

**ENVIRONMENTAL AND TECHNOLOGICAL SOLUTIONS
FOR THE PROTECTION AND SUSTAINABLE USE
OF WATER RESOURCES**

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INTRODUCTION

Water resources are a key component of the natural resource potential of territories, underpinning ecosystem functioning, economic development, and the quality of life of the population. Amid global transformations associated with climate change, increasing anthropogenic pressure, urbanisation, industrialisation, and unequal access to safe and high-quality water, the protection of water bodies is becoming particularly important. The deterioration of surface water and groundwater quality, depletion of water resources, disruption of natural hydrological regimes, and accumulation of pollutants in aquatic ecosystems pose risks not only to the environment but also to the socio-economic development of territories.

Anthropogenic pressure on water resources results from the discharge of insufficiently treated municipal and industrial wastewater, agricultural and stormwater runoff, excessive water abstraction, hydraulic modification of water bodies, and changes in the natural regime of catchments. Municipal wastewater is a source of organic, nutrient, and microbiological pollution, whereas industrial effluents may contain heavy metals, petroleum products, phenols, salts, dyes, and persistent organic compounds¹. Surface runoff from agricultural land and urbanized areas contributes to the input of nitrogen and phosphorus compounds, pesticides, suspended solids, petroleum products, and microplastics into water bodies. The combined effects of these factors lead to eutrophication, deterioration of oxygen conditions, accumulation of toxic substances in bottom sediments and biota, siltation, biodiversity loss, and depletion of water resources².

¹ Carey R. O., Hochmuth G. J., Martinez C. J., Boyer T. H., Dukes M. D., Toor G. S., Cisar J. L. Evaluating nutrient impacts in urban watersheds: challenges and research opportunities. *Environmental Pollution*. 2013. Vol. 173. P. 138–149. DOI: <https://doi.org/10.1016/j.envpol.2012.10.004>.

² Giri S., Qiu Z. Understanding the relationship of land use and water quality in twenty first century : a review. *Journal of Environmental Management*. 2016. Vol. 173. P. 41–48.

Particular attention should be paid to the growing water demand in agriculture, industry, energy production, and the municipal sector. Intensive water abstraction from natural sources, combined with droughts, uneven precipitation patterns, and rising temperatures, increases the risk of water scarcity and reduces the capacity of aquatic ecosystems for natural recovery³. Under such conditions, even relatively small amounts of pollutants may cause significant environmental impacts because of reduced water availability and diminished natural dilution of wastewater.

The relevance of this study is determined by the need to identify effective environmental and technological solutions aimed at reducing pollution of water bodies, improving wastewater treatment efficiency, and developing resource-efficient water-use models. Of particular importance is the transition from a predominantly reactive approach focused on mitigating the consequences of pollution to a preventive model that involves segregating contaminated streams at their points of generation, reducing wastewater volumes, introducing low-waste technologies, implementing water recirculation systems, and reusing treated water. This approach makes it possible to reduce both water abstraction from natural sources and the pressure on treatment facilities and aquatic ecosystems.

In the context of sustainable development, the protection of water bodies and the rational use of water resources are essential conditions for environmental safety, sustainable natural resource management, and enhancing the resilience of territories to contemporary environmental and socio-economic challenges. This issue is directly aligned with Sustainable Development Goal 6, “Clean Water and Sanitation”, which aims to ensure access to water, adequate wastewater treatment, and the sustainable management of water resources⁴. At the same time, the introduction of water-saving technologies, water reuse, and closed-loop production cycles contributes to Sustainable Development Goal 12, “Responsible Consumption and Production”. The link with Sustainable Development Goal 13, “Climate Action”, is determined by the need to adapt water management systems to droughts, floods, and uneven water availability. The protection of river basins also contributes to the achievement of Goals 14 and 15, as the condition of surface waters directly affects coastal, marine, and terrestrial ecosystems⁵.

³ Intergovernmental Panel on Climate Change. Climate change 2023: synthesis report. Geneva : IPCC, 2023. URL: <https://www.ipcc.ch/report/ar6/syr/>.

⁴ United Nations. Goal 6: Ensure access to water and sanitation for all. United Nations Sustainable Development Goals. URL: <https://www.un.org/sustainabledevelopment/water-and-sanitation/>.

⁵ UNESCO World Water Assessment Programme. The United Nations World Water Development Report 2024: Water for prosperity and peace. Paris : UNESCO, 2024. URL: <https://unesdoc.unesco.org/ark:/48223/pf0000388948>.

The aim of the study is to substantiate environmental and technological solutions for water treatment and priority areas of rational water use in the context of sustainable development. To achieve this aim, the main treatment methods and technological systems were compared in terms of their efficiency, application conditions, and water reuse potential, while approaches to the development of recirculating water-supply systems and improved water-use efficiency were also summarised.

1. Environmental and technological solutions for water treatment and pollution reduction in water bodies

Reducing pollution of water bodies requires the implementation of a set of environmental and technological solutions aimed at wastewater treatment, localisation of pollution sources and prevention of pollutant input into the aquatic environment. Under current conditions, the effectiveness of water protection activities is determined by the combination of technological modernisation of treatment facilities, local treatment of wastewater at the points of generation, the application of combined treatment methods, advanced treatment of water before discharge into water bodies, and the use of nature-based solutions to reduce surface runoff and restore the natural functions of aquatic ecosystems.

Traditional approaches to water treatment involve the sequential application of mechanical, physicochemical, chemical, biological and combined methods. Mechanical treatment is used to remove coarse impurities, suspended solids, sand, sludge and other insoluble components. Such processes include screening, sedimentation, filtration, grit removal and flotation. Despite its relative simplicity, mechanical treatment is an important initial stage, as it reduces the load on subsequent technological stages and improves the efficiency of further treatment⁶.

Physicochemical treatment methods are used to remove colloidal, finely dispersed, and dissolved pollutants. These include coagulation, flocculation, adsorption, ion exchange, membrane processes, electrochemical methods, oxidation, and other water treatment techniques. Such methods are particularly important for treating industrial wastewater, which may contain heavy metals, petroleum products, phenols, synthetic organic compounds, dyes, salts, and other persistent pollutants⁷. The advantage of physicochemical technologies is their capacity for the targeted removal of specific groups of pollutants; however,

⁶ Nachiyar C. V., Rakshi A. D., Sandhya S. N., Jebasta B. D., Nellore J. Developments in treatment technologies of dye-containing effluent: A review. *Case Studies in Chemical and Environmental Engineering*. 2023. Vol. 7. P. 100–139. DOI: 10.1016/j.csee.2023.100339.

⁷ Kato S., Kansha Y. Comprehensive review of industrial wastewater treatment techniques. *Environmental Science and Pollution Research*. 2024. Vol. 31. P. 51064–51097. DOI: 10.1007/s11356-024-34584-0.

their application requires the optimisation of reagent and energy consumption, as well as consideration of secondary waste generation.

For industrial wastewater, an important direction is local treatment directly at enterprises or production sites where specific pollutants are generated. This makes it possible to avoid mixing highly concentrated or toxic wastewater with the general wastewater flow, increase treatment efficiency and reduce the load on municipal wastewater treatment facilities⁸.

One of the widely used physicochemical methods for treating industrial wastewater is coagulation and flocculation, which are applied to remove colloidal, fine dispersed and partially dissolved pollutants. These processes are particularly effective when wastewater contains suspended particles, dyes, petroleum products, heavy metal compounds and other persistent pollutants that are difficult to remove using mechanical methods alone. The essence of the method lies in the introduction of coagulants into the water being treated, which promote destabilisation of the colloidal system, neutralisation of particle charges and the creation of conditions for their subsequent enlargement and sedimentation⁹. The sequence of coagulation and flocculation processes during industrial wastewater treatment is schematically presented in Figure 1.

