Journal of Technology Studies
November 2026, Volume: 3, Issue: 4, pp. 15−21
DOI: https://doi.org/10.36719/3104-4735/6/15-21

Modern Water Purification Technologies: Integrated Treatment Processes and Sustainable Applications

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Abstract. *Water purification is essential for protecting public health, supporting economic activity, and reducing pressure on freshwater resources. This article reviews conventional and advanced technologies used to improve the quality of surface water, groundwater, and saline sources. It outlines the roles of source protection, coagulation and flocculation, sedimentation, granular and membrane filtration, adsorption, and disinfection within a multi-barrier treatment approach. Particular attention is given to membrane processes, including microfiltration, ultrafiltration, nanofiltration, reverse osmosis, forward osmosis, and electrodialysis, with emphasis on their separation mechanisms, operational requirements, and limitations. The study uses a narrative and comparative review of technical literature, standards, and recent research, including work published in Azerbaijani scientific journals on Caspian Sea desalination and water-resource protection. The comparison shows that no single method is suitable for every source: treatment trains should be selected according to raw-water quality, target contaminants, required water quality, energy demand, maintenance capacity, and residual management. The article concludes that combining appropriate treatment stages with routine monitoring and effective source-water governance offers a practical basis for reliable and sustainable water purification.*

Keywords: *water purification, drinking-water quality, coagulation and flocculation, filtration, membrane technologies, reverse osmosis, nanofiltration, disinfection*

Introduction

Access to safe water depends not only on the availability of water resources but also on the ability to protect, treat, distribute, and monitor them. Surface water and groundwater may contain microbial hazards, suspended matter, dissolved salts, natural organic compounds, and contaminants introduced by agriculture, industry, and urban activity. The World Health Organization (WHO, 2026) therefore frames drinking-water safety as a preventive, risk-based process that extends from the catchment to the consumer and combines health-based targets, water safety planning, and independent surveillance.

Treatment technologies are most effective when they form part of an integrated system rather than being selected as isolated devices. Source protection, pretreatment, clarification, filtration, disinfection, and routine monitoring each address different classes of hazards. For Azerbaijan, the protection and sustainable management of water resources are also important institutional and environmental priorities, particularly where pollution pressures and transboundary water issues are involved (Allahverdiyev, 2025).

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Received: 2 Jule 2026; Accepted: 6 October 2026; Published online: 9 November 2026
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This article reviews the principal processes used in modern water purification, compares conventional and membrane-based technologies, and considers the conditions under which household and small-scale systems may be appropriate. The aim is to provide a concise technical overview that connects treatment performance with source-water quality, operational requirements, and long-term sustainability.

Methods

The article is based on a narrative review and comparative analysis of technical books, drinking-water guidance, standard analytical methods, and recent research relevant to water treatment. Technologies are compared according to their principal removal mechanisms, target contaminants, operating requirements, maintenance needs, and potential environmental trade-offs. Particular attention is paid to filtration and membrane processes because they play a central role in the treatment of turbid, saline, and dissolved-contaminant-bearing waters. The discussion also draws on recent Azerbaijani research addressing nanofiltration in hybrid Caspian Sea desalination systems and the legal protection of national water resources (Ahmadova & Rustamli, 2026; Allahverdiyev, 2025). This is a narrative technical review; it does not report new laboratory experiments or claim a systematic database search. In practice, raw-water and treated-water samples should be collected and analysed using validated procedures, such as those described in Standard Methods (American Public Health Association et al., 2017).

1. Water Sources and Common Contaminants

The principal sources used for water supply are surface waters, including rivers, lakes, and reservoirs, and groundwater stored in aquifers. Their quality varies with geology, land use, climate, and human activity. Surface waters are generally more exposed to runoff, erosion, wastewater discharges, and seasonal changes. They may contain suspended sediments, algae, natural organic matter, nutrients, pathogenic bacteria, viruses, and protozoa. Agricultural and urban runoff can also introduce pesticides, nitrates, hydrocarbons, and other chemical substances (WHO, 2026).

