi.org/10.1016/j.jenvman.2024.120345

Mofatto, P., Cosenza, A., Di Trapani, D., Wu, L., Ni, B., & Mannina, G. (2024). Carbon footprint reduction by coupling intermittent aeration with submerged MBR: A pilot plant study. *Journal of Environmental Chemical Engineering, 12*(3), 113115. https://doi.org/10.1016/j.jece.2024.113115

Nasrulin, A., & Kan, E. (2023). The method of hydroecological monitoring for hydropower and hydraulic facilities of the Kashkadarya region of Uzbekistan. *AIP Conference Proceedings, 2612,* 050011. https://doi.org/10.1063/5.0113349

Rahman, K., Saadi, S., Rawahi, M., Van Afferden, M., Bernhard, K., Friesen, J., & Müller, R. (2024). Small decentralized technologies for high-strength wastewater treatment and reuse in arid and semi-arid regions. *Environments, 11*(7), 142. https://doi.org/10.3390/environments11070142

Rahman, T., Roy, H., Islam, M., Tahmid, M., Fariha, A., Mazumder, A., Tasnim, N., Pervez, M., Cai, Y., Naddeo, V., & Islam, M. (2023). The advancement in membrane bioreactor

(MBR) technology toward sustainable industrial wastewater management. *Membranes*, *13*(2), 181. https://doi.org/10.3390/membranes13020181

Rong, C., Song, Y., Yan, W., Zhang, T., & Li, Y. (2025). Anaerobic membrane bioreactor and Anammox in municipal wastewater treatment: Mainstream versus side-stream, challenges, and prospects. *Renewable and Sustainable Energy Reviews, 209*, 115154. https://doi.org/10.1016/j.rser.2024.115154

Sagdullaeva, B., Ginatullina, E., & Tashev, R. (2022). Ecological and hygienic assessment of the river Kashkadarya and drainage canal water in the intensively irrigated region of Uzbekistan. *Hygiene and Sanitation*, *101*(2), 132–138. https://doi.org/10.47470/0016-9900-2022-101-2-132-138

Salokhiddinov, A., Mirzaqobulov, J., Radkevich, M., Ismailkhodjaev, B., Alibayeva, Z., & Abdumajidov, E. (2023). Study of climate change patterns of the Kashkadarya River basin based on GIS technologies. *E3S Web of Conferences*, *386*, 06006. https://doi.org/10.1051/e3sconf/202338606006

Sharapova, M. A., & Uzakov, Z. Z. (2024). Vegetation cover of deserts and tugai forests in the Kashkadarya basin. *Universum. Chemistry and Biology: Electronic Scientific Journal*, *3*(117). (in Russian)

Stokey, E., & Zeckhauser, R. (1978). *A primer for policy analysis*. W. W. Norton & Company.

Suyunov, A., Suyunov, S., Khushmurodov, F., Suyunov, S., Omonov, I., & Eshboev, B. (2025). Ecological consequences of the desertification process in the agrolandscapes of the Kashkadarya oasis. *BIO Web of Conferences*, *160*, 02006. https://doi.org/10.1051/bioconf/202516002006

Tay, M., Liu, C., Cornelissen, E., Wu, B., & Chong, T. (2018). The feasibility of nanofiltration membrane bioreactor (NF-MBR)+reverse osmosis (RO) process for water reclamation: Comparison with ultrafiltration membrane bioreactor (UF-MBR)+RO process. *Water Research*, *129*, 180–189. https://doi.org/10.1016/j.watres.2017.11.013

Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R., & Burton, F. L. (2014). *Wastewater engineering: Treatment and resource recovery* (5th ed.). McGraw-Hill Education.

Tran, D., You, S., Bui, X., Wang, Y., & Ramos, A. (2024). Anaerobic membrane bioreactors for municipal wastewater: Progress in resource and energy recovery improvement approaches. *Journal of Environmental Management*, *366*, 121855. https://doi.org/10.1016/j.jenvman.2024.121855

Ward, S., Farmani, R., Haines, V., & Butler, D. (2012). Analysing the economic feasibility of decentralised water recycling systems. *Water Research*, *46*(12), 3851–3866. https://doi.org/10.1016/j.watres.2012.04.031

World Health Organization. (2006). *Guidelines for the safe use of wastewater, excreta and greywater: Volume 2. Wastewater use in agriculture*. Geneva: World Health Organization

Yu, H., Johir, M., Ansari, A., & Nghiem, L. (2025). Anaerobic membrane bioreactors for treating high organic content wastewater and reducing fugitive greenhouse gas emission. *Environmental Science: Water Research & Technology, 11*. https://doi.org/10.1039/D5EW00071H

Yu, W., Liu, H., Lin, H., Lee, M., & Hou, C. (2024). Synergizing MBR and MCDI systems as a sustainable solution for decentralized wastewater reclamation and reuse. *Sustainable Environment Research*, *34*, 217. https://doi.org/10.1186/s42834-024-00217-x

Zerbe, R. O., & Bellas, A. S. (2006). *A primer for benefit-cost analysis*. Edward Elgar Publishing.

Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

How to cite this article (APA)

Maria, R., Azamat, M., & Meili, A. MEMBRANE BIOREACTORS FOR WATER PROTECTION IN KASHKADARYA PROVINCE, UZBEKISTAN. Veredas Do Direito, e234139. https://doi.org/10.18623/rvd.v23.n2.4139