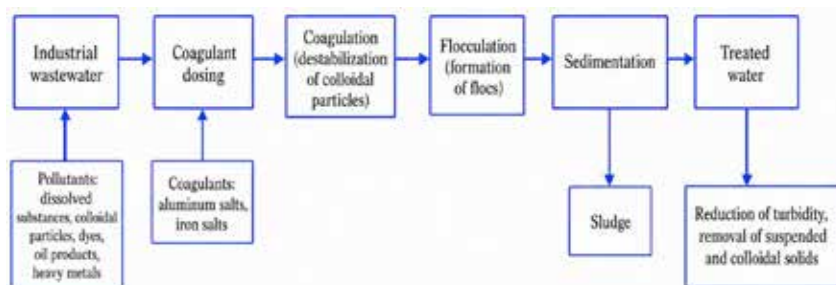


Fig. 1. Scheme of the coagulation and flocculation process during industrial wastewater treatment

Source: developed by the author

The processes of coagulation and flocculation include several main stages: the inflow of polluted wastewater, coagulant dosing, neutralisation of the charge

⁸ Sharma R., Verma N., Lugani Y., Kumar S., Asadnia M. Conventional and advanced techniques of wastewater monitoring and treatment. *Green Sustainable Process for Chemical and Environmental Engineering and Science. Elsevier*. 2021. P. 1–48. DOI: 10.1007/s11356-024-34584-0.

⁹ Sharghi E. A., Davarpanah L. Optimization of chemical coagulation–flocculation process of detergent manufacturing plant wastewater treatment for full-scale applications: a case study. *Desalination and Water Treatment*. 2022. Vol. 262. P. 38–53. DOI: <https://doi.org/10.5004/dwt.2022.28494>.

of colloidal particles, formation of flocs during flocculation, sedimentation and separation of sludge¹⁰. As a result, water turbidity decreases, the concentration of certain pollutants is reduced, and the water becomes more suitable for further treatment or reuse¹¹. The advantages of this method include the effective removal of suspended and colloidal particles, as well as a reduction in the content of some heavy metals and dyes; however, its application is associated with reagent consumption and sludge generation.

Membrane treatment is also a modern physicochemical method for the advanced removal of pollutants from water. The essence of the process is that polluted water, after preliminary treatment, is supplied under pressure to a membrane module, where a semi-permeable membrane separates the flow into two components: permeate, which is the treated water passing through the membrane, and concentrate, which is the stream containing retained pollutants¹². Depending on the type of membrane, the process can ensure the removal of suspended solids, microorganisms, organic pollutants, dyes, salts and other impurities.

Common membrane processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), which differ in their contaminant retention capacity and operating pressure requirements. Ultrafiltration is mainly used to remove suspended and colloidal particles, high-molecular-weight organic compounds, and microorganisms, whereas reverse osmosis provides more advanced removal of dissolved salts and low-molecular-weight contaminants.

One effective option for advanced treatment is the sequential application of ultrafiltration and reverse osmosis (UF/RO). In this treatment scheme, ultrafiltration serves as a membrane pretreatment stage, reducing the concentration of suspended and colloidal matter and lowering the risk of fouling of reverse osmosis membranes¹³. At the subsequent stage, reverse osmosis removes dissolved impurities and produces water suitable for reuse in technical and industrial processes (Figure 2).

¹⁰ Jachimowicz P., Cydzik-Kwiatkowska A. Coagulation and flocculation before primary clarification as efficient solutions for low-density microplastic removal from wastewater. *International Journal of Environmental Research and Public Health*. 2022. Vol. 19, no. 20. Art. 13013. DOI: 10.3390/ijerph192013013.

¹¹ Aloui F., Kchaou S., Sayadi S. Physicochemical treatments of anionic surfactants wastewater: effect on aerobic biodegradability. *Journal of Hazardous Materials*. 2009. Vol. 164, No. 1. P. 353–359. DOI: <https://doi.org/10.1016/j.jhazmat.2008.08.009>.

¹² Robinson S., Bérubé P. R. Membrane ageing in full-scale water treatment plants. *Water Research*. 2020. Vol. 169. Art. 115212. DOI: <https://doi.org/10.1016/j.watres.2019.115212>.

¹³ Fatima F., Du H., Kommalapati R. R. A Sequential Membrane Process of Ultrafiltration Forward Osmosis and Reverse Osmosis for Poultry Slaughterhouse Wastewater Treatment and Reuse. *Membranes (Basel)*. 2023. Vol.1 3, No. 3. Art. 296. DOI: <https://doi.org/10.3390/membranes13030296>.

Membrane treatment makes it possible to obtain high-quality water suitable for technical processes, cooling, recirculating systems, or reuse after further treatment. The advantages of membrane technologies include high selectivity and consistent treated-water quality, whereas their main limitations are energy consumption, membrane fouling, the need for periodic cleaning, and the subsequent management of the concentrate.

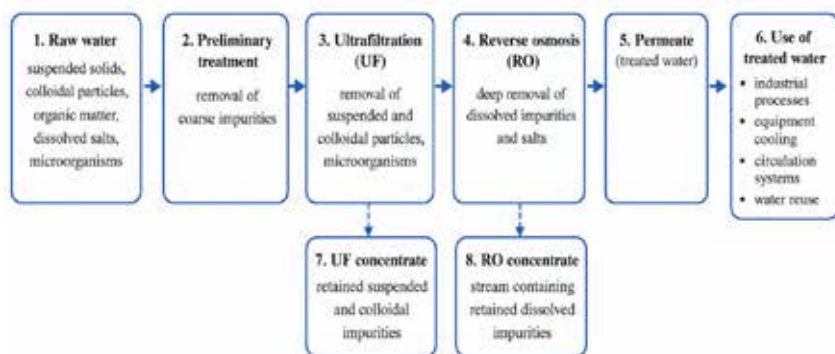


Fig. 2. Schematic diagram of membrane water treatment using ultrafiltration and reverse osmosis

Source: developed by the author

Biological treatment methods are based on the ability of microorganisms to degrade or transform organic pollutants. They are widely used for treating municipal and mixed wastewater dominated by biodegradable organic matter and nitrogen and phosphorus compounds. Such technologies include activated sludge tanks, biofilters, bioreactors, constructed wetlands, and other biological treatment systems¹⁴. The efficiency of biological methods depends on wastewater composition, temperature, oxygen concentration, the loading rate applied to activated sludge or biofilms, and the stability of the operating regime.

The intensification of biological treatment is of particular importance, including the use of combined aerobic-anaerobic processes, bioreactors with attached biomass, membrane bioreactors, nitrogen and phosphorus removal systems, and advanced treatment technologies. Such solutions make it possible to increase the removal of organic matter and nutrients, reduce the risk of

¹⁴ Dotro G., Langergraber G., Molle P., Nivala J., Puigagut J., Stein O., von Sperling M. Treatment wetlands. *Biological Wastewater Treatment Series*. Vol. 7. IWA Publishing, 2017. 172 p.

eutrophication of water bodies and improve the quality of treated water before its discharge or reuse.