Groundwater is often less turbid because soil and geological layers provide a degree of natural filtration. Nevertheless, groundwater may contain naturally occurring dissolved substances, including arsenic, fluoride, iron, manganese, and salts, depending on local geology. Nitrate contamination may arise from fertilisers, animal waste, or poorly managed sanitation systems. Consequently, the choice of treatment should be based on a site-specific analysis rather than on the assumption that surface water is always more contaminated or that groundwater is inherently safe. Protecting water sources and strengthening pollution-prevention measures are necessary complements to treatment at the plant or household level (Allahverdiyev, 2025; WHO, 2026).

2. Conventional Water Treatment Processes

2.1. Pretreatment, Coagulation, Flocculation, and Sedimentation

Pretreatment removes coarse debris and prepares raw water for subsequent processes. Bar screens, strainers, and grit-removal units protect pumps and other equipment from leaves, branches, sand, and similar material. Where necessary, pH adjustment and chemical conditioning are used to create conditions suitable for clarification.

Coagulation involves adding a coagulant, commonly an aluminium- or iron-based salt, to destabilise fine suspended and colloidal particles. During flocculation, controlled mixing encourages these particles to combine into larger aggregates, or flocs, that can be removed by sedimentation or flotation. The required coagulant dose and operating pH depend on the raw-water characteristics and should be established through appropriate testing, such as jar tests. Poor control may increase

chemical consumption, produce excessive sludge, or reduce downstream filtration performance (Bratby, 2016; Crittenden et al., 2012).

Sedimentation allows heavier flocs to settle under gravity before filtration. It reduces the solids load on filters and can improve the stability of the overall treatment train. Sludge generated during clarification must be collected and managed safely; returning untreated sludge or wash water to the source may reintroduce contaminants.

2.2. Filtration and Adsorption

Filtration removes particles that remain after clarification and, depending on the filter medium and operating conditions, can reduce a portion of the microbial load. Rapid gravity or pressure sand filters use granular media and are commonly applied after coagulation and sedimentation. Their performance depends on media characteristics, filtration rate, bed depth, pretreatment quality, and filter operation. Accumulated solids increase head loss, so periodic backwashing is required (Crittenden et al., 2012).

Slow sand filters operate at lower filtration rates and rely on both physical retention and biological activity within the upper layer of the filter bed. They can be useful for small or decentralised supplies where land and operating time are available. However, their performance depends on appropriate maturation, careful operation, and suitable raw-water turbidity. Ceramic household filters are another point-of-use option; field performance varies with design, manufacturing quality, handling, and maintenance, so products should be selected on the basis of independent testing rather than general claims (Lantagne, 2001).

Activated carbon is used primarily to adsorb taste and odour-causing compounds and certain dissolved organic substances. It may be installed as granular activated carbon in treatment plants or as a replaceable cartridge in household devices. Activated carbon is not a universal barrier: it does not reliably remove dissolved salts, and its performance depends on the contaminant, contact time, carbon condition, and replacement schedule. It should therefore be selected for a defined treatment objective and combined with other processes when necessary (Crittenden et al., 2012).

2.3. Disinfection

Disinfection is intended to inactivate pathogenic microorganisms remaining after clarification and filtration. Chlorine-based compounds are widely used because they are effective against many bacteria and viruses and can maintain a disinfectant residual in the distribution system. Their application requires control of dose, contact time, pH, and water quality; reaction with natural organic matter may form disinfection by-products. Ultraviolet (UV) treatment inactivates microorganisms without adding a chemical residual, but its performance depends on adequate UV transmittance, lamp condition, and the absence of excessive turbidity. Disinfection should therefore be treated as one barrier within a multi-stage process, not as a substitute for removing particles and chemical contaminants (WHO, 2026).

3. Advanced and Membrane-Based Technologies

3.1. Microfiltration and Ultrafiltration

Microfiltration and ultrafiltration use pressure-driven membranes to retain suspended particles and microorganisms according to membrane characteristics and operating conditions. They can provide a compact alternative or supplement to granular filtration and are often used as pretreatment for more selective membrane processes. Their limitations include membrane fouling, pressure loss, cleaning requirements, and the need for appropriate management of backwash streams and cleaning wastes.

Membrane integrity and treated-water quality should be monitored throughout operation (Crittenden et al., 2012; WHO, 2026).