A membrane bioreactor is one of the most effective modern technologies for intensifying biological wastewater treatment, as it combines the processes of biodegradation of pollutants by activated sludge and membrane separation of treated water. In such a system, wastewater enters an aeration tank, where activated sludge microorganisms degrade organic matter, participate in nitrification and denitrification processes, and also contribute to reducing the content of nitrogen and phosphorus compounds¹⁵. After biological treatment, the water passes through a membrane module, which retains suspended solids, microorganisms and activated sludge particles, ensuring the production of high-quality permeate (Figure 3).

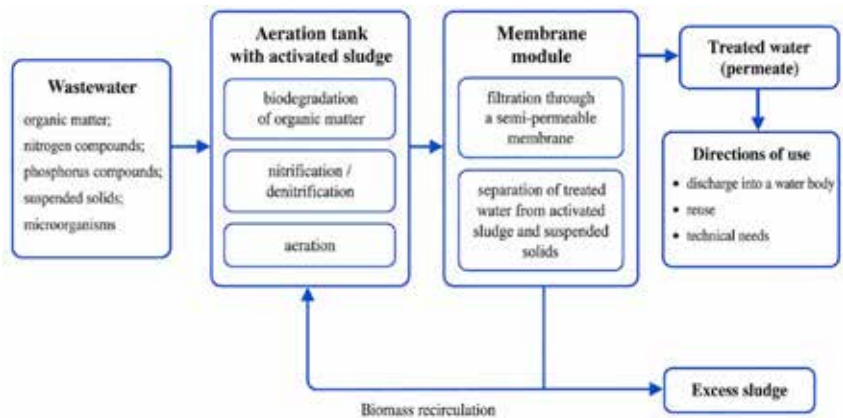


Fig. 3. Scheme of wastewater treatment in a membrane bioreactor

Source: developed by the author

The advantage of a membrane bioreactor lies in the combination of biological treatment with physical barrier separation, which makes it possible to improve the quality of treated water, reduce the content of organic matter and nutrients, and ensure the possibility of water reuse for technical needs or its safe discharge into a water body. The efficiency of such a system depends on the composition of wastewater, dissolved oxygen concentration, temperature, the load on activated sludge, the condition of membranes and the stability of the technological regime¹⁶.

¹⁵ Мокієнко А. В. Актуальні водні проблеми. Інноваційні водні технології. Острог, 2024. 381 с.

¹⁶ Melin T., Jefferson B., Bixio D., Thoeye C., De Wilde W., De Koning J., van der Graaf J., Wintgens T. Membrane bioreactor technology for wastewater treatment and reuse. *Desalination*. 2006. Vol. 187, No. 1–3. P. 271–282. DOI: <https://doi.org/10.1016/j.desal.2005.04.086>.

A separate important direction for reducing pollution of water bodies is the treatment of stormwater runoff from urbanised areas. Stormwater formed during precipitation or snowmelt washes pollutants from roads, industrial sites, car parks, building roofs and other impervious surfaces. It may contain petroleum products, heavy metals, suspended solids, microplastics, residues of de-icing agents, organic impurities and other pollutants. In the absence of proper treatment, such runoff directly enters rivers, water bodies or stormwater drainage systems, increasing chemical and mechanical pollution of the aquatic environment.

Both engineering and nature-based solutions can be used for stormwater treatment. Engineering structures include grit chambers, oil separators, sedimentation tanks, filtration units, local treatment facilities and storage reservoirs. They ensure the retention of sand, suspended solids, petroleum products and other impurities before water is discharged into natural water bodies or drainage systems. At the same time, engineering solutions alone are often insufficient for the comprehensive regulation of surface runoff, especially under conditions of intensive urbanisation, expansion of impervious surfaces and increasing frequency of extreme precipitation events.

In this regard, nature-based solutions are becoming particularly important, as they combine the functions of treatment, retention, infiltration and natural runoff regulation. Such solutions include rain gardens, constructed wetlands, infiltration basins, green ditches, riparian buffer strips, phytoremediation areas and vegetated filtration systems¹⁷. Their action is based on the use of natural processes: filtration through the soil-vegetation layer, sedimentation of suspended solids, uptake of nutrients by plants, microbiological transformation of organic matter, sorption of pollutants and slowing of surface runoff (Table 1, Figure 4).

A key advantage of nature-based solutions is their multifunctionality. They not only contribute to the treatment of stormwater and surface runoff but also improve local hydrological conditions, reduce the risk of localised flooding, support biodiversity, enhance green infrastructure in urban areas, and increase the resilience of built-up territories to climate change. When combined with conventional engineering structures, such solutions make it possible to develop a more flexible and environmentally balanced system for surface runoff management.

¹⁷ International Union for Conservation of Nature. Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS. 1st ed. Gland, Switzerland : IUCN, 2020. 30 p.

Table 1

**Main nature-based solutions for water treatment
and surface runoff regulation**

Nature-based solution	Main purpose	Main environmental effect
Rain gardens	Retention and partial treatment of stormwater runoff	Reduction of surface runoff volume; retention of suspended solids and nutrients
Infiltration basins	Accumulation and infiltration of rainwater into the soil	Reduction of peak runoff, groundwater recharge and lower risk of flooding
Constructed wetlands	Biological advanced treatment of water and retention of pollutants	Reduction in the content of organic matter, nitrogen, phosphorus and suspended particles
Bioplato systems	Advanced treatment of wastewater or stormwater involving higher aquatic plants	Reduction of nutrient load and improvement of water quality
Riparian buffer strips	Interception of pollutants at the boundary between the catchment and the water body	Reduction of the input of soil particles, nutrients and agrochemicals into water bodies
Phytoremediation areas	Uptake and transformation of pollutants by plants	Reduction in the concentration of selected pollutants and ecological stabilisation of the area
Green ditches and biochannels	Slowing, retention and preliminary treatment of surface runoff	Reduction of runoff velocity, sedimentation of suspended solids and partial filtration of pollutants
Vegetated filtration systems	Filtration and advanced treatment of rainwater and stormwater	Improvement of water quality and reduction of the load on stormwater drainage systems

The informed selection of a wastewater treatment method requires consideration of its technological implementation and subsequent operation. Important factors include application conditions, typical limitations, the generation of by-products and secondary streams, and the potential for treated water reuse. A comparative assessment of the treatment methods and technological systems considered according to these criteria is presented in Table 2.

A quantitative comparison was performed for the removal of chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), suspended solids, total nitrogen, and total phosphorus by mechanical, physicochemical, biological, and membrane treatment methods, membrane bioreactors, and nature-based systems. These indicators were selected because they are widely reported for different treatment technologies, whereas data on heavy metals, specific organic compounds, and microbiological contaminants are less consistent. For each

method, a representative value close to the midpoint of the reported efficiency range was selected. The numerical values used in the comparison were derived from the studies cited in the source notes to Figures 5 and 6. The values are indicative, as influent composition and operating conditions varied among the source studies, and should not be interpreted as directly comparable under identical conditions.

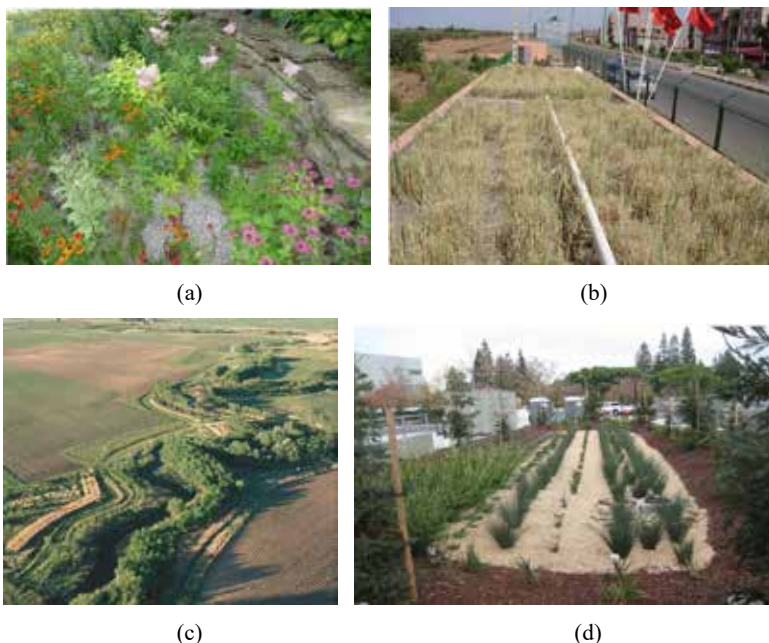


Fig. 4. Examples of nature-based solutions: (a) rain garden¹⁸; (b) constructed wetland¹⁹; (c) riparian buffer strip²⁰; (d) stormwater bioretention area²¹

¹⁸ Steakley J. Rain garden (2014): photograph. Wikimedia Commons, 2014. URL: [https://commons.wikimedia.org/wiki/File:Rain_garden_\(2014\).JPG](https://commons.wikimedia.org/wiki/File:Rain_garden_(2014).JPG).

¹⁹ SuSanA Secretariat. Constructed wetland (5547195530): photograph / photo by H. Hoffmann. Wikimedia Commons, 2009. URL: [https://commons.wikimedia.org/wiki/File:Constructed_wetland_\(5547195530\).jpg](https://commons.wikimedia.org/wiki/File:Constructed_wetland_(5547195530).jpg).

²⁰ United States Department of Agriculture. Riparian buffer on Bear Creek in Story County, Iowa: photograph. Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Riparian_buffer_on_Bear_Creek_in_Story_County_Iowa.JPG.

²¹ Guzzardo Partnership. 2012-12-04 Stormwater Bio-Treatment Area: photograph. Wikimedia Commons, 2012. URL: https://commons.wikimedia.org/wiki/File:2012-12-04_Stormwater_Bio-Treatment_Area.jpg.

Table 2

Comparative characteristics of the operational features of the main water treatment methods and technological systems

Key application conditions and limitations	By-products or secondary streams	Treated water reuse potential
Mechanical treatment		
Involves the use of screens, grit chambers, sedimentation tanks, or filters and the periodic removal of retained impurities. It does not remove dissolved organic matter, salts, or nutrient compounds.	Sludge, grit, and retained solid waste	When used alone, it generally does not provide water quality suitable for reuse.
Physicochemical treatment		
Requires the selection and dosing of reagents, pH adjustment, appropriate contact time, and controlled mixing conditions. Its efficiency depends on wastewater composition, and the resulting sludge requires further management.	Chemical sludge, spent sorbents, and regeneration solutions	Reuse is possible after additional treatment in accordance with the requirements of the intended application.
Combined UF/RO membrane system		
Requires water pretreatment, operating pressure, membrane fouling control, and periodic membrane cleaning. The concentrate must be treated or properly discharged.	UF retentate, RO concentrate, and membrane cleaning water	High potential for reuse for technical and selected industrial purposes, provided that the required water quality standards are met.
Activated sludge biological treatment		
Requires stable oxygen and temperature conditions, maintenance of the required activated sludge concentration, and an acceptable organic loading rate. It is sensitive to toxic substances and abrupt changes in wastewater composition.	Excess activated sludge	Reuse is generally possible after tertiary treatment and disinfection.
Membrane bioreactor (MBR)		
Requires stable biological operating conditions, aeration, transmembrane pressure control, and regular membrane cleaning. Its operation is more complex than that of conventional biological treatment systems.	Excess activated sludge and membrane cleaning solutions	High potential for reuse in technical and industrial systems.
Nature-based solutions		
Require sufficient land area and consideration of the hydrological regime, vegetation selection, and climatic conditions. Their efficiency may vary depending on the season and hydraulic loading.	Accumulated sediment and plant biomass	Depends on the type of system, the quality of the treated water, and the requirements of its intended use.

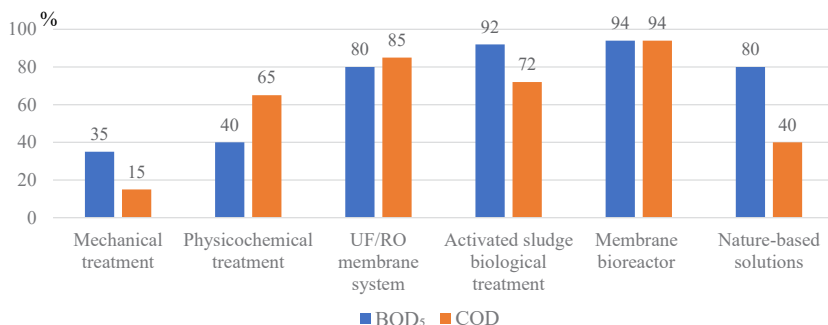


Fig. 5. Comparative efficiency of organic pollution removal by BOD₅ and COD using different water treatment methods, %

Source: compiled by the author based on data from the cited studies^{22, 23, 24, 25, 26}

The comparison results reveal substantial differences among the methods in both the removal efficiency of individual pollutant groups and the conditions required for their technological implementation. The diagram in Figure 5 shows that the highest efficiency of organic pollution removal is achieved by membrane bioreactors (MBRs) and conventional activated sludge treatment, owing to the direct involvement of microorganisms in the degradation of organic compounds. Membrane treatment (UF/RO) also demonstrates high performance, although it is less effective than biological methods in terms of BOD₅ removal because membranes function primarily as physical barriers and are less efficient in removing dissolved, readily oxidizable compounds. Notably, nature-based solutions, despite their relatively moderate COD removal efficiency, provide a sufficiently high level of BOD₅ reduction due to the biological activity of microorganisms and vegetation within these systems. Mechanical and physicochemical treatment remain the least effective methods

²² Oakley S. Preliminary treatment and primary settling. Global Water Pathogen Project / eds. J. B. Rose, B. Jiménez-Cisneros. East Lansing, MI : Michigan State University; UNESCO, 2018. 21 p.

²³ Carnevale Miino M. et al. Treatment of a Real Brewery Wastewater with Coagulation and Flocculation: Impact on Organic Substance and Nutrient Concentrations. *Applied Sciences*. 2025. Vol. 15(6). Art. 2999. DOI: <https://doi.org/10.3390/app15062999>.

²⁴ Kitanou S. et al. A comparative examination of MBR and SBR performance for municipal wastewater treatment. *Water Practice & Technology*. 2021. Vol. 16, No. 2. P. 582–591. DOI: <https://doi.org/10.2166/wpt.2021.016>.

²⁵ Ghonimy M. et al. Improving Wastewater Quality Using Ultrafiltration Technology for Sustainable Irrigation Reuse. *Water*. 2025. Vol. 17(6). Art. 870. DOI: <https://doi.org/10.3390/w17060870>.

²⁶ Gizińska-Górna M. et al. Reliability and Efficiency of Pollutant Removal in Four-Stage Constructed Wetland of SSVF-SSHF-SSHF-SSVF Type. *Water*. 2020. Vol. 12(11). Art. 3153. DOI: <https://doi.org/10.3390/w12113153/>.

for organic pollution removal, confirming their primary role as preliminary stages of wastewater treatment.