3.2. Nanofiltration and Reverse Osmosis

Nanofiltration (NF) is particularly useful for reducing hardness and retaining many multivalent ions and selected organic compounds. Reverse osmosis (RO) applies greater pressure across a semipermeable membrane and is used to reduce dissolved salts and a broad range of dissolved contaminants. Both processes can produce high-quality permeate, but their efficiency depends on feed-water composition, membrane selection, pressure, recovery ratio, and pretreatment. Scaling and fouling can reduce flux and increase energy use; the concentrate stream also requires environmentally appropriate management (Crittenden et al., 2012).

The use of nanofiltration as a pretreatment step is relevant to hybrid desalination systems. This study examines the use of nanofiltration within hybrid systems for the treatment of Caspian Sea water and discusses its potential to prevent the formation of sulfate deposits (scaling) on reverse osmosis membranes and thermal distillation surfaces in subsequent stages (Ahmadova & Rustamli, 2026). This local study provides a useful example of how membrane selection and pretreatment can be adapted to the chemical composition of a specific water source. Its findings should be interpreted in the context of the feed-water conditions and system configuration considered by the authors.

3.3. Forward Osmosis and Electrodialysis

Forward osmosis uses an osmotic pressure difference between feed water and a concentrated draw solution to move water through a semipermeable membrane. It may be considered for selected concentration or desalination applications, although the draw solution must subsequently be regenerated and this can add energy demand and process complexity. Electrodialysis uses an electric field and ion-selective membranes to move dissolved ions from one stream to another. It is generally considered for brackish or moderately saline water; its suitability depends on salinity, water recovery, electricity cost, and scaling or fouling risks. These methods should be evaluated against RO and other options using site-specific technical and economic data.

Table 1
Comparative overview of selected water purification technologies

Technology	Main treatment function	Advantages	Main limitations / controls
Coagulation and flocculation	Destabilises colloids and aggregates fine particles for later removal.	Improves clarification and reduces the solids load on filters.	Coagulant dose and pH need optimisation; sludge must be managed.
Sand filtration	Retains suspended particles and reduces turbidity after clarification.	Established, relatively simple treatment stage.	Requires suitable pretreatment, head-loss monitoring, and backwashing or surface cleaning.
Activated carbon	Adsorbs selected dissolved organic compounds and taste- or odour-causing substances.	Can improve aesthetic quality and reduce some organic contaminants.	Does not remove dissolved salts reliably; media must be replaced or regenerated.

Technology	Main treatment function	Advantages	Main limitations / controls
Microfiltration / ultrafiltration	Membrane barrier for particles and many microorganisms.	Compact process; can serve as a pretreatment or clarification step.	Membrane fouling, integrity monitoring, cleaning, and residual management are required.
Nanofiltration / reverse osmosis	Removes selected dissolved ions and, in RO, a broad range of dissolved salts.	Suitable for softening, demineralisation, and desalination.	Energy demand, scaling, fouling, pretreatment, and concentrate disposal must be considered.
Chlorination / UV disinfection	Inactivates susceptible microorganisms.	Chlorine can provide a residual; UV avoids chemical addition.	Chlorine may form by-products; UV needs clear water and reliable power; neither removes dissolved chemicals.

Source. Compiled by the author based on Bratby (2016), Crittenden et al. (2012), and WHO (2026).

Membrane technologıes and emergıng contamınants. Recent research has increasingly focused on improving membrane-based water purification technologies to address the limitations of conventional treatment methods. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis differ in their separation mechanisms and effectiveness in removing suspended particles, microorganisms, dissolved salts, and emerging chemical contaminants. The performance of these technologies depends on membrane composition, pore structure, surface properties, and the physicochemical characteristics of the source water. Studies have demonstrated that membrane modification and the incorporation of nanomaterials can improve filtration performance and contribute to the removal of a broader range of pollutants (Aziz et al., 2024; Cevallos-Mendoza et al., 2022). Furthermore, recent developments in membrane science have explored integrated separation and degradation approaches for emerging pollutants that may not be adequately eliminated through conventional treatment processes (Zhao et al., 2024). However, membrane fouling, energy consumption, and maintenance requirements remain important factors when selecting an appropriate treatment system.