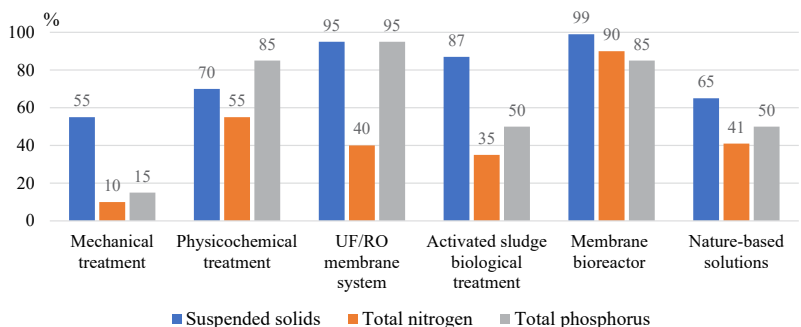


Fig. 6. Comparative removal efficiency of suspended solids, total nitrogen, and total phosphorus using different water treatment methods, %

Source: compiled by the author based on data from the cited studies^{27, 28, 29, 30, 31}

For the three indicators – suspended solids, total nitrogen, and total phosphorus (Figure 6) – the membrane bioreactor demonstrates the highest overall efficiency, combining biological nutrient removal with the membrane’s high retention capacity for suspended solids. Membrane treatment (UF/RO) also provides high removal efficiencies for suspended solids and phosphorus, whereas its nitrogen removal efficiency remains moderate. Nature-based solutions demonstrate moderate removal of nitrogen and phosphorus, while their effectiveness depends considerably on system design, vegetation, hydraulic loading, and operating conditions. Physicochemical treatment and membrane bioreactors show similarly high phosphorus removal efficiencies,

²⁷ Kitanou S. et al. A comparative examination of MBR and SBR performance for municipal wastewater treatment. *Water Practice & Technology*. 2021. Vol. 16, No. 2. P. 582–591. DOI: <https://doi.org/10.2166/wpt.2021.016>.

²⁸ Ghonimy M. et al. Improving Wastewater Quality Using Ultrafiltration Technology for Sustainable Irrigation Reuse. *Water*. 2025. Vol. 17(6). Art. 870. DOI: <https://doi.org/10.3390/w17060870>.

²⁹ Diallo H. M. et al. Evaluation of the potential ultrafiltration to improve the quality of secondary effluents in tertiary treatment and reuse. *Physics and Chemistry of the Earth, Parts A/B/C*. 2024. Vol. 135. Art. 103672. DOI: <https://doi.org/10.1016/j.pce.2024.103672>.

³⁰ Denisova V. et al. Comparison of phosphorus removal efficiency of conventional activated sludge system and sequencing batch reactors in a wastewater treatment plant. *Agronomy Research*. 2020. Vol. 18. P. 771–780. DOI: <https://doi.org/10.1515/AR.20.049>.

³¹ Gizińska-Górna M. et al. Reliability and Efficiency of Pollutant Removal in Four-Stage Constructed Wetland of SSVF-SSHF-SSHF-SSVF Type. *Water*. 2020. Vol. 12(11). Art. 3153. DOI: <https://doi.org/10.3390/w12113153/>.

although they rely on different removal mechanisms. Mechanical treatment has the lowest performance for all three indicators because it does not provide targeted nutrient removal.

Thus, the quantitative and qualitative comparison does not support identifying any single method as universally superior. High treatment efficiency should be assessed together with technological requirements, by-product generation, water reuse potential, and operational limitations. The most appropriate approach is to develop combined treatment schemes in which mechanical treatment is used for preliminary water preparation, biological and physicochemical processes remove the main pollutants, membrane technologies provide advanced treatment, and nature-based solutions reduce nutrient loads and contribute to the ecological stabilisation of the aquatic environment.

The effective integration of engineering treatment methods, on-site wastewater treatment, and nature-based elements makes it possible not only to reduce pollutant concentrations but also to prevent further degradation of aquatic ecosystems, decrease wastewater discharge volumes, and promote more sustainable water-use models.

2. Rational water use within the sustainable development framework

Rational water use is one of the key prerequisites for sustainable development, as water resources support the functioning of natural ecosystems, human well-being, and the development of industry, agriculture, energy production, and municipal services. Under conditions of increasing water scarcity and deteriorating water quality, the transition from the traditional model of intensive water consumption to a resource-efficient model of water management is becoming particularly important³².

The need to adopt rational water-use models is confirmed by the sectoral structure and regional distribution of global water abstraction. According to the *FAO AQUASTAT Water Data Snapshot 2025*, in 2022 agriculture accounted for 71.5% of global water abstraction, industry for 15.3%, and the municipal sector for 13.2%. The highest abstraction volumes were recorded in Southern Asia, Europe and Northern America, and Eastern Asia, whereas the lowest were observed in Oceania and Sub-Saharan Africa (Figure 7). Trends for 2015–2022 indicate increasing water abstraction in several regions exposed to a heightened risk of water scarcity, reflecting the uneven implementation of resource-efficient water-use models³³.

³² Jamali B., Bach P. M., Deletic A. Rainwater harvesting for urban flood management: An integrated modelling framework. *Water Research*. 2020. Vol. 171. Art.115372. DOI: <https://doi.org/10.3390/w12113153>/<https://doi.org/10.1016/j.watres.2019.115372>.

³³ Hernández Lagana M., Mejías Moreno P. *AQUASTAT Water Data Snapshot 2025*. Rome : FAO, 2025. 48 p. DOI: <https://doi.org/10.4060/cd7054en>.

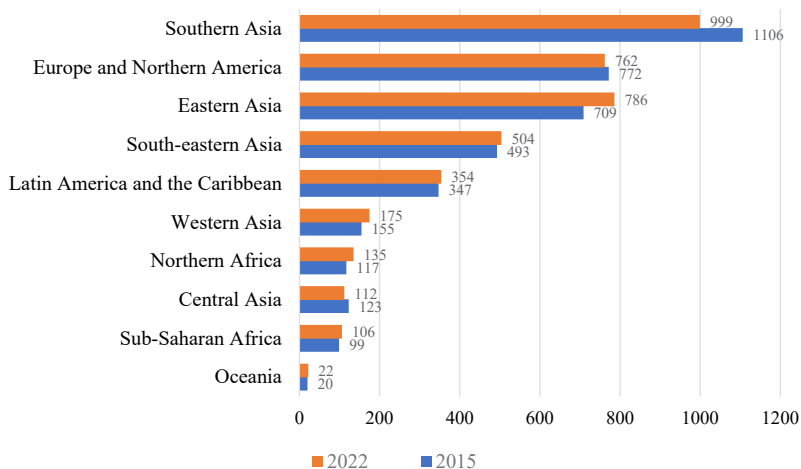


Fig. 7. Total water abstraction by world region in 2015 and 2022, billion m³

Source: compiled by the author based on FAO AQUASTAT data³⁴

The availability of renewable water resources per capita has declined by 7% over the past decade, from 5.719 to 5.326 m³. North Africa, Southern Asia, and Western Asia have the lowest freshwater availability per capita, while Kuwait, the United Arab Emirates, Qatar, and Yemen are among the countries with the lowest total volumes of renewable water resources³⁵.

The analysis of global water-use trends is particularly relevant when compared with Ukraine's national indicators. According to the *FAO AQUASTAT Water Data Snapshot 2025*, Ukraine exhibits a water-use profile that differs substantially from the global average, while partially corresponding to the characteristics of the region to which it is assigned in the AQUASTAT classification – Europe and Northern America.

Unlike the global structure of water abstraction, in which agriculture accounts for the largest share, industry is the main water user in Ukraine, representing 44.8% of total water abstraction, while agriculture accounts for only 21.1% and the municipal sector for 34.0% (Figure 8(a)). This distribution is broadly similar to the overall water-use structure of Europe and Northern

³⁴ Jamali B., Bach P. M., Deletic A. Rainwater harvesting for urban flood management: An integrated modelling framework. *Water Research*. 2020. Vol. 171. Art. 115372. DOI: <https://doi.org/10.3390/w12113153/https://doi.org/10.1016/j.watres.2019.115372>.

³⁵ UN sounds alarm over rising demands on water resources as scarcity increases. UN News, 2025. URL: <https://news.un.org/en/story/2025/12/1166582>.

America, but differs in the notably higher share of municipal water use, which may reflect the specific characteristics of the national economy and municipal infrastructure.

Water stress reflects the relationship between the volume of water abstraction and the available renewable water resources: the higher its level, the greater the pressure on water resources³⁶. Renewable water resources in Ukraine amount to 4,270 m³ per capita, which is below the global average; however, the country’s water stress level remains relatively low at 6.3%³⁷. This is considerably lower than both the global average and the value for Europe and Northern America (Figure 8(b)), indicating a comparatively favourable balance between water abstraction and available renewable water resources. At the same time, the predominance of the industrial and municipal sectors in the structure of water abstraction makes the implementation of resource-efficient technologies in these sectors a priority.

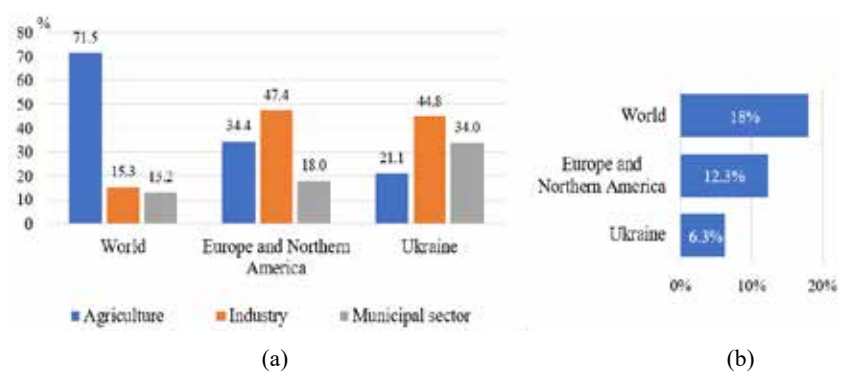


Fig. 8. Comparison of Ukraine’s water-use indicators with global and regional values in 2022: (a) structure of water abstraction by economic sectors, %; (b) water stress level, %

Source: compiled by the author based on United Nations data for (a) and UN-Water data for (b) ^{38, 39}

³⁶ United Nations. The Sustainable Development Goals Extended Report 2025. Clean Water and Sanitation. URL: https://unstats.un.org/sdgs/report/2025/extended-report/Extended-Report-2025_Goal-6.pdf.
³⁷ Progress on Level of Water Stress. UN-Water. URL: <https://sdg6data.org/index.php/en/indicator/6.4.2>.
³⁸ UN sounds alarm over rising demands on water resources as scarcity increases. UN News, 2025. URL: <https://news.un.org/en/story/2025/12/1166582>.
³⁹ United Nations. The Sustainable Development Goals Extended Report 2025. Clean Water and Sanitation. URL: https://unstats.un.org/sdgs/report/2025/extended-report/Extended-Report-2025_Goal-6.pdf.

Rational water use involves not only reducing water abstraction from natural sources but also improving water-use efficiency at all stages of the water management cycle. These stages include water abstraction, treatment, transportation, use in industrial or domestic processes, wastewater treatment, water reuse, and safe return to the natural environment. The main areas of rational water use, the mechanisms for their implementation, and the expected outcomes for sustainable development are summarised in Figure 9.

One of the key areas of rational water use is reducing water losses during transportation and distribution. Deteriorated water-supply networks, frequent pipeline failures, and insufficient monitoring of consumption volumes lead to the inefficient use of water resources. Therefore, the modernisation of water infrastructure, the introduction of metering systems, automated leak detection, network zoning, and digital water-supply management are essential conditions for improving the reliability of water provision.

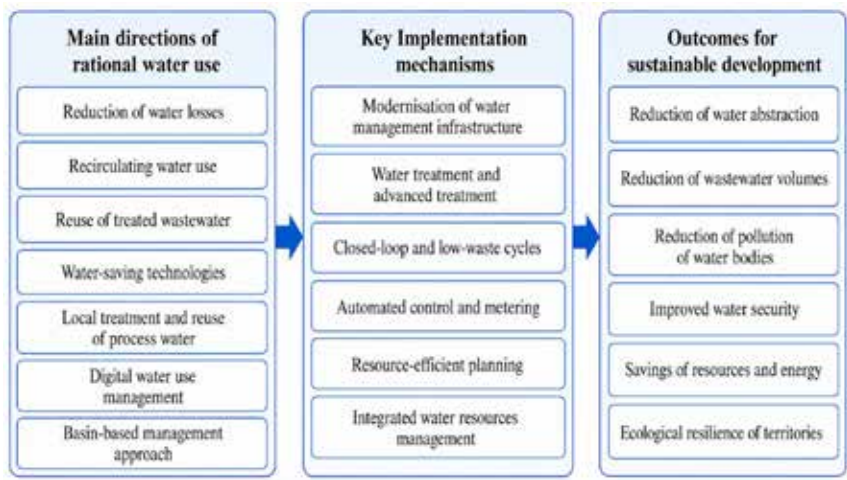


Fig. 9. Main areas of rational water use within the sustainable development framework

Source: developed by the author

An essential component of rational water use is the introduction of water-saving technologies in the municipal, industrial, and agricultural sectors. In the municipal sector, this involves the use of water-efficient equipment, consumption metering and monitoring systems, and the modernisation of water-supply and wastewater infrastructure. In industry, appropriate measures include

optimising technological processes, reducing the water intensity of production, and introducing closed-loop systems. In agriculture, effective solutions include drip irrigation, precision farming, soil conservation technologies, regulation of irrigation rates, and the use of treated wastewater, provided that sanitary and environmental requirements are met⁴⁰.

Rational water use is closely linked to the principles of the circular economy, within which water is regarded not as a single-use resource but as an element of a closed-loop system. This involves its treatment and reuse in industrial or economic processes, the recovery of valuable components, and the reduction of waste generation. Such an approach contributes to reducing the water footprint of products, decreasing polluted wastewater discharges, and improving the overall environmental efficiency of production.

In industry, the practical implementation of these principles is most commonly associated with recirculating and closed-loop water-supply systems. These systems involve the use of water in technological processes, followed by treatment, cooling, or advanced treatment and its return to the production cycle. Local treatment of individual process water streams plays a particularly important role, as it reduces the load on centralized wastewater treatment facilities and limits the discharge of excess wastewater⁴¹. The schematic diagram of recirculating water use and water reuse within an industrial water-supply system is presented in Figure 10.

A rational industrial water-use system includes the abstraction and treatment of fresh water, its use in technological processes, local treatment or cooling, advanced treatment, and the return of part of the water to the production cycle. Only the portion of wastewater that cannot be reused after treatment is discharged into a water body.

The reuse of treated wastewater is a promising approach to improving resource efficiency. With an appropriate level of treatment, such water can be used for non-potable purposes, including irrigation of green spaces, cleaning of indoor and outdoor areas, equipment cooling, firefighting, agricultural irrigation, and replenishment of non-potable storage reservoirs. This is particularly important for regions experiencing water scarcity and high pressure on natural water sources⁴².