Mıcrobıologıcal safety and ıntegrated water treatment. An important aspect of water purification is the reliable removal or inactivation of microbiological contaminants. Recent systematic reviews indicate that the effectiveness of physical treatment processes, including granular filtration, slow sand filtration, membrane separation, and clarification, varies depending on the type of microorganism, source-water quality, and operational conditions (Burke et al., 2025). At the household level, ceramic filters, membrane-based systems, ultraviolet irradiation, thermal treatment, and chemical disinfection represent important approaches to improving drinking-water safety. Nevertheless, their effectiveness depends not only on the technical characteristics of the devices but also on proper operation, regular maintenance, and consistent use (Rao et al., 2025). In this regard, the integration of several treatment stages provides a more comprehensive approach to water purification. Combining source-water protection, pre-treatment, filtration, and disinfection is consistent with established water-treatment principles and international drinking-water quality recommendations (Bratby, 2016; Crittenden et al., 2012; World Health Organization [WHO], 2017).

4. Household and Point-of-Use Treatment

Household and field-based systems are designed for situations where a centralised supply is unavailable, unreliable, or requires an additional treatment barrier. Common options include ceramic and other mechanical filters, chlorine-based disinfectants, UV devices, and small reverse-osmosis

units. The appropriate option depends on the contaminants present: disinfection can reduce microbial risk but does not remove dissolved metals or salts, while membrane systems may reduce dissolved contaminants but require more careful maintenance and management of reject water. Household devices should be used according to validated performance claims and manufacturer instructions, and treated water must be stored in clean, covered containers to avoid recontamination (Lantagne, 2001; WHO, 2026).

No single household technology addresses every possible hazard. For example, a particle filter may improve clarity without removing dissolved chemicals; chlorine may inactivate many pathogens but is less effective against some chlorine-resistant protozoa; and UV treatment is less reliable when water is highly turbid. Where chemical contamination is suspected, a microbial disinfection method alone is insufficient. Source-water testing and selection of a treatment method certified for the contaminant of concern are therefore essential.

Discussion

The review indicates that treatment selection should begin with an assessment of raw-water quality and the intended use of the treated water. A conventional treatment train combining coagulation, flocculation, sedimentation, filtration, and disinfection may be appropriate for many surface-water supplies. Where dissolved salts, hardness, or selected micropollutants are the main concern, membrane technologies may be required. In all cases, the additional benefits of advanced treatment should be weighed against energy consumption, chemical use, maintenance capacity, concentrate or sludge disposal, and the ability to monitor performance over time.

The Azerbaijani studies considered here highlight two complementary dimensions of water security. Ahmadova and Rustamli (2026) address a technical challenge in Caspian Sea desalination by examining nanofiltration as part of a hybrid treatment train. Allahverdiyev (2025), by contrast, focuses on the legal and institutional protection of water resources and the need for effective implementation, monitoring, and coordination. Taken together, these works reinforce the point that sustainable water purification depends on both suitable engineering and sound resource governance.

Performance verification should be part of routine operation. Monitoring may include turbidity, pH, conductivity, disinfectant residual, membrane pressure and flux, and relevant microbiological or chemical parameters. The indicators selected must match the source-water risks and treatment objectives. Sampling and laboratory analysis should follow recognised procedures, and results should be interpreted against the applicable national requirements and current international guidance (American Public Health Association et al., 2017; WHO, 2026).

Conclusion

Water purification is most reliable when it is designed as a multi-barrier process that combines source protection, appropriate pretreatment, clarification, filtration, and disinfection. Conventional processes remain important for removing suspended solids and controlling microbial hazards, while membrane technologies extend treatment capability to dissolved salts, hardness, and selected chemical contaminants. Nanofiltration can also serve as a useful pretreatment in hybrid desalination systems, provided that its performance is evaluated for the specific feed-water composition.

The selection of a treatment system should be based on verified water-quality data, the intended use of the treated water, operational capacity, energy requirements, maintenance needs, and safe management of treatment residuals. Household devices can provide an additional barrier in appropriate settings, but they are not interchangeable and should not be assumed to remove all contaminants. Ultimately, reliable water purification requires regular monitoring, transparent management, and effective protection of water sources alongside technological improvement.

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