⁴⁰ Офіс сталих рішень. Повторне використання води: Кращий європейський досвід. URL: <https://ukraine-oss.com/povtorne-vykorystannya-vody-krashhyj-yevropejskyj-dosvid>.

⁴¹ Sharma K., Nagabhooshanam N., Dasi S., Guntaj J., Srinivas B., Kaur K., Rajaram A. Design and implementation of closed-loop water reuse systems in urban and industrial settings for maximizing resource recovery and minimizing waste. *Desalination and Water Treatment*. 2024. Vol. 320. Art.100850. DOI: <https://doi.org/10.1016/j.dwt.2024.100850>.

⁴² Ramin E., Faria L., Gargalo C. L., Ramin P., Flores-Alsina X., Andersen M. M., Gernaey K. V. Water innovation in industrial symbiosis : A global review. *Journal of Environmental Management*. 2024. Vol. 349. Art. 119578. DOI: <https://doi.org/10.1016/j.jenvman.2023.119578>.

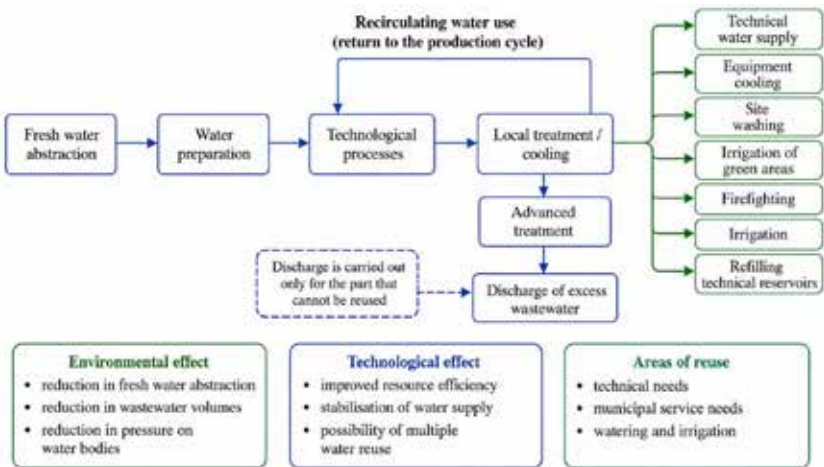


Fig. 10. Schematic diagram of recirculating water use and water reuse within an industrial water-supply system

Source: developed by the author

Despite the considerable potential for treated wastewater reuse, actual global rates remain far below the available potential. According to a study conducted by Utrecht University and the United Nations University Institute for Water, Environment and Health (UNU-INWEH), of the total volume of wastewater generated worldwide each year – 359.4 billion m³, based on 2015 data – only 63% is collected through centralized sewerage systems, 52% undergoes treatment, and just 11% of the total volume is reused (Figure 11)⁴³. According to UN-Water estimates, the potential volume of wastewater available for reuse worldwide is approximately 320 billion m³ per year, which is more than ten times the combined capacity of all existing desalination plants globally⁴⁴. More recent data indicate that, as of 2022, safe treatment covered 56–58% of domestic wastewater and only 38% of industrial wastewater⁴⁵. This confirms that treated wastewater reuse remains an underused opportunity for improving the resource efficiency of water use.

⁴³ Jones E. R., van Vliet M. T. H., Qadir M., Bierkens M. F. P. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth System Science Data*. 2021. Vol. 13, No. 2. P. 237–254. DOI: <https://doi.org/10.5194/essd-13-237-2021>.

⁴⁴ Progress on Wastewater Treatment (SDG indicator 6.3.1). *UN-Water*, 2024. URL: <https://sdg6data.org/en/indicator/6.3.1>.

⁴⁵ Water Quality and Wastewater. *UN-Water*, 2024. URL: <https://www.unwater.org/water-facts/water-quality-and-wastewater>.

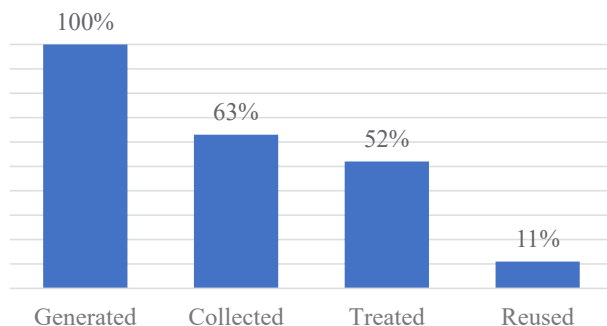


Fig. 11. Global wastewater flows, % of total wastewater generated (359.4 billion m³/year; 2015 data)

Source: compiled by the author based on data from Jones et al.⁴⁶

Bridging the gap between the volume of wastewater treated and the amount actually reused largely depends on the implementation of specific water-saving technologies at the level of individual economic sectors. To summarize the quantitative performance indicators of such approaches, a table was developed based on an analysis of scientific and industry sources. It presents the main water-saving technologies applicable across different sectors of the economy and the expected water savings confirmed by the relevant studies (Table 3). The indicators provided enable a well-founded comparison of the potential of different technological solutions and help identify priority areas for their implementation according to the sector-specific characteristics of water use.

The data summarised in Table 3 indicate that the greatest water-saving potential is associated with technological solutions in the industrial sector, particularly closed-loop cooling systems, which can reduce water use by up to 70%, and recirculating water-supply systems, which can provide savings of up to 50–60%. This is explained by the possibility of repeatedly using the same volume of water within the technological cycle without substantial losses through evaporation or discharge.

In agriculture, which remains the largest consumer of water resources globally, the introduction of drip irrigation and precision farming technologies can provide water savings ranging from 15% to 70%, depending on the crop, soil conditions, and the initial irrigation method. This confirms the considerable untapped potential for improving water-use efficiency in the agricultural sector.

⁴⁶ Ramin E., Faria L., Gargalo C. L., Ramin P., Flores-Alsina X., Andersen M. M., Gernaey K. V. Water innovation in industrial symbiosis: A global review. *Journal of Environmental Management*. 2024. Vol. 349. Art. 119578. DOI: <https://doi.org/10.1016/j.jenvman.2023.119578>.

Table 3

Water-saving technologies by economic sector and their expected water-saving effects

Technology	Sector of application	Reported or expected water savings, %
Drip irrigation	Agriculture	30–70% compared with conventional sprinkler or surface irrigation ¹
Precision agriculture (variable rate irrigation, VRI)	Agriculture	15–50% compared with standard uniform irrigation ²
Water-efficient plumbing fixtures (aerators, faucets, dual-flush toilets)	Municipal sector	20–30%, depending on the type of fixture ³
Recirculating and closed-loop water-supply systems in industrial processes	Industry	Up to 50–60% of the enterprise's total water consumption ⁴
Closed-loop cooling systems	Industry, digital infrastructure	Up to 70% compared with open evaporative cooling systems ⁵
Reuse of treated wastewater for technical and irrigation purposes	Municipal sector, agriculture	Depends on the extent to which primary water abstraction is replaced; assessed individually for each facility

Technologies used in the municipal sector, particularly water-efficient plumbing fixtures, demonstrate a more moderate but consistent water-saving effect of 20–30%. These savings can be achieved with relatively low capital investment and short payback periods, making such solutions an accessible means of improving water-use efficiency in households and public buildings. At the same time, the effect of treated wastewater reuse cannot be expressed as a universal quantitative value, as it depends on the characteristics of each facility, including its water consumption, the technical feasibility of replacing primary water abstraction, and the required level of advanced treatment. Therefore, a separate technical and economic assessment is required in each specific case. Overall, the data confirm that the greatest effect can be achieved through the integrated rather than isolated implementation of the technologies considered across the industrial, municipal, and agricultural sectors.

The practical implementation of rational water-use principles can be observed in the activities of international companies across various economic sectors, where water-use efficiency is becoming an integral component of environmental policy and production modernisation. In the food industry, Nestlé improves water-use efficiency at its manufacturing sites, monitors water abstraction and discharge quality, and introduces water reuse and recirculation. As a result, between 2010 and 2024, water abstraction per tonne of product was

reduced by 20%, contributing to lower freshwater consumption and reduced pressure on aquatic ecosystems⁴⁷.

In the chemical industry, BASF provides a notable example by applying on-site treatment of industrial wastewater, membrane bioreactors, and water quality monitoring systems. As of 2024, the company had achieved 65% of its target for implementing sustainable water management at production sites located in water-stressed areas. By 2030, it plans to ensure full coverage of such sites, which account for approximately 90% of the company's total water abstraction⁴⁸. This example demonstrates the importance of combining conventional treatment technologies with modern high-efficiency advanced treatment methods.

In the beverage industry, Coca-Cola companies implement water treatment, recirculation, and reuse during equipment cleaning, container preparation, and other technological operations. Between 2015 and 2024, the Water Use Ratio was reduced from 1.98 to 1.78 litres of water per litre of beverage produced, corresponding to an approximately 10% improvement in water-use efficiency⁴⁹. These measures help reduce specific water consumption per unit of product and decrease wastewater generation.

Water-use efficiency is also becoming increasingly important for the digital infrastructure sector, particularly in data centre operations. Microsoft is introducing technologies aimed at reducing freshwater use and improving the efficiency of cooling systems. From the early 2000s to 2023, the water-use intensity of its data centres decreased by more than 80%⁵⁰. In fiscal year 2025, Microsoft replenished more than 14 million m³ of water globally, exceeding its total water withdrawals for the first time and marking an important milestone towards becoming water positive by 2030⁵¹.

The examples presented confirm that, in contemporary practice, rational water use is implemented through a combination of technological, organizational, digital, and managerial solutions. At the same time, the effectiveness of such measures increases when they are introduced within the framework of integrated water resources management, which involves coordinating the interests of different water users, considering the ecological needs of aquatic ecosystems,

⁴⁷ Nestlé's Sustainability Strategy. The Sustainable Innovation, 2026. URL: <https://thesustainableinnovation.com/nestle-sustainability/>.

⁴⁸ BASF. E3 water: BASF report 2024. URL: <https://report.basf.com/2024/en/combined-managements-report/consolidated-sustainability-statement/environment/e3-water.html>.

⁴⁹ The Coca-Cola Company. 2024 Environmental Update. URL: <https://www.coca-colacompany.com/content/dam/corporate/us/en/reports/2024-environmental-update/2024-environmental-update.pdf>.

⁵⁰ Sustainable by design: Transforming datacenter water efficiency. Microsoft Cloud Blog, 2024. URL: <https://www.microsoft.com/en-us/microsoft-cloud/blog/2024/07/25/sustainable-by-design-transforming-datacenter-water-efficiency/>.

⁵¹ Microsoft. 2026 Environmental Sustainability Report. 2026. URL: <https://surl.li/zwvnvzh>.

applying the river-basin management principle, and integrating the quantitative and qualitative aspects of water use. Within this approach, decisions concerning water abstraction, wastewater discharge, wastewater treatment, the protection of water bodies, and the development of water infrastructure should be made with regard to the condition of the entire river basin rather than individual administrative or industrial areas.

Within the sustainable development framework, rational water use performs not only an environmental but also a socio-economic function. It contributes to ensuring access to high-quality water, reducing risks to public health, improving the reliability of water supply, and strengthening the environmental safety of territories. In the long term, the rational use of water resources is a prerequisite for adaptation to climate change, the prevention of water scarcity, and the maintenance of the resilience of natural and economic systems.

CONCLUSIONS

The study has demonstrated that the protection of water bodies and rational water use are essential components of sustainable development, as water resources support the functioning of natural ecosystems, industrial processes, food security, and quality of life. Under conditions of climate change, increasing anthropogenic pressure, and growing risks of water scarcity, water protection measures should be regarded as part of an integrated environmental safety system.

It has been established that effective water treatment requires an integrated approach combining mechanical, physicochemical, biological, membrane, and nature-based methods with on-site industrial wastewater and stormwater treatment. The comparison showed that no single method can be regarded as universally superior. Membrane bioreactors provide the highest overall removal efficiency for organic matter, suspended solids, and nutrients, whereas nature-based solutions are particularly important for regulating surface runoff and providing complementary removal of nutrients and suspended solids. The most appropriate approach is to develop combined treatment schemes that take into account wastewater composition, the nature of pollution, operational limitations, and the potential for treated water reuse.

The analysis of water-use indicators showed that agriculture accounts for the largest share of water abstraction globally, whereas the industrial and municipal sectors predominate in Ukraine. Despite Ukraine's relatively low level of water stress, the specific structure of water abstraction, losses in water-supply networks, and insufficient levels of treated wastewater reuse necessitate the targeted implementation of resource-efficient solutions.

It has been substantiated that rational water use should be regarded as a component of a resource-efficient and circular development model. Its priority areas include reducing water losses, modernizing water infrastructure, introducing water-saving technologies, implementing recirculating water use, applying on-site treatment of process streams, reusing treated wastewater, and adopting a river-basin approach to water resources management. The implementation of these measures contributes to reducing water abstraction and wastewater generation, decreasing pressure on water bodies, and enhancing the water security of territories.

The review of current practices confirmed the feasibility of shifting from the linear “abstraction – use – discharge” model to recirculating and closed-loop water-supply systems. Water recirculation, treated wastewater reuse, modernisation of treatment systems, and monitoring of specific water consumption make it possible to improve resource efficiency both in traditionally water-intensive industries and in emerging economic sectors.

An important prerequisite for the further development of sustainable water use is the comprehensive assessment of the effectiveness of combined water treatment technologies, nature-based solutions, and water reuse and recirculation systems, taking into account the environmental, technological, and economic feasibility of their implementation. A well-founded combination of these approaches creates the conditions for reducing anthropogenic pressure on aquatic ecosystems, improving resource efficiency, and ensuring the long-term water security of territories.

SUMMARY

The article substantiates environmental and technological solutions for water treatment and identifies priority areas of rational water use in the context of sustainable development. Mechanical, physicochemical, biological, membrane-based, and nature-based methods of wastewater treatment are considered. These methods are comparatively assessed in terms of their efficiency in removing organic matter, suspended solids, and nutrients; application conditions; by-product generation; and the potential for treated water reuse. It is established that the choice of treatment method should take into account wastewater composition, the nature of pollution, application conditions, and treated-water quality requirements, while the highest efficiency can be achieved by combining complementary technologies in integrated treatment schemes. Current trends in global and national water use, the sectoral structure of water abstraction, and water stress levels are analysed. The need to reduce water losses, modernize water infrastructure, introduce water-saving technologies, and implement recirculating and closed-loop water-supply systems is substantiated. The role

of treated wastewater reuse and the transition from a linear water-consumption model to a resource-efficient circular model is highlighted. It is concluded that integrating treatment technologies, nature-based approaches, and rational water use provides a foundation for reducing anthropogenic pressure on water bodies and ensuring long-term water security.

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